MICROMIRRORS FOR INTEGRATED TUNABLE MID-INFRARED DETECTORS AND EMITTERS

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ABSTRACT

The mid-infrared range is of interest in spectroscopic applications, due to the large number of organic compounds that exhibit characteristic absorption bands in this spectral region. Semiconductor technology, however, has been developed mainly for the near-infrared, for applications in telecom, as well as in the far-infrared, mostly driven by the interest in thermographic applications.

In this thesis, micromirrors for novel integrated narrow-band tunable mid-infrared detectors and emitters are presented. Both such detectors and emitters can be fabricated by placing an active layer inside a resonant microcavity, which consists of two reflectors facing each other. Both narrowband mid-infrared sensors and lasers can be fabricated using epitaxial growth of lead-chalcogenides on silicon substrates. With the same materials, high reflectivity distributed Bragg reflectors can be fabricated, which can be used as resonant cavity mirrors. The resonance wavelength for sensors and for lasers depends on the cavity length. Length and finesse of the resonant cavity determine the resonance wavelength and the detection (emission)
Abstract

linewidth. One possibility to make the sensor or the laser tunable over a certain wavelength region is to vary the cavity length. This can be achieved through a mechanically moving micromirror at one end of the resonant cavity.

The challenges for such mechanically moving micromirrors lie in the fabrication of high quality reflective surfaces with a movement perpendicular to the wafer surface in the range of the detection wavelength, i.e. of some micrometers for the mid-infrared. The suspensions have to be designed sufficiently soft for obtaining reasonably low actuation voltages for the required displacements, but sufficiently stiff in order to retain adequate mechanical stability. Reflectivity, curvature and parallelism of the movable micromirrors in the resonant cavity have to be controlled in order to adapt the resonant cavity layout and finesse to the needs of the relevant application.

Within the scope of this thesis, two variants of micromirrors for integrated tunable detectors and emitters have been investigated, including design, process development and fabrication. The micromirrors were fabricated in the device layer of a Silicon-On-Insulator wafer using Deep Reactive Ion Etching and standard microfabrication technology. Using these fabrication methods, very compact integrated systems can be manufactured. Both micromirror variants are equally suited for implementation in tunable detectors and tunable emitters. In both variants, the displacement vertical to the wafer surface is obtained by electrostatic actuation, on the one hand with actuation electrodes in a parallel plate configuration, and on the other hand with comb drive actuators.

The layout includes the design of the micromirror, the configuration of the suspension beams and the electrostatic actuator design in order to obtain the desired displacements. The typical micromirror square length is between 300 µm and 600 µm, thickness 10 µm, and the suspensions are accommodated in a square frame with a typical length ranging from 0.8 mm to 1.5 mm. However, there remains room for further minimizing the footprint.

The micromirrors fabricated in this work showed displacements around 3 µm at 30 V actuation voltage, depending on the geometry. High mirror reflectivity was achieved by a 60 nm thin gold coating. The micromirrors’ radii of curvature have been adjusted precisely in the range of centimeters by applying an additional chrome thin film on the mirror, and separated actuation electrodes allowed tilting of the micromirrors in order to achieve a parallel alignment inside the resonant cavity. The mechanical resonance frequencies occur above a few kHz and may be adjusted by the design of the mirror geometry and the suspensions. At atmospheric pressure, the mechanical resonances are strongly degraded by squeeze-film air damping, reducing
Q-factors typically below 100. At low pressures, below 1 μbar, Q-factors increase typically over 3’000.

In collaboration with the Thin Film Physics group at ETH Zürich, fabricated micromirrors of both types have been joined successfully with photodiodes to form tunable resonance cavity enhanced detectors. During assembly, temperatures are kept below 110°C in order to avoid diffusion processes which could deteriorate the device performance.

The use of the micromirrors allowed the realization of very compact tunable detector systems in the mid-infrared. These are the first tunable resonant cavity enhanced detectors in the mid-infrared that have been presented to date. Using parallel plate actuated micromirrors, detectors with a single mode tuning range from 4.85 μm to 5.15 μm have been presented, and using comb drive actuated micromirrors, a wide wavelength tuning range from 4.7 μm to 5.4 μm has been achieved.

The detector performance was limited by the broadened linewidth due to finesse degradation, among others influenced by reflectivity, curvature and departure from parallelism. The detector linewidth was about 0.1 μm. A narrower linewidth can be obtained with a higher initial cavity length, thus a higher operating resonance mode, however, to the cost of a reduced free spectral range, i.e. a reduced tuning range. Alternatively, linewidth reduction can be achieved by increasing the cavity finesse which can be obtained by fabrication process improvements.

Finally, a spectroscopic application has successfully been demonstrated using a tunable mid-infrared resonant cavity enhanced detector, which was used to detect carbon monoxide in a 5 cm long gas cell filled with a carbon monoxide partial pressure of 250 mbar. In a further step, implementation of the micromirrors in vertical external cavity surface emitting lasers is envisioned. The developed micromirrors are suitable for these applications without modification in the fabrication process; the expected narrow emission linewidth of a few nanometers make them among others potentially interesting for spectroscopic applications.
ZUSAMMENFASSUNG


Zusammenfassung


Im Rahmen dieser Dissertation wurden zwei Varianten von Mikrospiegeln untersucht. Prozessentwicklung und Herstellung erfolgten mittels Tiefenätzen und mikrotechnischer Standardfabrikationsmethoden in Silizium, was die Herstellung äußerst kompakter Systeme erlaubte. Beide Mikrospiegelvarianten eignen sich sowohl für einen Einsatz in durchstimmbaren Detektoren als auch in durchstimmbaren Emissoren. Bei beiden Varianten wird die notwendige Verschiebung des Mikrospiegels mittels elektrostatischer Anregung erreicht. Im ersten Fall sind die Elektroden als Plattenkondensator angeordnet, im zweiten Fall sind die Elektroden als comb-drives realisiert.

Die Auslegung umfasste die Gestaltung des Mikrospiegels, die geometrische Anordnung der Aufhängungen und die elektrostatischen Aktoren um die gewünschte Verschiebung zu erreichen. Die quadratischen Mikrospiegel haben typischerweise eine Seitenlänge von 300 μm bis 600 μm, eine Dicke von 10 μm, und die Aufhängungen sind in einer quadratischen Aussparung mit einer Seitenlänge von typischerweise 0.8 mm bis 1.5 mm angeordnet. Eine weitere Reduktion dieser Grundfläche ist jedoch möglich.

Bei einer Anregungsspannung um 30 V konnten die hergestellten Mikrospiegel um ca. 3 μm verschoben werden. Hohe Reflektivität wurde mittels einer 60 nm dünnen Goldbeschichtung erreicht. Krümmungsradien im Bereich von Zentimetern konnten durch Auftragen einer zusätzlichen dünnen Chromschicht gezielt eingestellt werden. Mehrere getrennte Aktuationslektroden erlauben das Verkippen der Mikrospiegel wodurch eine parallele Ausrichtung innerhalb des Mikroresonators
ermöglicht werden kann. Die mechanischen Resonanzfrequenzen liegen im Bereich von mehreren kHz und können mit der Anordnung und Geometrie der Aufhängung eingestellt werden. Bei atmosphärischem Umgebungsdruck wurden Q-Faktoren typischerweise unter 100 gemessen. Insbesondere die Luft zwischen den Kondensatorplatten dämpft hierbei die mechanischen Resonanzen. Bei einem Druck unter 1 µbar konnten entsprechend höhere Q-Faktoren, typischerweise mehr als 3’000 gemessen werden.

In Zusammenarbeit mit der Dünnschichtphysikgruppe der ETH Zürich wurden hergestellte Mikrospiegel erfolgreich mit Infrarotsensoren zu durchstimmbaren Detektoren verbunden. Beim Zusammenfügen wurde insbesondere darauf geachtet, dass die Prozesstemperaturen 110°C nicht überschreiten, um Diffusionsprozesse zu unterbinden, welche zu Performanceeinbussen führen könnten.

Mit den hergestellten Mikrospiegeln konnten äußerst kompakte, durchstimmbare Detektorsysteme realisiert werden. Dies ist der erste Bericht über durchstimmbare resonanzverstärkte Detektoren im mittleren Infrarotbereich. Bei einer Detektorversion basierend auf der Plattenkondensatorvariante konnte die Detektionswellenlänge eines einzelnen Mode über einen Bereich von 4.85 μm bis 5.15 μm vorschoben werden, mittels eines comb-drive Aktuators konnte ein Wellenlängenbereich von 4.7 μm bis 5.4 μm abgedeckt werden.

Die Detektorperformance wurde durch eine relativ breite Linienbreite beschränkt, welche durch eine verminderte Güte der Kavität hervorgerufen wurde, unter anderem bedingt durch Einflüsse von Reflektivität, Krümmung und Parallelität. Die gemessene Linienbreite betrug ungefähr 0.1 μm. Zum einen kann eine schmalere Linienbreite mit einer grösseren Resonatorlänge erreicht werden, d.h. wenn der Detektor in einem höheren Mode betrieben wird. Dies geht jedoch zu Lasten der freien Weglänge und beschränkt somit den durchstimmbaren Wellenlängenbereich. Eine weitere Strategie für eine verbesserte Linienbreite besteht in der Erhöhung der Güte des Resonators, was unter anderem durch Optimierungen im Herstellungsprozess erreicht werden kann.

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1. **INTRODUCTION**

Miniaturized tunable optical elements, such as tunable detectors or tunable emitters, keep drawing attention among others in optical communication, process control, visualization applications, hyperspectral imaging or space technology fields. Their small size and the potential for significant cost reduction compared with conventional tunable optical systems make them economically interesting in a wide range of applications.

Such tunable optical elements allow scanning through a part of the spectrum of electromagnetic radiation. This spectral information is on one hand of interest for imaging applications, as the wavelength contains additional information to the intensity of a recorded signal. On the other hand, a tunable detector allows dividing electromagnetic radiation from a broadband source into its spectral components, which is essentially a spectrometer. With tunable emitters, the wavelength tuning allows e.g. intracavity absorption spectroscopy or, in telecom applications, coding of information not only in the temporal but in the spectral domain as well, commonly known as wavelength division multiplexing (WDM).
The devices developed and presented in this thesis are laid out for the mid-infrared domain of the electromagnetic spectrum. With single devices, infrared spectroscopy can be performed, and an arrangement of detectors in arrays allows employing the tunable detectors in Adaptive Focal Plane Arrays (AFPA) in multispectral infrared thermography.

1.1. Motivation

The mid-infrared (mid-ir) region of the electromagnetic spectrum, with wavelengths ranging from about 3 μm to 10 μm, is of special interest, as many compounds have strong absorption lines in this region. For example interesting for fire detection are the absorption lines of carbon monoxide (CO, 4.6 μm), carbon dioxide (CO₂, 4.3 μm), nitric oxide (NO, 5.3 μm, 5.5 μm) or nitrogen dioxide (NO₂, 3.4 μm, 6.2 μm), as will be discussed in chapter 6.

Technology, however, has developed on the one hand mainly for telecom wavelength applications at 1.55 μm, or generally for the near-infrared below 3 μm [1], or on the other hand for the infrared domain around and above 10 μm, driven by applications in thermal imaging [2]. Optical materials such as AlAs, GaAs, Si, Ge, InP and InAs have a bandgap from 0.4 eV to 2 eV, which corresponds to wavelength of 0.5 μm to 3 μm. For longer wavelengths, in thermography, mainly Mercury Cadmium Telluride (MCT) detectors are used, with absorption wavelengths depending on the mercury content. In the mid-ir, InSb is a commonly used material for wavelengths from 1 μm to 5 μm. Less commonly used PbTe and PbSe compounds exhibit bandgaps below 0.4 eV, and absorption can be achieved with bandgap engineering by alloying with Sn, Sr or Eu, from below 3 μm up to more than 20 μm.

With these lead-chalcogenide materials, narrowband detector systems and emitters in the mid-infrared wavelength region can be fabricated. Such detectors can be realized using the Resonant Cavity Enhanced Detector (RCED) principle by placing an active photosensitive layer inside a Fabry Pérot cavity formed by two mirrors [3]. The detectors are sensitive at the optical resonances, which depend on the distance between the two mirrors of the cavity. Such an arrangement leads to higher peak quantum efficiencies compared to detector systems based on a combination of a broad-band photo detector with an external filter. Systems of the latter type have recently been realized using MEMS technology (a discussion follows in section 2.3). The RCED approach allows an additional reduction of the noise level due to the smaller active detector volume. Single narrow band wavelength detectors with a fixed mirror distance have been realized for the mid-infrared in the Thin Film
Physics group at ETH Zurich [4]. Displacing one of the cavity mirrors allows then changing the cavity length and thus selecting the detection wavelength.

With the same materials, emitters can be realized as lasers in a configuration known as Vertical External Cavity Surface Emitting Lasers (VECSELs). To do so, an optically active gain medium is placed in a resonant cavity between two mirrors. Again, the wavelength depends on the optical resonances, which depend on the distance between the two mirrors forming the cavity. Displacing one of the cavity mirrors allows changing the cavity length and thus selecting the emission wavelength.

Both, tunable mid-IR detectors and emitters, require good optical quality of the micromirrors for wavelengths of a few micrometers. The applications in RCEDs and VECSELs require such micromirrors with a vertical movement with respect to the wafer surface with a movable range and the resonant cavity dimensions in the range of a few micrometers as well. All these requirements are achievable with standard microfabrication technology. A vast range of different micromirrors have been presented in recent years. Most of these micromirrors are tilting devices for displaying and barcode reading applications, either continuously movable or only with binary states, or movable in the wafer plane for example in optical switches. For continuously tunable RCEDs and VECSELs, a continuously displaceable, vertically to the wafer surface moving micromirror is required. Similar micromirrors have been presented for example in microspectrometers and tunable optical filters.

A range of competitive strategies has been suggested, and partially they have been realized, for making RCEDs and VECSELs tunable in recent years. These included for example electrically or thermally tunable RCEDs. The tuning range of these devices is however very limited, usually some tens of nanometers, and they are sensitive in the near infrared. Tunable lasers using a moving micromirror have been presented by different groups, but for these emitters as well, they are mostly tunable only over a short wavelength domain of some tens of nanometers. A detailed discussion about micromirrors in similar optical systems and about tunable detectors and emitters comparable to the ones presented in this thesis follows in chapter 2.

This project is thus situated in a very competitive and active research field. However, to our knowledge, neither integrated widely tunable narrowband RCEDs nor VECSELs using mechanically displaceable micromirrors as tuning mechanism have been presented for the mid-IR wavelength domain by other research groups so far.
1.2. Project Environment

The research of this thesis has been carried out in the context of an innovation project supported by the Gebert Rüf Stiftung. The foundation supports especially projects that focus on innovative concepts of high relevance and scientific quality that satisfy the basic criteria of originality, effectiveness, transfer potential and interdisciplinarity. For this project, the development of the photosensitive part, based on lead-chalcogenide epitaxial materials, has been located at the Thin Film Physics (TFP) Group at the ETH Zurich. The development of the movable micromirror, main subject to this thesis, has been located at the Institute of Mechanical Systems (IMES) at the ETH Zurich. The close collaboration between the two groups was essential for the success of this project. The working principle of narrowband Resonant Cavity Enhanced Detectors (RCEs) with a fixed resonant cavity distance (thus not tunable), has been demonstrated by the TFP in 2005 [4]. Based on the success, the project for adaptation of this concept to a integrated, miniaturized tunable mid-ir RCE has been initiated. This included the design adaptation of the optical layers, and the development of original movable micromirrors.

1.3. Objectives

This thesis focuses mainly on the development of the micromirrors that are compatible with the diode layout developed at the TFP group to form an integrated, miniaturized tunable mid-ir RCED. The aim was to develop a micromirror design, which is compatible with the diodes developed in the TFP group, however as versatile as possible in order to make an integration with other optical components possible as well. One possible extension is the integration with optically active elements, in order to possibly fabricate in a very similar manner tunable mid-ir Vertical External Cavity Surface Emitting Lasers (VECSELs). A first objective was the design, fabrication and characterization of the micromirrors. Thereupon followed integration with the diodes and the characterization of the complete device. Finally, an application of the sensor system for gas detection had to be demonstrated.
2. **MICRO OPTO-ELECTROMECHANICAL SYSTEMS (MOEMS)**

Micro-Electromechanical Systems (MEMS) are referred to as systems that usually incorporate several electronic and mechanical components with typical feature size in the micrometer domain, but can reach with smallest features down to nanometers and largest features up to several millimeters. Common to all these devices is in general, that they are not fabricated using standard mechanical fabrication processes such as turning, milling or drilling, which encounter their limits before reaching these small scales. Microsystems rely therefore rather on microfabrication techniques than on these conventional fabrication techniques. These microfabrication techniques developed with the advances in miniaturization of electronic components after the invention of the first transistor in the late 1940’s at Bell Labs. The fundamentals of microfabrication processes will not be addressed in this thesis. The ‘Fundamentals of Microfabrication’ by Marc Madou provides a good reference for an overview of microfabrication methods [5]. Hence, the development of
MEMS followed the development in micro-electronics. Although the potential of such miniaturized components was already addressed in the famous talk by R. Feynman in 1959 ‘There is plenty of room at the bottom’ [6], the dawn of MEMS did not rise before the late 1960’s. It is commonly agreed that the first MEMS device was a gold resonating Metal-Oxide-Semiconductor (MOS) gate structure [7]. Subsequently, the technology allowed combining electrical, electronic, mechanical, optical, material, chemical, and fluids engineering disciplines at micro scales. As MEMS developed technology driven, one often refers in this context then also to Microsystem Technology (MST, mainly in Europe).

The prime examples for commercialized MEMS to this day are pressure sensors in altimeters, accelerometers for airbag deploying in the automobile industry, and, more recently, advanced devices in the consumer electronics market such as the Digital Light Processor (DLP) by Texas Instruments (TI) or inertial sensing devices such as gyroscopes and accelerometers, e.g. in mobile phones or in user interfaces for video game consoles.

Interest on combining optical components into MEMS arose during the telecommunication boom in the 1990’s, resulting in advances in Micro-Opto-Electromechanical Systems (MOEMS). Telecom applications were mainly developed for the near infrared (NIR) as the minimal loss in optical fibers is encountered at 1.55 μm transmission wavelength. However, the technological advances in various fields pushing towards longer wavelengths allowed realization of complex devices in the infrared as well.

Spectrometers allow the separation of electromagnetic radiation into the basic spectral components. Modern laboratory spectrometers are nowadays available as table-top systems (e.g. Bruker). For portable applications, these systems have been miniaturized by reducing the size of the individual elements by several companies (e.g. ArcOptix, Bruker). However, microfabrication methods allowed integration of the most important optical elements on a single chip, leading to a drastically decreased size of such systems. These MEMS based microspectrometer systems can be classified by the way of separating the light in the individual spectral components. In the following, an overview over MEMS based realizations of the essential components for infrared spectrometers during the last decade is given. The focus shall be on systems that are comparable to the devices described in this thesis. A good overview over realized MEMS Spectrometers, covering mainly the visible spectrum, can be found in Crocombe’s 2008 reviews series [8, 9, 10, 11]. Mid-Infrared microspectrometer systems are discussed in Graaf’s 2008 thesis [12] with a focus on the different elements needed in microspectrometer systems (IR-source, detectors, etc.).
2.1. Diffractive Grating Microspectrometers

Diffractive grating based spectrometers rely on a grating to separate the electromagnetic radiation into its basic spectral components. Both transmission gratings and reflection gratings can be used. MEMS based spectrometers using a transmission grating have been presented [13, 14], however, most MEMS realizations demonstrated so far are based on reflective diffraction gratings. Relatively simple systems can be fabricated using fixed gratings. A fixed grating is inserted in the optical path. The diffracted light is then shone on a detector line array and the spatial intensity distribution measured at the detector pixels corresponds to the detected spectrum. Such a fixed reflective diffraction grating based microspectrometer has been presented by Grabarnik et al. [15].

![Figure 2-1](image)

*Figure 2-1 – Fixed grating based microspectrometer: a) concept b) Scanning Electron Microscope (SEM) recording of the grating and c) realized device (after [15]).*

In order to overcome the need of a detector array and replace it by one single detector, most commonly, a Czerny-Turner configuration is used, where a diffractive grating is rotated and the spectral component’s intensity is scanned over a broadband detector according to Figure 2-2. In the same figure, a realization of a MEMS based diffraction grating is shown. It has been presented by the Fraunhofer Institute for Photonic Microsystems [16, 17, 18]. Electrostatic actuators in a vertical comb drive configuration are used to induce the rotation of the grating. Silicon suspensions attached to the grating serve as torsion springs. The comb drives are actuated with pulsed voltages typically < 60V between the frame and the grating plate, which induces a sinusoidal oscillation of the grating plate. The oscillation frequencies, depending on the design, lay in the range from about 100 Hz to some kHz with high deflection angles exceeding 10° [16].
In order to scan through the spectrum it is also possible to vary the grating itself. Possibilities include variation of the grating width or the grating depth. Precise fabrication of a large number of grating grooves with variable depth is needed for this. The small size and the large number of grooves necessary have inhibited the improvement of these systems despite early reportings on successful realizations [19]. However, MEMS fabrication technologies recently allowed the successful implementation of a miniature lamellar grating interferometer [20]. The grating facets are fabricated in the device layer of a Silicon on Insulator (SOI) wafer. The fixed facets remain attached to the oxide, whereas the movable facets are connected to a comb drive actuator which allows in-plane displacements with respect to the fixed facets. This MEMS device has been implemented in the commercially available microspectrometer by ArcOptix [21]. Different types of microspectrometers cover the visible and the near infrared up to 2600 nm using InGaAs detectors.
2.2. Fourier Transform Microspectrometers

In Fourier Transform Spectroscopy, the spectrum is obtained from the interferogram of two interfering electromagnetic waves from a Michelson Interferometer. A path difference is introduced in a sample beam with respect to a reference beam. The intensity of the two combined beams is recorded as an interferogram on a detector while scanning through the optical path difference, and the spectrum is finally obtained by a Fourier Transformation of the recorded interferogram. A detailed investigation of the possibilities with miniaturized Fourier Transform Spectrometers can be found in the 2002 thesis by Omar Manzardo [22].

In a Michelson Interferometer configuration, the path difference is obtained by scanning a movable micromirror in the delay line as shown in Figure 2-4.

An integrated MEMS Fourier Transform Spectrometer was presented by Manzardo et al. [23]. The movable micromirror (75 μm x 500 μm) was fabricated in the device layer of a SOI wafer by deep reactive ion etching. The actuation was performed with in plane moving electrostatic comb drive actuators. By applying voltages of ±10 V, a displacement of 77 μm has been achieved, which corresponds to a resolution of 5.2 nm at 633 nm. The device presented is a very elegant design of a miniaturized Michelson Interferometer based Fourier Transform spectrometer with the potential of a high degree of integration. However, there remain unresolved issues concerning the non-linearity of the comb drives and the optical flatness of the vertical mirror, which exhibits scallops after the Deep Reactive Ion Etch (DRIE) step. The surface roughness was measured 36 nm root mean square and the vertical angle was 89.3°.
In order to use the flat surface of a wafer for the reflective mirror surface, Sandner et al. [24] suggested a vertically moving micromirror for a Fourier Transform Spectrometer in a Michelson Interferometer configuration. Figure 2-5 shows the concept drawing of the Michelson Interferometer. The MEMS device is arranged horizontally and allows varying the optical path difference in the probe beam. An integrated laser reference interferometer accessing the backside of the micromirror allows precise position readout. The interferogram is recorded with a Peltier cooled MCT detector.

The movable micromirror for this spectrometer has been fabricated in the device layer of a SOI wafer. The actuation is obtained by electrostatic comb drive actuators. The out-of-plane movement is obtained by applying a rectangular actuation voltage pulse to the comb drives, close to double the mirror resonance frequency with 50% duty cycle. With the applied voltage switched on, the mirror is moving towards the center position. When the actuation voltage is switched off, due to inertia, the mirror moves on, crossing the center position. As soon as the voltage is switched on again, the mirror movement changes direction back towards the center position. In this way, an oscillating displacement is obtained, which is started by an increasing frequency sweep.
Driving the micromirror in a resonance mode, large out of plane movements of ±100 μm have been obtained at 5 kHz. Newer designs propose movements up to ±250 μm at 1 kHz. At these frequencies, high speed spectra recordings can be performed. However, the devices have to be operated at low pressure in order to minimize air damping effects. Therefore, they are placed inside a vacuum packaging. Dynamic mirror deformation is also an issue, but 300 nm root mean square (rms) deformation have been proposed with an improved design, which would meet a λ/10 condition at the lower limit of the intended region of operation from 3 μm to 10 μm. The MEMS mirror is shown in Figure 2-6.

**Figure 2-5** – Microsized Fourier Transform Spectrometer in a Michelson Interferometer configuration. a) Concept including the movable micromirror and the laser reference interferometer for the micromirror position readout and b) realized microspectrometer including housing (after [24]).

**Figure 2-6** – SEM images of the vertically moving micromirror used in the Fourier Transform spectrometer by Sandner et al. [24]. The inset shows the out of plane movement of the micromirror actuated with comb drive actuators and driven in resonance (after [24]).
2.3. Tunable Fabry-Pérot Cavities

A wavelength selective detector can be fabricated by combining a photodetector, sensitive over a broad wavelength band, and a narrowband tunable filter. Typical realizations of tunable filters are tunable Fabry-Pérot (FP) cavities. They consist of an optical cavity defined by two parallel mirrors, one of which is movable. The distance between the two mirrors has to be in the order of magnitude of the targeted detection wavelength. Numerous tunable Fabry-Pérot devices have been fabricated for the near- and mid-infrared during the last years [25]. Three systems with a comparable concept to the detectors presented in this thesis are presented and analyzed.

A miniaturized tunable detector system has been presented by the Microelectronics Research Group (Prof. Lorenzo Faraone) at the University of Western Australia [26, 27]. A tunable Fabry-Pérot filter based on a movable silicon nitride membrane is combined with an HgCdTe (MCT) infrared detector as shown in Figure 2-7. The cavity mirrors are fabricated using alternating layers of germanium and silicon oxide. With the germanium cut-on bandedge at 1.6 μm and the detector cutoff wavelength at 2.5 μm, the device is maintained in a single mode operation. The relatively compliant suspension (thickness around 1 μm [28] and length 40 μm – 100 μm) allows a movement of the 100 μm x 100 μm mirror of 0.5 μm. The wavelength tuning range obtained with this system is 2.2 μm to 1.85 μm using a maximum actuation voltage of 7.5 V. Despite the symmetry of the layer stack, internal stresses led to mirror bow. The curve apex was up to 100 nm for a 100 μm mirror, which corresponds to a radius of curvature of 1.25 cm.

The fabrication process was optimized for monolithic integration of the tunable Fabry-Pérot on the MCT detectors [28]. The detectors do not tolerate high temperatures, therefore the fabrication process is limited to low temperatures (<125°C).

The tunable optical detection system allows selecting wavelength bands in the range from 1.6 μm to 2.5 μm. The advantage of such an approach, is the possibility of using commercially available MCT detector arrays, and then fabricate the tunable filters on top of these.
A similar system based on a micromachined silicon membrane has been developed by Neumann et al. [29, 30]. As shown in Figure 2-8, the silicon membrane is suspended by silicon hinges and the distributed Bragg reflectors are formed by alternating layers of silicon dioxide and silicon nitride. The fabrication process involves four different wafers and is relatively complex. Due to the parallel spring suspensions and the thick mirror membrane, the mirror plates can be kept parallel and the curvature is reduced to a minimum. The fabricated mirrors were 2.2 mm x 2.2 mm in size and the maximum elevation of 35 nm over the mirror length corresponds to a radius of curvature of 69 m. Two detector versions have been presented, with long and short initial cavity lengths respectively, having corresponding tuning ranges from 3.0 \( \mu \text{m} \) to 4.1 \( \mu \text{m} \) and 3.9 \( \mu \text{m} \) to 5.0 \( \mu \text{m} \) respectively.

**Figure 2-7** – Tunable infrared detector system top view (a), cross section (b) and packaged mid-infrared microspectrometer device (c) (after [27]).
2 Micro Opto-Electromechanical Systems (MOEMS)

Figure 2-8 – Tunable Fabry-Pérot filter by Neumann et al. [29]: cross section (a), device overview (b) and packaged tunable infrared detector (c) (after [29]).

The Massachusetts, USA, based company Axsun has recently commercialized a microspectrometer based on a tunable MEMS Fabry-Pérot filter. The MEMS tunable filter is based on the research by Crocombe et al. [31] and has been patented [32]. It is fabricated heterolithically using several wafers. Optical tuning has been reported from 1525 nm to 1550 nm, but several 100 nm tuning range are envisioned.

Figure 2-9 – Tunable MEMS Fabry-Pérot filter implemented in the commercial Axsun microspectrometers: schematic cross section to the left and top view of a realized device to the right (after [31]).
2.4. Tunable RCEDs

Tunable Resonant Cavity Enhanced Detectors (RCEDs) have so far not been presented for the mid-infrared domain. Most of the research has been concentrated on the visible or near-infrared for applications in wavelength division multiplexing (WDM) systems in telecom. Different concepts for wavelength selection with RCEDs have been suggested and realized during the past 25 years.

The most straight forward approach for a ‘tunable’ RCED consists in a placement of RCEDs with different fixed cavity lengths in an array [33]. The tuning is thus obtained with a spatial discrimination of the different detection wavelengths. This WDM detection scheme is fairly simple, but limited to a small channel number. The shared power over the detector array is another limitation of the system. The concept of such a detector is shown in Figure 2-10.

A single-pixel wavelength tunable RCED can be obtained by a change in the refractive index $n$ of the (solid) material in the resonant cavity, changing the optical cavity length and thus the detection wavelength. The refractive index change can be obtained by an applied electrical field. Such a system based on an AlGaAs detector has been realized by Waclawek et al. [34, 35]. In this system, the change in refractive index is coupled with a quantum confined Stark effect, where excitonic absorption peaks shift to red with increasing field strength. The combined effect allows electrical wavelength tuning from 855 nm to 875 nm with a tuning voltage from 0 V to 3 V as shown in Figure 2-11.
Further near-infrared realizations have been published recently. In 2005, Mao et al. [36] presented a tunable RCED structure, where the wavelength is selected by a change in refractive index $n$ of the (solid) cavity length obtained by a temperature change. A tuning of $\Delta n = 0.037$ is achieved with a temperature change of 37°C induced by a circular TiPtAu heater placed around the mesa of the photodetector. Wavelength tuning from 1.4760 μm to 1.4905 μm has been achieved with this device.

Wavelength tuning can also be obtained by a physical change in the cavity length. The first such integrated micro opto-electromechanical system (MOEMS) has been suggested in 1995 [37], but has not been realized so far. The suggested system consists of a micromachined electrostatically controlled membrane and an InGaAs
based detector. The system was intended for a wavelength division multiplexing application, ranging from 0.9 μm to 1 μm. The detector layout and characteristics are shown in Figure 2-13.

Figure 2-13 – Suggested realization of an integrated tunable RCED by Ünlü et al. [37]. Working principle (a) and theoretical tuning capabilities (b). The displacement of an electrostatically actuated, micromachined movable mirror leads to a change in cavity length and thus to a change of the detected wavelength (after [37]).

Wu et al. realized in 1996 a tunable RCED [38] operating at 900 nm, using an InGaAs detector and AlGaAs Distributed Bragg Reflectors (DBR). The movable DBR is suspended on a cantilever (Figure 2-14a). Tuning was achieved electrostatically, a wavelength shift of 30 nm has been obtained with an actuation voltage of 7 V (Figure 2-14b).

Figure 2-14 – Tunable RCED (a) with a movable micromirror suspended on a cantilever. Tuning over 30 nm was achieved (b) with an electrostatic actuation voltage of 7 V (after [38]).
2.5. Tunable VECSELs

Surface emitting semiconductor lasers allow access to the emitted radiation on the surface of a semiconductor chip or wafer. Compared to the predominant edge emitting lasers, in such Vertical Cavity Surface Emitting Lasers (VCSELs) the resonator cavity has to be fabricated in layers on the wafer rather than at the cleaved semiconductor crystal / air interfaces. This can be achieved with highly perfected layers grown by epitaxy, arranged in highly reflective Distributed Bragg Reflectors (DBRs). The possibility to incorporate an external cavity allows an arrangement of integrated Vertical External Cavity Surface Emitting Lasers (VECSELs). As the external cavity is often not mentioned explicitly, the abbreviations VCSEL and VECSEL are used somewhat in equal measure. Similar configurations include Vertical Cavity Semiconductor Optical Amplifiers (VCSOAs) [39].

The access to the laser mode provided by the external cavity may be exploited for intra-cavity frequency doubling or passive mode-locking by inserting a respective functional element inside the external laser cavity. High beam quality, high continuous-wave output power and the possibility of realizing compact sources of ultrashort pulses at high average power are the main advantages of such VECSEL systems as pointed out in the review on VECSELs by Tropper et al. [40].

VECSELs presented so far have mostly been realized for wavelengths in the visible or in the near-infrared. An overview can be found in the above mentioned review on VECSELs [40]. The first mid-infrared VECSEL has been presented by the Thin Film Physics Group at the ETH Zürich [41], with an emission wavelength of 5.3 μm and an external cavity length of approximately 5 cm.

Tunability in VECSELs can be achieved by several means: e.g. by varying the active layer bandgap thermally, by inserting a wavelength selective element (filter) in the external cavity or by changing the external cavity length. The latter is of interest, when the cavity is short and the tuning is performed without mode-hopping in a single longitudinal mode. This requires a very compact realization of the VECSEL, which is realizable with MEMS technology. A number of realizations have been reported (an overview can be found in [39]). As an example, the realization of Maute [42] and Halbritter [43] are presented here, due to the similarity of their realized system to the VECSEL presented in this thesis. The working principle is shown in Figure 2-15a.
The MEMS movable DBR is deflected by an injected heating current. Due to the differences in thermal expansion coefficient of the DBR materials used, the membrane deflects, thus the cavity length is changed and tuning is achieved.

Based on this tuning mechanism, VECSELS have been fabricated exhibiting a tuning range of up to 80 nm around 1.55 µm. The emission spectra and the tuning characteristics of such VECSELS are shown in Figure 2-16.

**Figure 2-15** – Operating principle (a) and realized VECSEL device (b) by Maute et al. (after [44]).

**Figure 2-16** – Recorded VECSEL emission spectra by Riemenschneider et al. [45]. Shown are the relative wavelength shift (a) and the absolute wavelength shift (b) for two different devices with their respective spectral envelope (after [45]).
3. FUNDAMENTALS

The theoretical concepts for tunable Resonant Cavity Enhanced Detectors (RCEDs) and tunable Vertical External Cavity Surface Emitting Lasers (VECSELs) are presented in this chapter. The focus is on the physical principles and the relationships that lead to the design parameters for the realized micro devices presented in chapter 5.

For the tunable RCEDs, the review article by Ünlü & Strite [3] and the ETH dissertation by Martin Arnold [46] may prove useful for further reading.

For the tunable VECSELs, the basic laser dimensioning can be deduced from Hogelink & Li [47] and the dissertation by Markus Maute [42] may serve as a reference for a comparable miniaturized tunable VECSEL system.
3.1. Tunable Resonant Cavity Enhanced Detectors

A Resonant Cavity Enhanced Detector (RCED) is obtained by placing a photosensitive device inside a Fabry-Pérot cavity as shown in Figure 3-1. The benefits of such a configuration are wavelength selectivity and increase of the resonant optical field inside the cavity. The increased optical field inside the cavity makes it possible to reduce the thickness of the active device structure, thus increasing the speed and the quantum efficiency at the resonant wavelengths. With a thinner active layer, the volume where generation-recombination noise and diffusion currents are generated is smaller than in a conventional photodiode. This results in an improved noise limit. Driven by wavelength division multiplexing applications, RCEDs have first been demonstrated for optical communication wavelengths [3]. For the mid-IR range, RCEDs using InAs, MCT and PbTe have been realized. An overview is given and discussed by Arnold [46].

![Figure 3-1 - Generalized Resonant Cavity Enhanced Detector with a photosensitive layer placed inside a Fabry-Pérot cavity.](image)

- $\alpha$: absorption coefficient in the active region
- $\alpha_{ex}$: absorption coefficient in the cavity outside the active region
- $R_1$, $R_2$: mirror intensity reflectivities
- $\Psi_1$, $\Psi_2$: phase shift at the mirrors
- $d$: active region thickness
- $L$: total cavity length
- $L_1$, $L_2$: partial cavity length
- $P_I$: infrared radiation power impinging on the detector
- $P_A$: power absorbed inside the active region
3.1.1. **Quantum Efficiency and Resonant Cavity Enhancement**

The quantum efficiency of a photodetector is defined as the probability that a single photon incident on the device generates an electron-hole pair which contributes to the detector current. For a highly sensitive photodetector, high quantum efficiency is desired. The resonance effect of the cavity in a RCED can be exploited to maximize the quantum efficiency. For a generalized RCED as shown in Figure 3-1, an analytical expression for the quantum efficiency can be established. For this, the optical power absorbed inside the active area $P_a$ is compared to the total power incident onto the detector $P_i$. Under the assumption, that all photogenerated carriers contribute to the detector power $P_a$, this corresponds to the quantum efficiency. The optical power inside the cavity can be calculated from the sum of the power of the forward traveling electromagnetic plane wave and the power of the backward traveling electromagnetic plane wave inside the cavity. This leads to the expression for the quantum efficiency $\eta$ [3]:

$$\eta = \frac{e^{-\alpha_c L_i} + e^{-\alpha_c L_o} R_i e^{-\alpha_c L}}{1 - 2 \sqrt{R_i R_o e^{-\alpha_c L} \cos(2\beta L + \Psi_i + \Psi_o) + R_i R_o e^{-2\alpha_c L}}} \left(1 - R_i \right) \left(1 - e^{-\alpha d} \right)$$  \hspace{1cm} (3.1)

Hereby, the following parameters are used:

- $\eta$: quantum efficiency
- $\alpha_c$: average absorption coefficient in the cavity $= \frac{\alpha_c (L_i + L_o) + \alpha d}{L}$
- $\beta$: propagation constant of the electromagnetic wave $= \frac{2n \pi}{\lambda}$
- $n$: average index of refraction inside the cavity
- $\lambda$: vacuum wavelength

This simplified model is used for description of the RCED behaviour. For a more precise model, a numerical method such as the matrix transfer method can be used (e.g. included in [46]). The simplified model does in particular not consider:

- the position of the absorber in the cavity (standing wave effect, cf. section 3.1.5)
- reflections at the interfaces of the active layer inside the cavity
- wavelength dependent reflectivity and phase shift at the DBRs (cf. section 3.4)
- different refractive indices inside the cavity
- wavelength dependent absorption of the different materials
In practical detector designs, the material around the active layer absorbs negligibly compared to the active layer, so $\alpha_{\text{ex}}$ can be neglected (except if the absorbing layer is extremely thin). The quantum efficiency (3.1) simplifies to:

$$\eta = \left( \frac{1 + R_2 e^{-a d}}{1 - 2 \sqrt{R_1 R_2 e^{-a d}} \cos(2 \beta L + \Psi_1 + \Psi_2) + R_1 R_2 e^{-2ad}} \right) \left( 1 - R_1 \right) \left( 1 - e^{-a d} \right) \quad (3.2)$$

The quantum efficiency maxima occur at the resonances. They are obtained from formula (3.1), with the cosine expression equal unity, i.e. when

$$2 \beta L + \Psi_1 + \Psi_2 = 2m\pi \quad \text{for} \quad m = 1, 2, \ldots \quad (3.3)$$

Introducing the resonance condition (3.3) in (3.2) the maximum quantum efficiency is obtained:

$$\eta_{\text{max}} = \frac{1 + R_2 e^{-a d}}{\left( 1 - 2 \sqrt{R_1 R_2 e^{-a d}} \right)^2 \left( 1 - R_1 \right) \left( 1 - e^{-a d} \right)} \quad (3.4)$$

By differentiation of (3.4) with respect to $R_1$ the maximum quantum efficiency condition is obtained:

$$R_{1,\text{max}} = R_2 e^{-2ad} \quad (3.5)$$

This means, that for a given $a d$, there is an optimum reflectivity $R_1$ for a given reflectivity $R_2$. The quantum efficiency as a function of the incident wavelength using formula (3.1) is represented in Figure 3-2 for a certain RCED design. With higher mirror reflectivities, higher and narrower detection peaks are obtained in general.

However, there will be a maximum quantum efficiency, when the condition (3.5) is fulfilled, after which increasing the reflectivity will lead to a decrease in quantum efficiency again. The figure shows this behaviour with different reflectivities $R_1$.

The cavity enhancement effect can be seen clearly: whereas a usual detector absorbs only $\left( 1 - e^{-a d} \right)$ (dashed line), the quantum efficiency of a RCED can be significantly higher, in optimized designs reaching nearly unity.
Figure 3-2 – RCED quantum efficiency $\eta$ for three different reflectivities $R_1$. The RCED design parameters are shown in the inset. The higher the reflectivity $R_1$, the narrower the detection peaks. The Free Spectral Range (FSR) corresponds to the distance between two neighbouring detection peaks. The resonance linewidth is characterized by the Full Width at Half Maximum (FWHM) of a detection peak.

3.1.2. Free Spectral Range

The distance between two absorption peaks inside the Fabry-Pérot cavity, is known as the Free Spectral Range (FSR). Introducing the propagation constant of the electromagnetic wave $\beta = \frac{2n\pi}{\lambda}$ in the resonance condition (3.3) the maxima occur at the wavelengths

$$\lambda_m = \frac{2nL}{m - \frac{\Psi_1}{2\pi} - \frac{\Psi_2}{2\pi}} \quad m = 1, 2, \ldots \quad (3.6)$$

With this, the distance between two neighbouring peak wavelengths can be expressed as
The Free Spectral Range, and thus the tuning range of the detector, gets therefore larger with smaller mode order \( m \) and the maximum Free Spectral Range can be obtained in the fundamental mode \( m = 1 \).

### 3.1.3. Resonance Linewidth

The resonance linewidth will eventually define the detector resolution. Defining the linewidth as the width of the resonance peak at half the height between a maximum and a minimum quantum efficiency, it can be deduced from formula (3.1). The linewidth \( \delta \lambda_m \) can then be calculated by [46]:

\[
\delta \lambda_m = \frac{8\pi n L \arccos \left( \frac{2 \sqrt{R_1 R_2 e^{-\alpha_c L}}}{1 + R_1 R_2 e^{-2\alpha_c L}} \right)}{(2\pi m - \frac{\Psi_1 - \Psi_2}{2})^2 - \arccos \left( \frac{2 \sqrt{R_1 R_2 e^{-\alpha_c L}}}{1 + R_1 R_2 e^{-2\alpha_c L}} \right)}
\]

(3.8)

Better detector resolution can be obtained with a narrower linewidth. From formula (3.8) it can be followed, that the linewidth gets narrower for higher modes \( m \), higher reflectivities at the cavity mirrors and lower absorption \( \alpha_c \) inside the cavity.

### 3.1.4. Finesse

Following the notation for Fabry-Pérot cavities, the reflectivity finesse \( F_R \) of a RCED can be defined by relating the resonance linewidth to the Free Spectral Range. By combining formulae (3.7) and (3.8), one obtains (using formula (3.6)) the theoretical value of the finesse depending on the reflectivities at the interfaces [46]:

\[
F_R = \frac{FSR}{\delta \lambda_m} = \frac{(2\pi m - \frac{\Psi_1 - \Psi_2}{2})^2 - \arccos \left( \frac{2 \sqrt{R_1 R_2 e^{-\alpha_c L}}}{1 + R_1 R_2 e^{-2\alpha_c L}} \right)}{4\pi \left( m - \frac{\Psi_1}{2\pi} - \frac{\Psi_2}{2\pi} \right) \left( 1 + m - \frac{\Psi_1}{2\pi} - \frac{\Psi_2}{2\pi} \right) \arccos \left( \frac{2 \sqrt{R_1 R_2 e^{-\alpha_c L}}}{1 + R_1 R_2 e^{-2\alpha_c L}} \right)}
\]

(3.9)
In a real device, plate defects and the finite aperture will decrease the detector finesse. According to the theory of Fabry-Pérot Filters as presented by Atherton [48], these can be added, forming the experimental effective finesse $F_E$:

$$\frac{1}{F_E} = \sqrt{\frac{1}{F_R^2} + \frac{1}{F_A^2} + \frac{1}{F_{DS}^2} + \frac{1}{F_{DG}^2} + \frac{1}{F_{DP}^2}}$$

(3.10)

where

- $F_{DS}$ is the finesse degradation due to a spherical bow of the mirror plate, described by the maximum excursion from the plane surface $t_m$.

- $F_{DG}$ is the finesse degradation due to the roughness of the mirror surface, characterized by the root-mean-square surface roughness $t_{RMS}$.

- $F_{DP}$ is the finesse degradation due to a departure $t_P$ from parallelism.

- $F_A$ is the finesse degradation due to a finite aperture. $\Omega$ is the solid angle of the cone of rays passing through the Fabry-Pérot cavity. For the Fourier Transform Infrared (FTIR) Setup used for the characterization, $\Omega$ is estimated $0.03\pi$ (FTIR: focus 10cm from output window, window 40mm).

Typical values for these defects of the realized micromirrors allow an estimation of the degraded finesse. The formula for each defect type, the defect parameter, and the range of measured values (cf. chapter 4) are shown in Table 3-1.

**Table 3-1 – Resonator cavity defect types and their characteristics [48].**

<table>
<thead>
<tr>
<th>Defect Type</th>
<th>Spherical Bow</th>
<th>Roughness</th>
<th>Parallelism</th>
<th>Aperture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finesse Degradation</td>
<td>$F_{DS} = \frac{\lambda}{2t_m}$</td>
<td>$F_{DG} = \frac{\lambda}{4.7t_{RMS}}$</td>
<td>$F_{DP} = \frac{\lambda}{\sqrt{3}t_p}$</td>
<td>$F_A = \frac{2\pi}{m\Omega}$</td>
</tr>
<tr>
<td>Defect Parameter</td>
<td>$t_m$ [nm]</td>
<td>$t_{RMS}$ [nm]</td>
<td>$t_P$ [nm]</td>
<td>Mode $m$ [-]</td>
</tr>
<tr>
<td>range (own values)</td>
<td>10 – 120</td>
<td>2 - 10</td>
<td>0 - 500</td>
<td>4 - 12</td>
</tr>
<tr>
<td>typical (own values)</td>
<td>50</td>
<td>5</td>
<td>200</td>
<td>7</td>
</tr>
</tbody>
</table>
Figure 3-3 – Finesse degradation influence on the detection linewidth (FWHM) for different defect types in 2 detector designs. Design (b) corresponds to a design with optimized reflectivities. Each dashed line represents the influence of a specific defect type on $F_R$ (blue line). The red line $F_E$ shows the overall experimental effective finesse. The linewidth decreases for higher modes, however, the Free Spectral Range (FSR) decreases with higher modes as well. In the used setup, illumination $F_A$ and parallelism $F_{DP}$ have the strongest impact on the detection linewidth (calculated with the typical defect data from Table 3-1; $n=1$).
With typical measured values, the influences of each respective defect type on the overall effective finesse have been calculated and are represented in Figure 3-3. Typically, orders above mode 3 can be exploited (lower modes are not accessible due to the material in diode, buffer and DBR, as well as a minimum air gap of at least 1 \( \mu \text{m} \)). With the typical defects, a linewidth of less than 100 nm can be obtained.

Besides the finite aperture \((F_A)\) due to the measurement setup, the limiting factor is the parallelism of the two cavity mirrors \((F_{DP})\). The curvature as well adds a non negligible part, whereas the surface roughness does almost not degrade the cavity finesse.

### 3.1.5. Standing Wave Effect

The electromagnetic field inside the cavity is not distributed homogeneously, it rather forms a standing wave. For thick absorbers, in comparison to the wavelength, this effect can be neglected, as several field maxima will lay within the absorber region. However, for thin absorbers, this standing wave effect (SWE) imposes constraints on the placement of the absorber inside the cavity. The standing wave effect has not been included in the above model of the quantum efficiency. The electric field distribution can be derived in a similar manner as the quantum efficiency, by adding the forward and the backward traveling waves (neglecting absorption, i.e. \(\alpha = 0\)) \([3]\):

\[
\frac{|E|^2}{|E_\infty|^2} = \frac{|1 - r_1^2|}{|1 - r_1 r_2 e^{i(2\beta L + \Psi_1)}|^2} \left( 1 + r_2^2 + 2r_2 \cos \left( 2\beta (L - z) + \Psi_1 \right) \right) \tag{3.11}
\]

where \(r_1\) and \(r_2\) are the amplitude reflectivities at the mirrors. This function depends on the wavelength as well as on the position \(z\) inside the cavity (Figure 3-4). Assuming no phase shift at the cavity mirrors, the electric field has a maximum at either limit of the cavity, independent from the resonant mode. In order to maximize quantum efficiency and thus sensitivity, a thin detector can therefore be placed at either end of the cavity. However, a wavelength dependent phase shift occurs at the fixed Bragg reflector, due to penetration of the electromagnetic wave into the mirror. This phase shift is though minimal at the DBR center wavelength and can generally be neglected at wavelengths close to the center wavelength in a first approximation, as shown in section 3.4. Assuming maximum quantum efficiency with a placement of the active layer at the end of the cavity, the SWE will not be included in the further modeling of the RCED. A formulation for including the SWE can be found in \([3]\).
Figure 3-4 – Electromagnetic field distribution inside the RCED cavity for the first 4 modes (mode 1 at 4 µm, mode 2 at 2 µm, mode 3 at 1.33 µm, mode 4 at 1 µm). For all modes, the field is maximum at the ends of the cavity for mirrors without phase shift. A thin diode is best placed in a maximum of the electric field, hence maximum quantum efficiency can be expected with a diode placement at one end of the cavity.

3.1.6. Wavelength Tuning

The wavelength tuning of the detector can be obtained by displacing one of the cavity mirrors. Figure 3-5 shows the interdependency of mirror position and detection wavelength. The wavelength dependent phase shift and the wavelength dependent reflectivity at the DBR have been neglected for simplicity.
**Figure 3-5**  a) Quantum efficiency in dependence of the movable mirror position. By displacing the movable mirror, the detection wavelength can be tuned. The lines in b) show the spectra at the respective mirror positions A, B and C. The insets show the design parameters used for the simulations.
The mirrors used for the realization of the tunable RCED are not perfect as assumed in the above calculations. At the movable mirror, a phase shift of \(\pi\), and at the fixed DBR, a wavelength dependent phase shift will occur (cf. section 3.4). The reflectivity of the DBR depends on the wavelength as well. Introducing the characteristics of the DBR as presented in section 3.4 (2.5 pairs PbTe(\(n=6.3\))/EuTe(\(n=2.4\)), center wavelength 5 \(\mu\)m), the tunability characteristic changes in the following way (cf. Figure 3-6):

- Due to the phase shift at the movable mirror, an additional \(\lambda/4\) has to be added to the cavity length. The detection peak at 4 \(\mu\)m in Figure 3-5a for a mirror distance of 2 \(\mu\)m is already reached at a mirror distance of 1 \(\mu\)m in Figure 3-6.

- The DBR reflectivity is limited to a bandwidth from about 3 \(\mu\)m to 7 \(\mu\)m. Outside this band, resonances cannot build up in the cavity.

- The DBR phase shift is wavelength dependent. At the center wavelength of 5 \(\mu\)m, it is zero, and increases with increasing distance from the center wavelength. This results in a bending of the detection curve far from the DBR center wavelength.

**Figure 3-6** – Quantum Efficiency in dependence of the movable mirror position for a RCED design taking into account the wavelength dependent reflectivity and phase shift of a Distributed Bragg Reflector (2.5 pairs PbTe/EuTe, center wavelength 5 \(\mu\)m).
3.1.7. **Detector Bandwidth**

The detector bandwidth is limited at the upper end by the diode cut-off wavelength. Electromagnetic radiation with longer wavelengths above the cut-off does not contribute to the signal. The cut-off wavelength at 100 K is 5.5 \( \mu m \) for lead-telluride (PbTe) and 6.9 \( \mu m \) for lead-selenide (PbSe). The cut-off may be shifted to longer wavelengths by alloying the semiconductor with tin (Sn). With a Sn content of 7%, the cut-off wavelength can be increased to 11.5 \( \mu m \). Alloying additional Strontium (Sr) or Europium (Eu) on the other hand, allow decreasing the band-gap and thus shifting the cut-off to lower wavelengths. In lead-chalcogenides, higher temperatures increase the band-gap and thus shift the cut-off to shorter wavelengths (e.g. at 300 K, the cut-off is 3.8 \( \mu m \) for lead-telluride (PbTe) and 4.5 \( \mu m \) for lead-selenide (PbSe)). The design of a RCED is therefore always optimized for a selected operation temperature.

In order to select only one resonance in the detector, the buffer layer (inside or outside the cavity) can be designed to absorb electromagnetic radiation of higher energy. The characteristics of the materials used are presented in [46] and summarized in chapter 3.3.

3.2. **Tunable Vertical External Cavity Surface Emitting Lasers**

Vertical External Cavity Surface Emitting Lasers (VECSELs) with a lasing wavelength in the mid-infrared (around 5 \( \mu m \)) have been realized recently by the ETH Thin Film Physics Group [49, 50, 51]. In the realized setup, a fixed DBR mirror with the active laser gain medium was combined with an external curved DBR mirror at a distance of about 5 cm. The device can be reduced in size by using the micromirrors developed in this work. The displacement of the micromirror allows hereby a tuning of the lasing wavelength. The design parameters for such an integrated tunable VECSEL are presented in this section.

3.2.1. **Laser Resonator Design**

The working principle of an integrated tunable mid-infrared VECSEL is shown in Figure 3-7. The laser resonator is formed by the fixed DBR mirror and the movable MEMS mirror. The active medium is pumped through the substrate by an external laser source (e.g. 2 \( \mu m \)) and the laser radiation is coupled out through the DBR mirror.
3.2.2. Longitudinal Mode Selection and Cavity Length

The resonance condition for a laser resonator is the same as for a RCED. As shown in section 3.4, there is a wavelength dependent reflectivity and phase shift at the DBR, as well as a constant phase shift at the gold mirror. For simplicity, in the following, a laser resonator in air \((n = 1)\) without phase shift at the resonator mirrors is considered. The resonating condition and the free spectral range thus simplify to

\[
\lambda_m = \frac{2L}{m} \quad (3.12)
\]

\[
FSR = \lambda_m - \lambda_{m+1} = \frac{\lambda_m}{m+1} \quad (3.13)
\]

Table 3-2 shows the relation between the first 10 longitudinal modes, the free spectral range and the cavity length for a laser with a resonating wavelength of 4.5 \(\mu m\). In order to obtain a maximum tunable range, the free spectral range has to be as large as possible. However, fabrication of the spacer layer gets more difficult for thinner layers, i.e. for lower cavity lengths.

Table 3-2 – Cavity length and free spectral range for a 4.5 \(\mu m\) MEMS VECSEL.

<table>
<thead>
<tr>
<th>Mode #</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSR [(\mu m)]</td>
<td>4.5</td>
<td>2.25</td>
<td>1.5</td>
<td>1.13</td>
<td>0.9</td>
<td>0.75</td>
<td>0.64</td>
<td>0.56</td>
<td>0.5</td>
<td>0.45</td>
</tr>
<tr>
<td>Cavity Length [(\mu m)]</td>
<td>2.25</td>
<td>4.5</td>
<td>6.75</td>
<td>9.0</td>
<td>11.3</td>
<td>13.5</td>
<td>15.7</td>
<td>18</td>
<td>20.3</td>
<td>22.5</td>
</tr>
</tbody>
</table>
The wavelength domain for a tunable mid-IR VECSEL is given by its wavelength dependent gain curve. Lasing can only occur in the region where the gain is higher than the losses. The gain curve for a 1 μm thick PbTe active layer is shown for different operating temperatures in Figure 3-8. In this simplified model, losses are neglected. It is assumed, that all photons (pump power 5W) generate electron-hole pairs and no recombinations occur. The material model and simulations are presented in detail by Rahim [52] and Khiar [53].

In order to have a maximum tunable range for a single longitudinal mode, the maximum cavity length (and thus the maximum operating mode) is given by the distance between the minimum and maximum lasing wavelength in the gain curve. Assuming a specific threshold, the differences $\Delta \lambda$ between the maximum and minimum wavelength are summarized in Table 3-3.

**Table 3-3** – PbTe laser gain bandwidth assuming a specific threshold.

<table>
<thead>
<tr>
<th>Temperature [K]</th>
<th>100</th>
<th>120</th>
<th>140</th>
<th>160</th>
<th>180</th>
<th>200</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \lambda$ at 2000cm$^{-1}$ [μm]</td>
<td>1.35</td>
<td>1.12</td>
<td>0.89</td>
<td>0.66</td>
<td>0.40</td>
<td>-</td>
</tr>
<tr>
<td>$\Delta \lambda$ at 3000cm$^{-1}$ [μm]</td>
<td>1.08</td>
<td>0.75</td>
<td>0.37</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
3.2.3. Transversal Mode Selection and Radius of Curvature

The spot sizes $w$ at the respective resonator mirrors for the fundamental transversal electromagnetic (TEM$_{00}$) mode in a plano-concave resonator are given [54] by

$$w_1^2 = w_0^2 = \frac{\lambda}{\pi} \sqrt{L\left(R_{c2} - L\right)} \quad (3.14)$$

$$w_2^2 = \frac{\lambda}{\pi} R_{c2} \sqrt{\frac{L}{R_{c2} - L}} \quad (3.15)$$

For a stable plano-concave resonator, the radius of curvature has to be larger then the cavity length. For a MEMS VECSEL, the length will be negligible in comparison to the radius of curvature, hence the formulae simplify to:

$$w_1^2 = w_0^2 = w_2^2 = \frac{\lambda}{\pi} \sqrt{LR_{c2}} \quad (3.16)$$

In a real laser, this spot size is limited by the mirror size or by a limiting aperture in the cavity (e.g. limits of the active laser material). Some fraction of the laser beam will be lost at these limits. These diffraction losses depend on the radius of curvature $R_{c2}$, $L$ and the aperture $a$, following the Fresnel number $N$:

$$N = \frac{a^2}{L\lambda} \quad (3.17)$$

**Figure 3-9** - Aperture size (a) and radius of curvature (b) for different Fresnel numbers $N$ for the different cavity lengths corresponding to the first 6 longitudinal modes for a 4.5 $\mu$m MEMS VECSEL (as shown in Table 3-2).
When \( N \) is small, the loss will be important and lasing cannot occur. For too high an \( N \), the losses are small, but multimode output will occur. By choosing an appropriate combination of radius of curvature and aperture (slightly above the \( \text{TEM}_{00} \) spot size), the fundamental transversal mode can be selected. Figure 3-9 shows the relation between the Fresnel number \( N \) and the aperture size, radius of curvature for the cavity lengths according to the longitudinal modes shown in Table 3-2.

Assuming the fundamental mode filling the complete aperture size \( (a = w_0) \), (3.16) gives the combinations of radius of curvature and aperture size

\[
R_{c2} = \frac{a^2 \pi^2}{\lambda^2 L} \quad (3.18)
\]

Figure 3-10 shows the appropriate combinations of aperture size and radius of curvature for single transversal mode operation. A radius of curvature in the range of centimeters has to be chosen for a single transversal mode operation at aperture sizes below 30 \( \mu \text{m} \).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure310.png}
\caption{Combinations of radius of curvature and aperture for a fundamental transversal mode selection for the 6 first longitudinal modes of a 4.5 \( \mu \text{m} \) MEMS VECSEL.}
\end{figure}
On the laser chip, the active medium is uniformly deposited over the whole chip size. The aperture may thus be limited by the pump laser spot size (~10 μm), the micromirror square size (300 μm – 600 μm). Additional freedom is given by the possibility to fabricate a limiting aperture inside the cavity with an opaque coating (e.g. a metal coating on the active layer) with a defined opening (e.g. obtained by wet-etching).

3.2.4. Wavelength Tuning

Neglecting the phase shift at the mirror surfaces (wavelength dependent for the DBR and π at the movable gold mirror, cf. section 3.4), and the reflection at the cavity-DBR interface (which can be achieved with an antireflection coating), the emission wavelength can be tuned by moving the external MEMS mirror by Δλ around the center wavelength λc:

\[
\frac{\Delta \lambda}{\lambda_c} = \frac{\Delta L}{L}
\]  

(3.19)

The maximum wavelength tuning is limited by the PbTe gain (cf. section 3.2.2). Assuming a maximum Δλ = 1.35 μm (threshold 2000cm⁻¹, operating temperature 100 K), the displacement range for the micromirror can be calculated using formula (3.19). Table 3-1 summarizes the necessary displacements for exploiting the maximum tuning range in a single longitudinal mode. In order to cover the full 1.35 μm, the device can be operated maximum at mode 3, i.e. a cavity length of 6.75 μm, requiring a mirror displacement of 2 μm.

Table 3-4 – Displacements for maximum wavelength tuning for the first 6 modes of a PbTe laser with 4.5 μm center wavelength.

<table>
<thead>
<tr>
<th>Mode #</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSR [μm]</td>
<td>4.5</td>
<td>2.25</td>
<td>1.5</td>
<td>1.13</td>
<td>0.9</td>
<td>0.75</td>
</tr>
<tr>
<td>Cavity Length [μm]</td>
<td>2.25</td>
<td>4.5</td>
<td>6.75</td>
<td>9.0</td>
<td>11.3</td>
<td>13.5</td>
</tr>
<tr>
<td>ΔL for tuning Δλ = 1.35 μm</td>
<td>0.68</td>
<td>1.35</td>
<td>2.03</td>
<td>2.70</td>
<td>3.38</td>
<td>4.05</td>
</tr>
</tbody>
</table>
3.3. Thin Film Materials

The materials used for the distributed Bragg reflector and the photodiode are IV-VI semiconductor materials (lead-chalcogenides or lead-salts). These materials show a low Auger recombination rate and are fault tolerant to defects. In proper composition, they exhibit absorption in the desired mid-infrared wavelength region. Fixed wavelength RCEDs have been presented [4] based on Schottky diodes and metal reflectors employing Lead-Selenides (PbEuSe or PbSnSe). The metal Schottky contact layer however, does not allow the electromagnetic radiation to pass into the external tunable cavity.

In comparison to fixed wavelength RCEDs, tunable RCEDs require a ‘transparent’ diode (except for the electronic absorption leading to the generated electron-hole pairs, which give rise to the photocurrent), which allows the light passing into the air cavity, thus reaching the second movable cavity mirror. As p-n diodes are difficult to realize with selenides, lead-tellurides (PbTe) where used for fabrication of such ‘transparent’ p-n diodes for the mid-infrared.

IV-VI semiconductor materials are not standard microfabrication materials. They can be grown by Molecular Beam Epitaxy (MBE) allowing alloying the material in desired compositions. As a low defect density is essential for the electro-optical interaction, the lattice mismatch as well as the thermal expansion mismatch between the grown layers has to be as low as possible. Having a similar lattice constant, crystalline BaF$_2$ is a good substrate for crystal growth. However, BaF$_2$ substrates are less common and difficult to handle (water soluble). Alternatively, silicon crystals can be used as substrates [55]. Due to a larger lattice mismatch, an intermediate CaF$_2$ layer as lattice matching layer is grown. Si based devices show however a higher defect density.

Table 3-5 summarizes the properties and the primary use of the materials used in this work. With lead-tellurides, p-n diodes can be realized, which absorb from below 3 $\mu$m up to over 30 $\mu$m. PbTe at 100 K has a cut-off wavelength at 5.5 $\mu$m. Adding Strontium (Sr) or Europium (Eu), changes the bandgap, and thus the cut-off wavelength:

- Additional Strontium (Sr) or Europium (Eu) content increases the band-gap and thus shifts the cut-off to shorter wavelengths.

- Additional Tin (Sn) content decreases the band-gap, thus shifts the cut-off to longer wavelengths.
Additionally, the band-gap depends strongly on the temperature. With increasing temperature, the semiconductor band-gap is increased, which, in contrast to many other semiconductors, shifts the cut-off to shorter wavelengths.

Detailed values of the wavelength shift due to alloying concentrations and due to temperature changes can be found in the thesis by Martin Arnold [46].

**Table 3-5** – Selected thin film material properties @ 100 K (a) summarized from Martin Arnold’s Thesis [46], b) from the Handbook of Chemistry and Physics [56]).

<table>
<thead>
<tr>
<th>Material</th>
<th>Transp. [μm]</th>
<th>n @ 5μm</th>
<th>α [10⁻⁴]</th>
<th>Deposition</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si a)</td>
<td>&gt;1.12</td>
<td>3.4</td>
<td>2.6</td>
<td>-</td>
<td>Substrate</td>
</tr>
<tr>
<td>BaF₂ a)</td>
<td>&gt;0.11</td>
<td>1.45</td>
<td>19.8</td>
<td>-</td>
<td>Substrate</td>
</tr>
<tr>
<td>CaF₂ a)</td>
<td>&gt;0.15</td>
<td>1.40</td>
<td>19.1</td>
<td>MBE</td>
<td>Lattice Match</td>
</tr>
<tr>
<td>PbTe a)</td>
<td>&gt;5.5</td>
<td>6.3</td>
<td>19.8</td>
<td>MBE</td>
<td>Diode</td>
</tr>
<tr>
<td>PbₓEu₁₋ₓTe a)</td>
<td>[3.0 - 5.5[</td>
<td>5.4 - 6.25</td>
<td>n. a.</td>
<td>MBE</td>
<td>DBR</td>
</tr>
<tr>
<td>PbₓSr₁₋ₓTe a)</td>
<td>[2.0 - 5.5[</td>
<td>5.3 - 5.8</td>
<td>n. a.</td>
<td>MBE</td>
<td>DBR / Diode</td>
</tr>
<tr>
<td>ZnO a)</td>
<td>[0.35 – 12]</td>
<td>2.8</td>
<td>2.9 b)</td>
<td>RF Sputt.</td>
<td>Transp. Cont.</td>
</tr>
<tr>
<td>EuTe a)</td>
<td>&gt; 0.6</td>
<td>2.4</td>
<td>13.6</td>
<td>MBE</td>
<td>DBR</td>
</tr>
<tr>
<td>ZnSe</td>
<td>n. a.</td>
<td>2.43 b)</td>
<td>3.1 b)</td>
<td>Evap.</td>
<td>AR Coating</td>
</tr>
<tr>
<td>Cr b)</td>
<td>&lt; 0.3</td>
<td>~ 4</td>
<td>4.9</td>
<td>Evap.</td>
<td>Curvature</td>
</tr>
<tr>
<td>Al b)</td>
<td>&lt; 0.08</td>
<td>8.58</td>
<td>23.1</td>
<td>Sputt.</td>
<td>Electrode</td>
</tr>
<tr>
<td>Au b)</td>
<td>&lt; 0.6</td>
<td>~ 1.5</td>
<td>14.2</td>
<td>Evap.</td>
<td>Refl. Coating/Contact</td>
</tr>
</tbody>
</table>
3.4. Distributed Bragg Reflectors

Distributed Bragg Reflectors (DBR), or Bragg mirrors, are multilayer optical systems that exhibit high reflectivity for a certain wavelength range. They are based on the reflection of the electromagnetic wave at the interfaces. By choosing alternating layers of low and high refractive indices with the appropriate optical length of a quarter wavelength each, constructive interference of the wave can be exploited to obtain high reflectivity, usually well above 99% for a certain wavelength range [57].

Using the simplified analytical expressions presented by Brovelli and Keller [58], the reflectivity of a DBR using the lead salt materials introduced in chapter 3.3 has been calculated. The very high contrast in index of refraction leads to a very high reflectivity for only a few alternating pairs [59]. Figure 3-11 shows the reflectivity for 1.5, 2 and 2.5 pairs of PbTe ($n=6.3$ at 100K) / EuTe ($n=2.4$ at 100K) layers (absorption in the layers neglected) for a DBR designed to a center mirror wavelength of 5 μm. The bandwidth extends from approximately 3 μm to 7 μm.

![DBR Reflectivity](image)

**Figure 3-11** – DBR Reflectivity. Already a few pairs of alternating layers PbTe/EuTe are sufficient for high reflectivities (center wavelength 5 μm).
At the DBR interface, a wavelength dependent phase shift occurs. In Figure 3-12, the wavelength dependent phase shift is shown for the DBR mirrors consisting of 1.5, 2 or 2.5 pairs of PbTe($n=6.3$)/EuTe($n=2.4$) layers (absorption in the layers neglected), designed to a center mirror wavelength of 5 μm.

![Phase Shift vs Wavelength Graph](image)

**Figure 3-12** – Wavelength dependent phase shift for a PbTe/EuTe DBR (center wavelength 5 μm).

The DBR phase shift can be interpreted as a penetration depth into the mirror, where a reflection without phase shift occurs. This penetration depth due to the phase shift has to be added to the air cavity length according to formula (3.6), in order to obtain the effective cavity length. The wavelength dependency of this addition to the air cavity length has as consequence that a linear movement of the external cavity mirror results in a non-linear tuning of the detection wavelength. This has been included in the simulations shown in section 3.1.6. The wavelength dependency however is small in the vicinity of the DBR center wavelength as can be seen in Figure 3-12.

The movable mirror is coated with a reflective metal coating. As the index of refraction is higher for the metal than the air cavity, a constant wavelength shift of $\pi$ occurs at the mirror interface.
4. M**ICROMIRRORS FOR TUNABLE MID-IR DETECTORS AND EMITTERS**

The tunable mid-infrared devices investigated in this thesis rely on mechanically moving micromirrors as key elements for tunability. Figure 4-1 shows a schematic representation of the tunable Resonant Cavity Enhanced Detector (RCED) design, and Figure 4-2 shows a schematic representation of a tunable Vertical External Cavity Surface Emitting Laser (VECSEL). The figures show representatively the implementation of a micromirror in a detector or a laser system.

Already in an early stage of the project, *electrostatic actuation* was chosen for the actuation mechanism. Electrostatic actuators can be obtained with standard microfabrication processes and with comparably high energy densities at the microscale, sufficiently large displacements can be achieved. *Magnetic actuation* has the advantage of even higher energy densities at the microscale, but the incorporation of magnetic materials usually makes systems bulky.
Piezoelectric actuation allows for large displacements over several micrometers as well, but is not (yet) commonly available in microfabrication processes. In MEMS commonly encountered thermal bimorph actuators usually operate at temperatures around 1000 K. At these temperatures, thermal radiation in the mid-infrared is emitted, which would influence the infrared detector system. The design and performance of these micromirrors was chosen to be implementable for the detectors as well as for the emitters. In this chapter, the design and the performance of the realized micromirrors are investigated.

**Figure 4-1** – Schematic representation of a tunable Resonant Cavity Enhanced Detector (RCED). In the cross section, the upper part shows a vertically moving micromirror, the top view shows the micromirror and its suspension (from [A2]).

**Figure 4-2** - Schematic representation of a tunable Vertical External Cavity Surface Emitting Laser (VECSEL). In the cross section, the upper part shows a vertically moving micromirror, the top view shows the micromirror and its suspension.
4.1. Micromirror Design Criteria

For all devices in common, design criteria were deduced either from simulations or from other design constraints. Table 4-1 gives an overview of the common design criteria.

These criteria leave freedom in the design of the micromirror suspension geometry. One or two suspension legs are not sufficient for a parallel plate movement, as rotations can occur. Three straight suspension legs are not an adequate design for the implementation in single crystalline silicon due to the fourfold symmetry of the crystal. Vertically moving micromirrors with three suspension legs in a circular arrangement have been presented [60]. However, circular structures inhibit high fill factors. More than four suspension legs constrain the system unnecessarily. Designs with four suspension legs were therefore investigated.

<table>
<thead>
<tr>
<th>Design Criterion</th>
<th>Value</th>
<th>Based on / limited by</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mirror Square Length</td>
<td>&gt; 300 (\mu m)</td>
<td>existing diode design (300 (\mu m)) [46]</td>
</tr>
<tr>
<td>Displacement</td>
<td>(~ 3 \mu m)</td>
<td>wavelength tuning (cf. sect. 5.1 and 3.2.4)</td>
</tr>
<tr>
<td>Curvature RCED</td>
<td>\textit{small}</td>
<td>low finesse degradation (cf. section 3.1.4)</td>
</tr>
<tr>
<td>Curvature VECSEL</td>
<td>1-10 cm</td>
<td>transversal mode selection (cf. sect. 3.2.3)</td>
</tr>
<tr>
<td>Surface Roughness</td>
<td>\textit{small}</td>
<td>good reflectivity</td>
</tr>
<tr>
<td>Fill Factor</td>
<td>\textit{high}</td>
<td>possible application in Focal Plane Arrays</td>
</tr>
<tr>
<td>Actuation Voltages</td>
<td>(~ 30 \text{ V})</td>
<td>possible integration with microelectronics</td>
</tr>
<tr>
<td>Maximum Stress</td>
<td>&lt; (~ 1.3 \text{ GPa})</td>
<td>ultimate strength of DRIE Si beams [61]</td>
</tr>
<tr>
<td>Suspension Width</td>
<td>&gt; (~ 5 \mu m)</td>
<td>DRIE fabrication technology limit at ETH</td>
</tr>
<tr>
<td>Mirror Thickness</td>
<td>&gt; (~ 5 \mu m)</td>
<td>DRIE fabrication technology limit at ETH</td>
</tr>
</tbody>
</table>
4.2. Parallel Plate Actuated Micromirror

4.2.1. Electrostatic Actuator Design

Electrostatic actuation is based on the electrostatic attraction force that arises between two oppositely charged parts. A simplified model for the micromirror consists in a parallel plate capacitor with one plate fixed and the other suspended elastically. A schematic representation of the parallel plate electrostatic actuator is given in Figure 4-3. In this simplified model, fringe field effects are neglected.

\[ k \quad \text{Suspension spring constant} \]
\[ A_{el} \quad \text{Electrode surface} \]
\[ d \quad \text{Initial distance between the electrodes} \]
\[ z \quad \text{Displacement of the movable electrode} \]
\[ \varepsilon \quad \text{Dielectric constant of air} \]
\[ m \quad \text{Mirror mass} \]
\[ U \quad \text{Applied voltage between the electrodes} \]

**Figure 4-3 – Schematic representation of the parallel plate electrostatic actuator.**

In an equilibrium position, the total potential energy of the system is given by the sum of the electrostatic energy stored in the capacitor \( C \) and the energy \( E \) stored in the spring.

\[
E = \frac{1}{2} CU^2 + \frac{1}{2} k z^2 \quad (4.1) \quad C = \varepsilon \frac{A_{el}}{d - z} \quad (4.2)
\]

The total energy of the system can then be rewritten by inserting the capacitance of a parallel plate capacitor. Taking the derivative with respect to the free coordinate \( z \), respectively \( d - z \), the force in the respective direction is obtained:

\[
E = \frac{1}{2} \frac{\varepsilon A_{el}}{d - z} U^2 + \frac{1}{2} k z^2 \quad (4.3) \quad F_{tot} = \frac{1}{2} \frac{\varepsilon A_{el}}{(d - z)^2} U^2 - k z \quad (4.4)
\]

In an equilibrium position, the net force on the mirror will be zero, hence:

\[
F_{tot} = 0 \quad (4.5) \quad k z = \frac{1}{2} \frac{\varepsilon A_{el}}{(d - z)^2} U^2 \quad (4.6)
\]
The force balance (4.6) on the electrostatic actuator for a certain applied voltage $U$ can be represented graphically as shown in Figure 4-4. Three regions can be distinguished:

- For $z < z_1$, the electrostatic force exceeds the restoring force and the movable plate will be moved further towards the fixed plate.

- For $z_1 < z < z_2$, the restoring force of the spring exceeds the electrostatic force, so the movable plate will be pulled back to the equilibrium position $z_1$.

- For $z > z_2$, the movable electrostatic force exceeds the restoring force and the movable plate will be moved further towards the fixed plate until the two plates touch. This effect is commonly known as pull-in effect.

The total force is zero at both equilibrium positions $z_1$ and $z_2$, but only $z_1$ is a stable position: any perturbation around the position $z_2$ will lead either to pull-in (for a small movement towards the fixed electrode) or the movable plate will fall back to the equilibrium in $z_1$ (for a small movement away from the fixed electrode).

![Graph showing force balance](image)

**Figure 4-4** - Schematic representation of the force balance on a suspended electrostatic parallel plate actuator (d=10). The stable equilibrium position is at $z=z_1$.

From the figure, it can be seen, that the slope at $z_1$ is negative. The stability condition requires thus mathematically expressed $\frac{\partial F_{\text{tot}}}{\partial z} < 0$, which leads to
This is the stability condition for the only stable position $z$ at an applied voltage $U$. When increasing the applied voltage $U$, the movable plate will move towards the fixed plate. By combining (4.6) in (4.7), a stable position can only be found while

$$z < \frac{d}{3}$$

For the applied voltage, this requires (by combining (4.8) in (4.7))

$$U < U_p = \left( \frac{2}{3} \right)^{\frac{1}{2}} \left( \frac{d}{\varepsilon A_d} \right)^{\frac{1}{2}}$$

When increasing $U$ above this pull-in voltage $U_p$ (i.e. when moving the movable plate over $z=d/3$), the system will suffer from the pull-in effect, i.e. when the restoring spring force cannot compensate the electrostatic force anymore and the movable plate will be pulled onto the fixed capacitor plate.

The equilibrium position of the movable capacitor plate $z$ for an applied voltage $U$ (4.6) can be written

$$2kz^3 - 4kdz^2 + 2kd^2z - \varepsilon A_d U^2 = 0$$

From this relation, the required applied voltage $U$ for a certain displacement $z$ can be calculated. For simplicity, the system has been solved numerically.

### 4.2.2. Suspension Geometry

The common design constraints given in section 4.1. allow to design the geometry of the four micromirror suspension legs, i.e. the thickness of the mirror and the suspensions and the suspension width and length. In investigations about the suspension geometry, two designs with four suspension legs have been retained and investigated in detail in the Bachelor Thesis by Ivan Züst [62]: one with straight suspensions departing from the corners of the micromirror (Figure 4-5b) and one with
a meander type suspension (Figure 4-5c). In the first series, using the DSP (Double Side Polished) based fabrication process, both types have been realized, in the second series, using the SOI (Silicon on Insulator) based fabrication process, only the folded structure was retained due to its better performance.

Figure 4-5 – Micromirror layout and design variables in a cross section (a) and a top view of the realized geometries with straight (b) and meander type suspension (c). The suspensions are described as indicated with the mirror square length $s$, the thickness $t$ and the length $l$ (straight) or $l_1$ and $l_2$ (meander) of a single micromirror suspension leg.

4.2.3. Displacement Simulations

A Finite Element (FE) Model has been built in ABAQUS. With a Python script, the geometry was changed in an automated manner. An orthotropic elastic material model was used for the single crystalline silicon, using the elastic constants by Hall [63]. The material orientation was chosen for a (100) wafer, where the mirrors were aligned parallel to the wafer flat. In this way, the lowest Young’s modulus is in direction of the suspension beams, allowing the softest suspension in these directions. The element type was chosen C3D20R (hexagonal bricks with 20 nodes, reduced integration, quadratic shape functions for representation of linear stress behaviour). With this element type, a minimum of 2 elements in thickness are sufficient to have a relative error of less than 0.5 % according to the convergence analysis in [62]. The meshing seeds (by size) were therefore set to half the thickness on the suspension leg edges. On the lateral mirror plate edges, 10 seeds were set, as the mirror itself does not undergo large deformations. Geometric nonlinearities were included in the calculations. No special precautions were however taken for mesh refinement in the corners as the displacements remain low.

The simulations allowed the mirror displacement $z$ for an applied electrostatic pressure $p_z = \frac{F}{A_{nl}}$ orthogonal to the mirror surface to be calculated, where $F$ is the...
applied force and $A_t$ the total electrode surface. The voltage necessary to induce this force at a capacitor plate distance $z$ can be deduced from the electrostatic force model of a parallel plate capacitor (from the electrostatic force part in formula (4.4)):

$$U = (d - z) \sqrt{\frac{2p}{\varepsilon}}$$  \hspace{1cm} (4.11)

The air gap between the electrodes is designed to $d = 10 \, \mu\text{m}$ preventing the mirror from pull-in at a maximum displacement of $z = 3 \, \mu\text{m}$ (for a sufficiently stiff spring). Clamped boundary conditions were used for the suspension beams fixed at the mirror frame. In the implemented finite element model, the electrostatic pressure was then incrementally increased from nil to 100 Pa. The resulting displacements $z_i$ for each applied pressure increment $p_{zi}$ were then combined with the corresponding pressure values in order to obtain the necessary voltage. According to formula (4.11), the results of these calculations are thus the displacements $z$ dependent on the applied voltage $U$.

A typical result showing the relationship between applied voltage and obtained displacement is represented in Figure 4-6. The system is stable for actuation voltages below the pull-in voltage $U_p$, which is reached at about one third of the initial air gap between the actuation electrodes.

![Figure 4-6](image)

**Figure 4-6** — Typical displacement curve for an electrostatically actuated micromirror. The system is stable up to the pull-in voltage, where the mirror displacement reaches about one third of the initial air gap.
The influence of the geometry on the suspension stiffness of the straight suspension type is mainly dominated by the bending of the suspension beams. In the meander type suspension, deformation due to torsion will add to the bending and further decrease the stiffness. Consider the bending of a single side clamped beam only, which is loaded with a concentrated force at its free end: the beam tip movement $\delta_z$ of such a cantilever follows the proportionality (4.12).

$$\delta_z (F_z) \propto \frac{l^3}{bt^3}$$

(4.12)

with $l$ the beam length, $b$ the beam width and $t$ the beam thickness. For low actuation voltages, a soft suspension is needed, which can thus be reached by long suspensions with small width and low thickness.

For the straight suspension design, the suspension length was varied by changing both mirror size and the square frame in which the mirror is accommodated.

![Figure 4-7](image)

**Figure 4-7** – Actuation voltage required for a 3 $\mu$m displacement for different frame lengths and mirror square lengths (thickness 5 $\mu$m, suspension width 5 $\mu$m).

The actuation voltages necessary for a mirror displacement of 3 $\mu$m are shown in Figure 4-7. In order to obtain such mirror displacements of 3 $\mu$m with actuation voltages below 50 V, the mirror frame length has to be more than 800 $\mu$m for a 300 $\mu$m square mirror. This corresponds to a single suspension leg length of more
than 350 μm. Mirror thickness and suspension width were both 5 μm. Lower actuation voltages are needed for increasing mirror frame length for a certain mirror size. For a certain mirror frame length, the actuation voltages first decrease with decreasing mirror size (as the suspension length increases, resulting in a more elastic suspension), and then increase again after having reached a minimum in between. This is due to the size of the electrodes, which were assumed to have the size of the mirror in these calculations. The smaller the mirror, the smaller thus the electrostatic force.

The simulation results show that for the geometry with straight suspensions, the limits of fabrication for suspension leg thickness and width introduced in section 4.2.2. are reached for actuation voltages around 30 V. The meander type suspension (Figure 4-5c) allows more flexibility in the design. Longer suspension legs can be accommodated using less space, which allows again using lower actuation voltages for comparable displacements.

![Simulation results](image)

**Figure 4-8** – Actuation voltage necessary for a certain mirror displacement obtained by finite element simulations for a mirror with meander type suspension. Longer and/or thinner legs allow more elastic suspensions requiring lower actuation voltages (mirror square length 500 μm, suspension leg width 20 μm).

Figure 4-8 shows simulation results for meander type geometries having a total length of 1430 μm or 720 μm per leg with a thickness of the freestanding structure varying from 4 to 10 μm (mirror square length is 500 μm and the leg width 20 μm).
The simulations show that thinning the device, prolonging or narrowing the legs, or shrinking the mirror plate size will lower the necessary actuation voltage; a respective inverse modification will have the opposite effect.

The actuation voltage for 3 μm displacement can be kept below 25 V as shown in Figure 4-8. For each curve, only the stable region is depicted. The simulations show typical instability due to pull-in after approximately $z = d/3 = 3.3$ μm.

All designs show a maximum mechanical stress below 100 MPa, as shown in Table 4-2 for different sizes of geometry with straight suspension beams.

**Table 4-2** – *Maximum mechanical stress for the geometry with straight suspension beams in different sizes.*

<table>
<thead>
<tr>
<th>Frame Length [μm]</th>
<th>Mirror Square Length [μm]</th>
<th>Maximum Stress [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>300</td>
<td>&lt; 30</td>
</tr>
<tr>
<td>1000</td>
<td>500</td>
<td>&lt; 50</td>
</tr>
<tr>
<td>1200</td>
<td>500</td>
<td>&lt; 70</td>
</tr>
<tr>
<td>1500</td>
<td>600</td>
<td>&lt; 90</td>
</tr>
</tbody>
</table>

The maximum stress appears for both geometries in the corners formed by the mirror and the suspension beams or at the clamping. The maximum stress in the meander type geometry is lower than in the geometry with straight suspension beams. All the values lie well below the ultimate strength of monocrystalline silicon beams obtained by DRIE, which is about 1.3 GPa for comparable Si structures [61]. Note that the mechanical stress calculations obtained with the FE model are approximate, as no special precautions were taken for mesh refinement in the corners. Experiments confirmed however that the mechanical stresses were well below the ultimate strength of silicon during operation.

The finite element simulations show that displacements of 3 μm can be obtained with actuation voltages in the order of 30 V. In this range, the electrostatic actuator is well below the physical limit of electrostatic breakthrough. Following the modified Paschen Law suggested by Schaffert [64], breakthrough voltages at an actuation gap of 10 μm are about 400 V.

For silicon micromirrors having a thickness in the order of a few microns, gravity induces displacements of typically tens of nanometers, which is negligible for micromirror displacements in the range of a few microns. However, detector and emitter performance will depend on the micromirror orientation.
In all simulations, the electrostatic force was modeled to be distributed over the whole micromirror surface. With the parallel plate electrostatic actuator model, fringing fields are neglected. In the mask design, four actuation electrodes were placed on the glass wafer, two of which were connected together on each side in the realized devices (cf. 8.2.1). By applying different voltages to the different electrodes, tilting of the micromirror can be achieved. For the detector application, this would allow to correct for a possible non-parallel alignment of the mirror towards the fixed part.

### 4.2.4. Mechanical Resonance Frequency Simulations

The micromirror model introduced for the electrostatic actuator can be used for determining the fundamental mechanical resonance frequency of the system. For this, the suspended micromirror can be considered as a harmonic oscillator following

$$m \frac{\delta^2 z}{\delta t^2} + kz = 0$$ (4.13)

The resonance frequency for the simple harmonic oscillator is given by

$$f_0 = \frac{\omega_0}{2\pi} = \frac{1}{2\pi} \sqrt{\frac{k}{m}}$$ (4.14)

The resonance frequencies have been calculated for 10 µm thick micromirrors for the five different designs with meander type suspensions that were implemented on the fabrication masks (Table 4-3). The spring constants have been obtained from the displacement simulations in section 4.2.3, and silicon density is 2.330 kg/m$^3$ [56]. In this simplified model, the suspension mass is neglected. The additional mass in the suspensions will decrease the resonance frequency (cf. FE simulations in Table 4-4).

**Table 4-3** – Resonance frequencies for micromirrors of the realized meander type geometries, modeled as ideal spring-mass oscillators (micromirror thickness 10 µm).

<table>
<thead>
<tr>
<th>Frame Length [µm]</th>
<th>Mirror Length [µm]</th>
<th>Mirror Mass $m$ [µg]</th>
<th>Spring Constant $k$ [N/m]</th>
<th>Resonance Frequency $f_0$ [kHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500</td>
<td>400</td>
<td>3.73</td>
<td>6.48</td>
<td>6.64</td>
</tr>
<tr>
<td>1500</td>
<td>500</td>
<td>5.83</td>
<td>6.16</td>
<td>5.18</td>
</tr>
<tr>
<td>1500</td>
<td>600</td>
<td>8.39</td>
<td>5.82</td>
<td>4.19</td>
</tr>
<tr>
<td>800</td>
<td>400</td>
<td>3.73</td>
<td>38.79</td>
<td>16.23</td>
</tr>
<tr>
<td>800</td>
<td>500</td>
<td>5.83</td>
<td>35.81</td>
<td>12.48</td>
</tr>
</tbody>
</table>
The resonance frequencies for higher modes have been investigated with the finite element model in ABAQUS (using global C3D20R element seeding, element length ~3 μm). Figure 4-9 shows a representation of the resonance mode shapes.

Figure 4-9 – Resonance mode shapes obtained by finite element simulation.

In Table 4-4, the mechanical resonance mode frequencies are grouped by the different realized geometries. The values are represented graphically in Figure 4-10.

Increasing the mirror size increases the resonance frequencies of mode 6 and 7, whereas the resonance frequencies of all other modes decrease. The change in resonance frequency is due to the change in mass and to the change in length of the suspension. According to formula (4.14), the resonance frequencies will decrease with increasing mass, which is the dominant effect for most of the resonance modes. However, the stiffness $k$ will increase when the suspension is shortened (increased mirror size). This is the dominant effect only for the modes 6 and 7. Both of these modes exhibit large bending in the suspensions and low movements of the mirror plate.
Table 4-4 – Resonance frequencies in kHz for different micromirror geometries with meander type suspension. Resonance frequencies above 100 kHz were not calculated (represented as -).

<table>
<thead>
<tr>
<th>Mirror Frame Length</th>
<th>1500 μm</th>
<th>800 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mirror Square Length</td>
<td>400 μm</td>
<td>500 μm</td>
</tr>
<tr>
<td>Resonance Mode 1</td>
<td>5.85</td>
<td>4.75</td>
</tr>
<tr>
<td>Resonance Mode 2</td>
<td>15.28</td>
<td>12.58</td>
</tr>
<tr>
<td>Resonance Mode 3</td>
<td>15.28</td>
<td>12.58</td>
</tr>
<tr>
<td>Resonance Mode 4</td>
<td>26.36</td>
<td>24.61</td>
</tr>
<tr>
<td>Resonance Mode 5</td>
<td>26.36</td>
<td>24.61</td>
</tr>
<tr>
<td>Resonance Mode 6</td>
<td>35.47</td>
<td>37.37</td>
</tr>
<tr>
<td>Resonance Mode 7</td>
<td>39.11</td>
<td>40.47</td>
</tr>
<tr>
<td>Resonance Mode 8</td>
<td>58.13</td>
<td>52.26</td>
</tr>
<tr>
<td>Resonance Mode 9</td>
<td>58.13</td>
<td>52.26</td>
</tr>
<tr>
<td>Resonance Mode 10</td>
<td>86.58</td>
<td>74.57</td>
</tr>
<tr>
<td>Resonance Mode 11</td>
<td>92.17</td>
<td>87.38</td>
</tr>
<tr>
<td>Resonance Mode 12</td>
<td>93.20</td>
<td>88.59</td>
</tr>
<tr>
<td>Resonance Mode 13</td>
<td>-</td>
<td>94.92</td>
</tr>
<tr>
<td>Resonance Mode 14</td>
<td>-</td>
<td>94.92</td>
</tr>
</tbody>
</table>

Figure 4-10 – Resonance frequencies below 100 kHz for different micromirror geometries with meander type suspension. With increasing mirror size, resonance frequencies generally decrease.
4.2.5. DSP-based Fabrication Process

For a first series of devices, a highly resistive double side polished (DSP) single crystalline silicon wafer was chosen as substrate (orientation (100), resistivity $\rho = 0.05 - 0.1 \, \Omega \text{cm}$). With standard photolithography and deep reactive ion etching, the 10 $\mu$m air gap between the parallel capacitor plates for the electrostatic actuation was formed (process step 1).

**Figure 4-11** – Schematic representation of the fabrication process for the micromirrors (upper part of Figure 4-1 (upside-down)). Substrates are a Double Side Polished single crystalline silicon wafer (515 $\mu$m) and a glass wafer (500 $\mu$m).
In order to define the actuation electrodes onto the highly resistive silicon micromirror, an aluminum layer was then sputtered on the wafer, and structured using a thick photoresist and wet etching (step 2). With a thick photoresist and deep reactive ion etching, the mirror and its suspension beams were structured in the subsequent step 3. In a similar way, an aluminum layer was deposited and structured by standard photolithography and wet etching to form the counter electrodes on the lower glass wafer (step 4). The structured silicon wafer including the mirror, suspension legs and the upper actuation electrodes was then bonded anodically to the glass wafer containing the lower actuation electrodes (step 5).

The individual devices were then separated using a wafer saw (step 6). In order to release the mirror and the suspension legs the devices were thinned by dry etching from the backside (step 7). The etching was stopped by optical inspection.

For reflective properties, a metal layer acting as reflective coating can then be deposited on the mirror surface using a shadow mask. For the DSP devices, the reflective coating has been omitted for simplicity. A schematic representation of the fabrication process is given in Figure 4-11.

The fabrication process based on DSP wafers has been used to fabricate a first series of devices. However, several fabrication steps impose constraints on the device performance. The most important constraint is given by the backside ICP etch step, during which the mirror surface is defined. The resulting surface is rough and the thickness variation over one single chip is not negligible, making this process hardly interesting for large scale processing. The difficulties were partially overcome with the SOI-based fabrication process.

### 4.2.6. SOI-based Fabrication Process

The second series of movable MEMS mirrors using parallel plate electrostatic actuators have been realized with a fabrication process using Silicon on Insulator (SOI) wafers (Device Layer (DL) 20 μm / Buried Oxide Layer (BOX) 4 μm / Handle Layer (HL) 350 μm) as shown in Figure 4-12. The highly p-doped device layer (resistivity $\rho = 0.0075 \ \Omega \text{cm}$) is structured in two steps, using standard photolithography and Deep Reactive Ion Etch (DRIE).

In a first step, the device layer has been etched to a depth of approximately 10 μm to define the electrostatic actuation gap (step 1). Etching the rest of the device layer down to the BOX defines the mirror and the suspension legs (step 2). The structured SOI wafer was then bonded anodically (step 4) to a glass wafer.
containing the aluminum counter electrodes (obtained by aluminum sputtering and wet etching as above, step 3). The wafers were then diced (step 5) and for the individual devices, the handle and the buried oxide layer have been removed by dry etching (step 6). A reflective gold coating was finally evaporated onto the movable mirror using a shadow mask (step 7).

**Figure 4-12** – Schematic representation of the fabrication process for the micromirrors (upper part of Figure 4-1 (upside-down)). Substrates are a single crystalline Silicon On Insulator (SOI) wafer (Device Layer 20 μm / Buried Oxide Layer 4 μm / Handle Layer 350 μm) and a glass wafer (500 μm).
The fabrication process based on SOI wafers proved to be reliable and relatively robust compared to the DSP wafer based fabrication process. However, several fabrication steps impose constraints on the device performance:

- During the ICP etch steps, the inhomogeneous etch results in a non uniform thickness distribution of the individual micromirrors over one wafer.
- During dicing, dust particles can enter with the wafer saw cooling water into the gap between the actuation electrodes. The water can be evaporated, but particles may remain.
- During the last RIE step used to remove the buried oxide layer, the micromirror surface is exposed to the ion bombardment. This results in a higher surface roughness and thus optical degradation of the micromirror.
- The anodic bonding step is performed at high temperature, which may be one of the causes for residual stress that causes the micromirror to curve (cf. section 4.2.7).

4.2.7. Static Measurements

Using double side polished wafers, the first movable devices have been fabricated (results published in [A1]). A micrograph of the structured actuation electrodes can be seen in the Scanning Electron Microscope (SEM) micrograph of Figure 4-13a. The picture has been taken after process step 4 (aluminum electrode etch).

![SEM image of a structured micromirror (before release). Four electrodes (Bright: Aluminum; Dark: Silicon) can be distinguished, which allow correction of mirror tilt due to manufacturing tolerances as the white light interferometer image (b) shows.](image)

**Figure 4-13** – a) SEM image of a structured micromirror (before release). Four electrodes (Bright: Aluminum; Dark: Silicon) can be distinguished, which allow correction of mirror tilt due to manufacturing tolerances as the white light interferometer image (b) shows.
In the micrograph, the four different electrodes are visible, which allow tilting of the micromirror devices: when the actuation voltage is applied to only two of four electrodes, the micromirror tilts, as can be seen in the White Light Interferometer (WLI) recording in Figure 4-13b. By choosing the appropriate voltages on the different electrodes, the mirror device can be adjusted for mirror tilt.

The fabricated devices were characterized using a Zygo White Light Interferometer (WLI). Due to the last fabrication step, the backside dry etch through the whole wafer thickness (550 μm), the surface was observed to be rough as can be seen in the WLI measurement results depicted in Figure 4-13b. Due to this roughness of the device surface, the displacement curve measurements were performed for a single point on the device. The displacement curve in dependence of the actuation voltage is shown in Figure 4-14. The error bars are estimated uncertainties due to surface roughness. With these measurements, the actuation voltages calculated in the finite element simulations have been confirmed.

Figure 4-14 – Measurements on micromirrors fabricated using double side polished wafers with two different mirror suspension geometries. For the straight suspension, the same mirror size needs longer suspension for comparable actuation voltages.

The micromirrors fabricated using DSP wafers exhibited considerable thickness variations over one device due to the inhomogeneous backside etch. The mirror has been observed to be thicker in the center and thinner to the edges of the chip,
varying in an estimated range from 5 to 10 μm. This thickness variation was comparable for all fabricated devices. Despite the thickness uncertainty, it can still be observed that the meander type suspension is more compliant than the geometry with straight suspension legs (Figure 4-14). This results in lower actuation voltages for the same displacement of the meander type devices, as expected from the finite element simulations.

The difficulties of poor surface quality and considerable thickness variation were partially overcome with the SOI-based fabrication process. By changing to the SOI wafer based process, reproducible production of micro mirror devices has been achieved. Using a Tencor Profilometer, measurements of the first dry etch step into the 20 μm device layer confirmed a suspension beam and mirror thickness of 9 μm. WLI measurements confirmed a good transfer of the mirror geometry from the mask into the silicon chip.

*Figure 4-15 – Mirror curvature due to released internal stresses in the SOI wafers: Cross section (a) and top view (b) of a White Light Interferometer measurement (no voltage applied). d₀ is the initial mirror elevation (silicon surface to top point of the curved mirror).*

The use of SOI wafers instead of DSP silicon wafers allowed improvement of the mirror surface flatness and increased process reliability compared to the first
design (results published in [A2]). However, the devices fabricated using SOI wafers suffered from a mirror bow due to internal stresses as can be seen in a non-proportional close up of the mirror center (Figure 4-15b).

The initial mirror elevation $d_0$ at zero applied voltage was measured in the mirror center from the silicon surface to the top point of the curved mirror as shown in Figure 4-15a. For this device, $d_0$ was 2.9 $\mu$m. The elevation measured over the whole mirror length is thereof about 300 nm. This corresponds to a curvature of about 10 cm. Typical $d_0$ were 1 $\mu$m to 5 $\mu$m, depending on mirror and suspension geometry, corresponding to radii of curvature were 0.1 m – 0.3 m. Such curvatures were observed directly after release of the device, before deposition of the reflective coating.

![Figure 4-15b](image)

*Figure 4-16 – Measured mirror displacement depending on the electrostatic actuation voltage for different gold coated devices (60 nm) varying in mirror size (400 $\mu$m x 400 $\mu$m or 500 $\mu$m x 500 $\mu$m) and with different initial displacements $d_0$. Thickness was about 9 $\mu$m for all devices, frame length 1500.*

The deposition of a 60 nm reflective gold coating on the 9 $\mu$m thick silicon mirror membrane does not change the curvature significantly. The internal stresses causing the mirror curvature are most probably due to the thermal treatment during the bond process and to initial residual stresses in the silicon device layer of the SOI wafer. Temperature adjustments during the anodic bonding process, a stiffness
increase of the mirror membrane or the deposit of a metal layer of adequate thickness on the mirror are possible strategies to reduce or compensate the curvature in a next generation. This is of essential importance in order to increase the optical performance of the detector system, as the curvature degrades the finesse of the optical cavity. A discussion about the influences on the performance limits introduced by mirror imperfections of tunable cavities [48, 65] is presented in section 3.1.4.

In order to characterize the micromirror displacement performance, the fabricated mirrors were investigated under a Zygo White Light Interferometer taking single measurements at increasing steps of applied electrostatic actuation voltages. The position was estimated to be the mean value of the mirror surface, error bars account for approximate position deviations from the mean. Movements of more than 3 μm were obtained with actuation voltages kept below 30 V. Displacement measurements are shown for five different gold coated micromirror devices in Figure 4-16.

![Figure 4-17](image)

**Figure 4-17** – Finite element simulations (lines) and measurements for different gold coated devices (data points) of the mirror displacement vs. applied voltage on the electrostatic actuators. Mirror square length is 400 μm, frame length 1500 μm, and thickness about t = 9 μm. The differences are due to variations in thickness and different initial displacements d₀.

The measured displacements are close to the displacements obtained by simulations as shown in Figure 4-17. One reason for the variations are due to
different curvatures of the different devices, resulting in a mirror center maximum
displacement $d_0$ as discussed above. Secondly, the thickness of one device to another
differs due to the inhomogeneity of the silicon etch. A third reason is the simplified
model of a parallel plate electrostatic actuator, in which the fringing fields were
neglected.

The pull-in effect has been observed experimentally. At high voltages, the
mirrors were pulled onto the electrodes on the glass wafer. The pull-in voltage
depends on the geometry and on the initial distance $d_0$ due to curvature. For the
1500 $\mu$m frame version, the pull-in was usually above 30 V, for the 800 $\mu$m frame
version, pull-in was not observed with voltages up to 60 V. The pull-in was observed
to be fully reversible, i.e. after a relaxation time without applied voltage, the mirror
snapped back to its original position. A graphic representation of a pulled-in
micromirror is shown in Figure 4-18. The investigations of the pull-in effect under the
WLI allowed determining the mirror thickness. Knowing the device layer thickness
(20 $\mu$m), and the aluminum electrode thickness (~200 nm), the mirror thickness has
been measured 9 $\mu$m for the device shown in Figure 4-18.

Figure 4-18 – Pull-in of a micromirror: at high voltages, the mirror snaps onto the
counter electrodes on the glass wafer.
4.2.8. Dynamic Measurements

The displacements measured characterize the static mirror position for an applied voltage. With mechanical resonances in vertical direction, however, the micromirrors can be used in a resonant operating mode in a tunable RCED, provided an adequate readout mechanism is implemented. Other mode shapes could moreover be of interest for various applications, such as tilting mirrors for bar code readers or displaying applications.

Dynamic characterization of the devices was also performed to investigate the system stability. The typical dynamic properties of a micromirror at atmospheric pressure with electrostatic actuation of the devices are depicted in Figure 4-19.

A Polytec Microsystem Analyzer Vibrometer was used for dynamic characterization of the presented micromirrors. Measurements were performed at atmospheric pressure with electrostatic actuation of the devices. The measured curve shows the frequency response to an applied periodic chirp signal of 30 V amplitude performed on a device with 400 µm x 400 µm mirror size, suspension length 1370 µm and a thickness of 9 µm. The figure illustrates the resonant mode shapes (from simulations) and the corresponding frequencies.

The measurement setup allowed characterization of movements in vertical direction only. The frequencies of those vertical resonance modes were measured and compared to the frequency analysis results obtained from the finite element model.

The numbering of the resonant modes corresponds to their appearance with increasing frequency in the finite element simulations. The resonance modes obtained from simulations appear in the same sequence as the measured ones. Each measured vertical mode could thus be identified and assigned to a vertical mode obtained from the simulation results. The resonance mode pairs 2/3, 8/9 and 13/14 appear at a single frequency each due to the mirror design symmetry.

Results for simulations and measurements on 25 devices are represented in Figure 4-20, while the complete data can be found in appendix 8.1. It can be seen, that frequencies from simulations were typically some percent higher than measured frequencies. These differences are partially due to the FE model (no special mesh refinements in the corners), partially to fabrication tolerances (suspension width not constant) and partially due to thickness variations because of the inhomogeneous dry etch of the silicon layer over the wafer size.
Figure 4.19 – Measurements of the mirror resonance frequencies and schematic representation of the different resonance modes obtained from the Finite Element Model frequency analysis. The modes which are not represented were not measured as their movement lies in the mirror plane.
Due to fabrication uncertainties, the design mirror thickness of 10 μm was not reached; the thickness of the realized devices is rather around 9 μm. Simulations with different thicknesses for one mirror type show lower resonance frequencies for thinner mirrors. This explains partially the fact, that measured devices exhibited lower resonance frequencies.

Uncertainties in the suspension geometry (e.g. width and clamping) due to fabrication issues may furthermore strongly influence the resonance frequencies. Additionally, squeeze-film air damping effects in the actuation gap have not been implemented in the FE model. The damping as well lowers the resonance frequencies, although to a smaller extent. Squeeze film air damping is discussed in section 4.2.9. A further reason for the differences is the curvature of the mirrors that has been observed in the fabricated devices (cf. section 4.2.7), but has not been included in the FE model.

Figure 4-20 – Resonance frequencies for several geometries, simulations (outlined elements) and measurements (filled elements) with standard deviation bars. If not stated otherwise, thickness is about 9 μm for measurements and 10 μm for simulations. Measurement results differ from the simulation results due to thickness variations, curvature and damping effects, which are not included in the simulations.
4.2.9. Damping

The micromirrors are subjected to various damping mechanisms. In general, damping may arise from friction, acoustic transmission, internal dissipation, air damping, etc. As summarized by Bao [66], the dominant damping mechanism in Microsystems is air damping, due to the large surface area to volume ratio. More specifically, it is pointed out, that the drag force damping is usually several orders of magnitude smaller than the squeeze film air damping. In the finite element simulations presented in the above section, damping effects have been neglected, as the influence on the resonance frequency is small and air damping has no influence on the static displacements. However, the maximum deflection of the micromirror when oscillating in its mechanical resonance modes is strongly influenced by air damping. In the following, the influence of squeeze film air damping of a square mirror plate is considered following the model by Bao [66], and compared to measurements.

When the mirror is moving perpendicular towards the glass support wafer (cf. Figure 4-5), the air film between the movable mirror and the fixed glass wafer is squeezed. When the mirror moves towards the glass plate, the pressure is increased so that some of the air flows out of the gap. When moving away from the glass support wafer, the pressure is lowered and air flows into the gap. This damping force can be modeled proportional to the velocity of the moving mirror. The differential equation for the fundamental mechanical resonance mode (cf. formula (4.13)) becomes

\[ m \frac{\delta^2 z}{\delta t^2} + c \frac{\delta z}{\delta t} + k z = 0 \]  \hspace{1cm} (4.15)

with \( c \) the coefficient of the damping force caused by the surrounding air. The factor \( c \) can be derived for a rectangular plate [66]:

\[ c = \frac{\mu \beta LB^3}{d^3} \]  \hspace{1cm} (4.16)

where \( L \) is the length, \( B \) the width of the rectangular plate, \( d \) the initial air gap, \( \mu \) the coefficient of dynamic viscosity (for air \( \mu = 1.8 \cdot 10^{-5} \)) and \( \beta \) a geometry factor depending on the ratio of \( B/L \). For a square plate, \( \beta = 0.42 \). For a square plate of length \( s \), the coefficient of the damping force simplifies to

\[ c = 0.42 \frac{\mu s^4}{d^3} \]  \hspace{1cm} (4.17)

The air damping coefficient is related to the damping ratio \( \zeta \) and to the quality factor \( Q \) of the system:
with \( m \) the mirror mass and \( \omega_0 \) the resonance frequency. The theoretical values for \( c \) and \( Q \) for a 400 \( \mu \)m square mirror are shown in Table 4-5. Only the pure vertical modes 1 and 7, which correspond to the model, are represented. The theoretical values are lower than the measured ones. This is due to the additional mass and damping in the suspensions, which has not been included in the model, and due to fabrication tolerances. The \( Q \) factors at normal pressure are very low, due to the strong damping.

<table>
<thead>
<tr>
<th>Mode #</th>
<th>Measurements</th>
<th>Theory</th>
<th>Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Freq. [kHz]</td>
<td>( w ) [rad/s]</td>
<td>( m ) [( \mu )g]</td>
</tr>
<tr>
<td>Mode 1</td>
<td>4.08</td>
<td>25'635</td>
<td>3.73</td>
</tr>
<tr>
<td>Mode 7</td>
<td>35.75</td>
<td>224'624</td>
<td>3.73</td>
</tr>
</tbody>
</table>

The resonance frequencies of the micromirrors have been measured as a function of the surrounding pressure. The dependence of the frequency response on the pressure is shown in Figure 4-21. The squeeze film air damping effect can be seen clearly in the strong damping of the resonance peaks with increasing surrounding pressure. When lowering the pressure, the \( Q \)-factors increase drastically after a certain transition pressure as shown in Figure 4-22, before stabilizing at even lower pressures. Three regions can be distinguished: in region A (10 – 1000 mbar), the \( Q \) factor is nearly independent of the pressure. In this region, the damping mechanism is mainly due to squeeze film air damping. When pumping below 10 mbar, the \( Q \) factor increases steadily, until about 0.01 mbar. In this region B, the air is rarefied and rarefied air damping is the dominant damping effect (presented in [66], not included in the model). At pressures below 0.01 mbar, the damping effects of internal friction and energy losses via the clamping have to be considered as well (region C). The noise and the increase in noise at about 2 kHz are measurement setup artifacts.

For applications in mechanical resonance, the micromirrors have thus to be operated at low pressures. The complete measurement data for all modes can be found in the appendix (8.1).
Figure 4-21 – Frequency response at different pressures. With decreasing pressure, squeeze film air damping is reduced and the amplitude increases (500 μm square mirror with 1500 μm suspension). For this device, resonances have been measured only below 10 mbar.

Figure 4-22 – Q factors at different pressures. The Q factor increases with decreasing pressure (400 μm square mirror with 1500 μm suspension; fitted lines for visualization purposes only).
4.3. Comb Drive Actuated Micromirror

In view of the large curvatures observed in the micromirrors using parallel plate electrostatic actuation (cf. section 4.2.7), alternatively electrostatic comb-drive actuation can be used for the vertical mirror movement. Realizations of such mechanisms have been presented by Overstolz [67], Noell et al. [60] or Inoue et al. [68]. The comb drives are hereby fabricated using SOI wafers. The thickness of the suspension beams and the actuation combs attached to the mirror differs from the thickness of the mirror and the fixed combs. In this way, the mirror plate can be fabricated much stiffer than the suspensions. Deformations due to internal stresses and due to the actuation are mainly induced into the suspension and not into the mirror plate in such a configuration. The mirror surface curvature is thus drastically reduced compared to the mirrors using the parallel plate electrostatic actuator design. The actuator design and fabrication process developed in this thesis is partially adapted from Overstolz and Noell et al. [60, 67].

4.3.1. Electrostatic Actuator Design

The vertical mirror movement can be obtained using a comb drive actuator, with different comb finger heights for the fixed and the movable fingers. The mirror displacement has been simulated for one single movable finger (low height $h_0$) at the distance $d_0$ from the fixed fingers (high height $h_1$) as shown in Figure 4-23a.

![Figure 4-23](image_url)

**Figure 4-23** – Comb drive actuator design: single movable finger (low height $h_0$) between two fixed fingers (high height $h_1$) (a) and electric field distribution for an applied voltage of 50 V (red) when the movable finger is at $z = 0$ (b).
The total force has then been obtained by multiplying the force for one single finger with the number of fingers for one specific geometry multiplied by the finger length. These forces are due to the asymmetry of the electric field which builds up when an actuation voltage between the movable mirror combs and the fixed combs is applied (Figure 4-23b). The electric field causes the movable combs to move vertically towards the center of the fixed comb fingers.

Similar to the analytical model for the parallel plate actuated micromirror (cf. section 4.2.1), the total potential energy can be expressed as

$$E_{tot} = \frac{1}{2}CU^2 + \frac{1}{2}kz^2$$  \hspace{1cm} (4.20)

However, the electrostatic energy cannot be modeled with a simple parallel plate capacitor, because the fringing fields cannot be neglected. The asymmetry of the electric field causes the vertical movement. The electrostatic energy per unit finger length for each vertical movable finger position $z$ for a fixed applied voltage $U_0$ was calculated with a finite element model in COMSOL. The obtained energy was observed to follow an exponential law. An exponential law was fitted to the obtained energy in dependence of the $z$-position of the movable finger.

$$E_{el,lin} = ae^{-bz} + c = \frac{1}{2}CU_0^2$$  \hspace{1cm} (4.21)

$a$, $b$, and $c$ are the fitting parameters, depending on the geometry and the applied voltage. The capacitance depending on the position $z$ is thus given by

$$\frac{1}{2}C = \frac{ae^{-bz} + c}{U_0^2}$$  \hspace{1cm} (4.22)

The force per unit finger length for any given applied voltage can then be obtained by taking the derivative with respect to the free coordinate $z$:

$$F_{el,lin} = -\frac{\partial}{\partial z} \left( \frac{1}{2}CU^2 \right) = \frac{ba}{U_0^2}e^{-bz}U^2$$  \hspace{1cm} (4.23)

which is the force per unit finger length at the position $z$ for a certain applied voltage for one single movable finger. It decreases exponentially with a movement in the positive $z$-direction. Figure 4-24 shows the electrostatic energy as results from the COMSOL simulations at different positions $z$ and the fitted exponential model, as
well as the corresponding force per unit length \( (U_0 = 50 \text{ V}, h_0 = 5 \mu\text{m}, h_1 = 20 \mu\text{m}, d_0 = 2 \mu\text{m} \) and width (each finger) \( w = 3 \mu\text{m}) \).

![Figure 4-24](image)

**Figure 4-24** – Electrostatic energy and force per unit length for an applied voltage of 50 V at different positions of the movable comb drive finger. The force decreases exponentially with increasing displacement \( z \).

Simulations have been performed varying the gap between the fixed and the movable fingers \( d_0 \), the fixed finger height \( h_1 \), and the movable finger height \( h_0 \). Table 4-6 summarizes the range of values for the different variables and their limiting criteria.

**Table 4-6** – Limiting criteria and value ranges for the variables used in the finite element simulations of the electrostatic comb drive actuators.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
<th>Based on / limited by</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finger Gap ( d_0 )</td>
<td>( 2.0 \mu\text{m} \leq d_0 \leq 4.0 \mu\text{m} )</td>
<td>Mask/Fabrication Capabilities</td>
</tr>
<tr>
<td>Fixed Finger Height ( h_1 )</td>
<td>( 20 \mu\text{m} \leq h_1 \leq 50 \mu\text{m} )</td>
<td>SOI Device Layer</td>
</tr>
<tr>
<td>Movable Finger Height ( h_0 )</td>
<td>( 5 \mu\text{m} \leq h_0 \leq 12 \mu\text{m} )</td>
<td>DRIE Fabrication Capabilities</td>
</tr>
</tbody>
</table>
The simulations for different gap width in Figure 4-25 show for small gaps strong forces at zero displacement \((z = 0)\) and exponentially decreasing forces while the comb fingers move in direction \(z > 0\). Because the inhomogeneity of the electric field is small, the acting forces become very small at bigger displacements \(z\) (Figure 4-25c). For wider finger gaps (Figure 4-25d), the inhomogeneity is bigger and thus the forces are smaller but decrease slower with increasing \(z\) (Figure 4-25e).

Figure 4-25 – Single comb finger pair design (a) and color representation of the electric field distribution for an applied voltage of 0 V at the fixed fingers (dark blue) and 50 V at the movable finger (red) for (b) zero displacement of a small gap and a slight displacement for a small gap (c) and a wide gap (d). The actuation force is higher for small gaps at zero displacement, but higher for large gaps at displacements over \(-2 \, \mu m\), as the inhomogeneity of the electric field is preserved longer (e).

Simulations of the fixed finger height \((h_1)\) by keeping the movable finger height \((h_0)\) constant, as well as simulations of the movable finger height \((h_0)\) while keeping the fixed finger height \((h_1)\) constant, show only small variations in the force per unit width compared to the overall force change over the whole displacement \(z\) (Figure 4-26). For these simulations as well, the electric field asymmetry preservation effect can be observed: forces are initially higher at zero displacement \((z = 0)\) for fingers having a small \(h_0\), but decrease faster while the comb fingers move towards \(z > 0\). Based on fabrication capabilities, the movable finger height was set to approximately 5 \(\mu m\). The fixed finger height was chosen 20 \(\mu m\), based on the availability of SOI wafers in stock at the IMES.
**Figure 4-26** – Movable finger displacements for different movable (a) and fixed (b) finger heights. The effect of the finger height variation on the actuation force is relatively small compared to the overall force change during displacement.

### 4.3.2. Suspension Geometry

A detailed analysis of the suspension geometries has been carried out in the master thesis by Philipp Rüst [69]. Only the retained geometries are presented here.

**Figure 4-27** – Micromirror design - cross section (a) and top view (b) of the 3 realized designs with 4 folded (A), 8 straight (B), and 4 straight suspensions (C).
Three suspension geometries have been retained for the fabrication: one with four folded suspension legs (A), one with eight straight suspension legs (B) and one with four straight suspension legs (C) with the dimensions as shown in Figure 4-27. The suspension geometries have been designed to have a spring constant around 1.5 N/m in order to allow a displacement of 3 μm at 50 V. Based on the results in section 4.3.1, the movable finger height $h_0$ was set to approximately 5 μm and the fixed finger height $h_1$ was chosen to be 20 μm. The design of the comb drive actuators is presented in the following sections. The exact spring constants and the parameters for the comb drive actuator designs of all realized micromirrors can be found in the appendix 8.2.2.

4.3.3. **Displacement Simulations**

From the simulated forces for a single comb drive finger, the displacement of the micromirror can be calculated. Assuming a suspension with a linear elastic response, the spring force will be proportional to the displacement. In an equilibrium position, the net force on the mirror will be zero, hence

\[
F_{hor} = 0 \quad \text{(4.24)} \quad \quad F_{spring} + F_{el} = 0 \quad \text{(4.25)}
\]

\[
-nlbae^{-kz} \frac{U^2}{U_0^2} - kz = 0 \quad \text{(4.26)} \quad \quad ze^{kz} = \frac{nlba \frac{U^2}{k}}{U_0^2} \quad \text{(4.27)}
\]

where $k$ is the spring constant, $n$ is the number of fingers and $l$ the individual finger length. The displacements $z$ for an applied voltage $U$ can thus be obtained solving

\[
bze^{kz} = \frac{nlba \frac{U^2}{U_0^2}}{k}
\]

The solution is obtained using the Lambert-W function [70]:

\[
z = \frac{1}{b} W \left( \frac{nlba \frac{U^2}{k}}{U_0^2} \right) \quad \text{(4.29)}
\]

Figure 4-28 shows the solutions of equation (4.29) for 4 different variants of a mirror with folded suspension. With more and longer comb drive fingers, higher displacements are obtained.
Since the spring constant $k$ is very similar for the different geometries, the displacement curves are very similar for all geometries. The values for a displacement at 50 V are summarized in the appendix (cf. 8.2.2) for all geometries.

![Figure 4-28](image)

**Figure 4-28** - Simulated micromirror displacements for an applied actuation voltage for different combinations of comb drive finger length and number of fingers.

Convergence analysis of the finite element model in COMSOL has been carried out and verified in the Master Thesis by Philipp Rüst [69]. In the same work, the suspension geometry was selected and investigated for lateral stability. The values for the spring constants $k$ depending on the suspension geometry were obtained by finite element simulations in COMSOL. As material, an orthotropic silicon crystal has been simulated using the elastic constants by Hall [63]. The retained geometries with their respective spring constants $k$ can be found in the appendix (section 8.2.2).

Observe, that the displacements do not depend on a ground voltage applied to the handle layer as for the micromirrors presented by Overstolz [67]. This is due to the freestanding comb drive structures which are obtained with the backside etch of the micromirrors (cf. fabrication step 6 in section 4.3.5).
4.3.4. Mechanical Resonance Frequency Simulations

Using the spring constants calculated for the micromirrors (cf. section 8.2.2), the resonance frequencies have been calculated for 20 μm thick micromirrors having the geometries that have been fabricated as shown in Table 4-7. The spring constants have been obtained from the displacement simulations in section 4.3.3, silicon density is 2'330 kg/m³ [56]. In this simplified model, the suspension mass is neglected. The additional mass in the suspensions will decrease the resonance frequency. Higher modes have been investigated in Master Thesis by Philipp Rüst [69].

<table>
<thead>
<tr>
<th>Suspension Geometry (cf. section 8.2.2)</th>
<th>Mirror Length [μm]</th>
<th>Mirror Mass ( m ) [μg]</th>
<th>Spring Constant ( k ) [N/m]</th>
<th>Resonance Frequency ( f_0 ) [kHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (folded)</td>
<td>300</td>
<td>4.19</td>
<td>1.47</td>
<td>18.7</td>
</tr>
<tr>
<td>A (folded)</td>
<td>400</td>
<td>7.46</td>
<td>1.47</td>
<td>14.0</td>
</tr>
<tr>
<td>B (8 straight)</td>
<td>300</td>
<td>4.19</td>
<td>1.39</td>
<td>18.2</td>
</tr>
<tr>
<td>B (8 straight)</td>
<td>400</td>
<td>7.46</td>
<td>1.39</td>
<td>13.7</td>
</tr>
<tr>
<td>C (4 straight)</td>
<td>300</td>
<td>4.19</td>
<td>1.5</td>
<td>18.9</td>
</tr>
<tr>
<td>C (4 straight)</td>
<td>400</td>
<td>7.46</td>
<td>1.5</td>
<td>14.2</td>
</tr>
</tbody>
</table>

Table 4-7 - Resonance frequencies for micromirrors of the realized geometries, modeled as ideal spring-mass oscillators (micromirror thickness 20 μm, suspension and comb masses neglected).
4 Micromirrors for tunable mid-IR detectors and emitters

4.3.5. Fabrication Process

The movable MEMS mirrors using electrostatic actuation in a comb drive configuration have been realized with a process using SOI wafers (Device Layer 20 μm / Buried Oxide Layer 4 μm / Handle Layer 350 μm) as shown in Figure 4-29.

Process Step 1
PECVD oxide
ca. 650 nm, at 300°C

Process Step 2
Photolitho S1813
Mask 1, Device Layer
RIE, Oxide Dry Etch
650 nm
Resist Removal
S1165, O2-Plasma

Process Step 3
Photolitho S1813
Mask 2, Device Layer
RIE, Oxide Dry Etch
"Self-Alignment"

Process Step 4
ICP, Dry Etch
ca. 5 μm
Resist Removal
S1165, O2-Plasma

Process Step 5
ICP, Dry Etch
Remaining Device Layer (Pattern Transfer)

Process Step 6
Backside Lithography (AZ 4562)
Mask 3, Frontside Protection on support wafer
ICP, Dry Etch
Backside Through Etch
HF (Vapor/Wet) Etch
Oxide Removal
(Critical Point Dryer)
Avoid Sticking

Process Step 7
Mirror Metal Deposit
Stencil, Au Evaporation

Figure 4-29 – Schematic representation of the fabrication process for the upper part of Figure 5-1 (upside-down). Substrate is a single crystalline Silicon On Insulator (SOI) wafer (Device Layer 20 μm / Buried Oxide Layer 4 μm / Handle Layer 350 μm).
The fabrication process is based on a process presented by Overstolz [67] and Noell et al. [60]. In a first step, a hard mask of roughly 600 nm silicon oxide is deposited on the SOI wafer. With standard lithography and RIE using a first mask, containing only the fixed fingers and the mirror, the oxide is opened to define the fixed combs and the movable mirror surface (step 2). After resist removal, a second photolithography step is performed on top of the silicon oxide, using a second mask. This mask includes the fixed fingers, the mirror, the suspension and the movable fingers. The alignment is performed in a Süss MA6 mask aligner, which allows alignment precision at about 1 μm. In order to account for misalignments even below 1 μm, the structures on the second mask are drawn slightly larger than on the first mask. When performing again a RIE step, the overlapping oxide is removed. In this way, a precise positioning of the movable fingers with respect to the fixed fingers is obtained (“self-alignment”; step 3). A first silicon DRIE etch step defines then the thickness of the suspension and the movable fingers (5 μm; step 4). After photoresist removal, a second silicon DRIE step transfers the pattern down to the buried oxide layer (also referred to as delay mask process; step 5). In this way, the movable comb fingers and the suspensions are defined. Backside lithography and silicon DRIE are used for the opening through the handle layer and HF etch (either vapour etch or liquid HF plus critical point drying) is used for removal of the masking oxide and the buried oxide, releasing the mirror (step 6). A reflective gold coating is finally evaporated onto the movable mirror using a shadow mask (step 7).

The fabrication process for the comb drive actuated micromirrors proved to be reliable and relatively robust. However, several fabrication steps impose constraints on the device performance:

- **During the ICP etch steps**, the inhomogeneous etch results in a non uniform thickness distribution of the individual micromirrors over one wafer.

- Additionally, due to **aspect ratio dependent etching** (ARDE), openings of larger size are etched at higher rates then small openings, leading to slightly different thicknesses of suspension and movable comb fingers. As well, during the backside etch, the openings under the suspensions are not etched completely, as they are much narrower than the mirror opening.

- The timing for the **HF vapour etching** needs to be controlled individually for the different geometries. Overetching of the folded suspensions released the support base and caused the fixed combs to bend, making actuation impossible.

- **After release** using the HF vapour etcher, some of the devices did not move. This might be, despite the vapour etch step, due to stiction, originating from the electrostatic clamping in the HF vapour etcher. Using a mechanical holder may prevent this.
4.3.6. Static Measurements

Figure 4-30 shows a SEM image of a fabricated micromirror, where the separation of the low height combs (dark) from the high height combs (bright) is visible. The realization of such vertically moving comb drive actuated micromirrors has been achieved with the described delay mask process. Mirrors having geometries comparable to the parallel plate actuated micromirror with mirror square length \( l = 300 \ \mu m \) and \( l = 400 \ \mu m \) have been realized. All measurements in this section have been performed after release, fabrication step 6, i.e. without the reflective Au coating.

![SEM images of fabricated comb-drive actuated micromirrors. a) Overview of a fabricated micromirror. b) Close-up combs and suspensions. The lower suspensions and combs on the mirror appear in dark (low height), while the elevated regions of the mirror surface and fixed combs appear bright (high height).](image)

Displacements of 2.5 \( \mu m \) at an actuation voltage of 30V have been measured using a WLI as predicted by finite element simulations (Figure 4-31). Measurements of three devices are shown, two with a folded, one with a straight suspension. The mirror square length is \( l = 400 \ \mu m \), comb drive finger gap is 3 \( \mu m \), finger width 2 \( \mu m \), length 100 (120) \( \mu m \), suspension width 10 (5) \( \mu m \) and length 780 (1340) \( \mu m \) for the straight (folded) suspension. There are non neglible differences between the individual devices as shown for two folded structures of the same type (A). They are due to the difference in thickness of the suspensions varying from one device to another, as a result of the inhomogeneous silicon dry etch over the wafer. For comparison, the simulations for thicknesses of 4 \( \mu m \) and 5 \( \mu m \) are shown for a straight suspension. The measured values lie well in the estimated thickness interval.
Figure 4-31 – Simulations and measurements of mirror displacements for actuation voltages applied at all comb drives simultaneously. The discrepancies between the theoretical and measured curves have their origin in thickness variations of the suspensions due to the fabrication process (approximate thickness: 5 μm).

The movable mirror can be tilted by applying different voltages to the different comb drives. In tunable RCEDs or tunable VECSELS, tilting the micromirror might compensate for a non parallel alignment of the movable mirror with respect to the DBR mirror. Such a non parallel alignment may originate from a variation of the SU8 spacer layer thickness (cf. Figure 5-1). By applying a voltage difference on two opposite comb drives while keeping the other comb drives grounded, a total angle variation of 0.23 degrees has been measured using a WLI as shown in Figure 4-32. This would compensate a thickness variation of the SU8 layer of up to 30 μm over the 7 mm wide spacer layer. This is far above the usually encountered thickness variations in such thin films which use to be well below 1 μm.

Due to the fabrication process and in contrast to the parallel plate actuated micromirror, the comb drive actuated micromirror exhibits after release a curvature towards the diode. Radius of curvature of the micromirror was measured using a WLI
to be about 1.2 m with a roughness of 2 nm (root mean square, corrected for the spherical bow). This is about a factor 10 increase in flatness compared to the parallel plate actuated micromirrors. The thickness variations for these micromirrors are minimal as they are given by the polishing step by the manufacturer of the SOI wafer.

![Figure 4-32](image)

**Figure 4-32** – Mirror tilting by applying a potential difference between two opposite comb drives for a micromirror suspended by 8 straight legs (suspension type B).

### 4.3.7. Dynamic Measurements

A Polytec Microsystem Analyzer Vibrometer was used for dynamic characterization of the presented comb drive actuated micromirrors. Measurements were performed at atmospheric pressure using electrostatic actuation of the devices. The frequency response to an applied periodic chirp signal of 30 V amplitude performed on a device with 8 straight suspension bars with a 300 μm x 300 μm mirror size (type B4) is shown in Figure 4-33. The suspension thickness for this specific device was around 18 μm due to process conditions. The figure illustrates the measured resonant mode shapes and the frequencies at which they appear. These are typical dynamic properties of a micromirror. However, mode shape and frequency depend strongly on the suspension and geometry parameters. With the measurement setup used, only movements in vertical direction were characterized.
The first three mechanical resonance modes of the comb drive actuated micromirrors lie below 100 kHz. For all types a parallel translational mirror movement and a tilting movement, similar to the first two modes of the parallel plate actuated micromirror, can be observed. These mechanical resonance modes depend strongly on the geometry of the mirror and the suspensions, whereby the thickness of the suspensions has a major influence. Geometries can be designed in such a way, that resonance frequencies around 10 kHz can be obtained for the vertical parallel mirror movement. Damping effects have not been included in the model for the comb drive actuated micromirrors. Measurements at lower pressures have not been performed for the comb drive actuated micromirrors.

**Figure 4-33** – Resonance frequency measurements for a comb drive actuated micromirror suspended with 8 straight suspension legs. Below 100 kHz, a vertical translational mode and two combined tilting modes at the same frequency have been identified.
4.4. Micromirror Curvature Adjustment

As shown in section 4.2.7 for the parallel plate actuated micromirror and in section 4.3.6 for the comb drive actuated micromirror, the released structures exhibit a certain curvature due to internal stresses. For a Fabry-Pérot detector, this curvature is unwanted. For VECSEL applications, a specific curvature is favourable for transversal mode selection, as shown in section 3.2. Due to the reflective metal coating on the freestanding silicon mirror membrane, a bimorph system is formed. Internal stresses exist in almost all deposited thin films and are usually unwanted. With a stress controlled deposit of a thin film however, the internal stresses can be exploited to obtain a specific curvature as needed for the VECSEL application. In general, all materials deposited as thin films on a silicon wafer exhibit intrinsic stresses and could be used for tailored stress layers for curvature adjustment.

4.4.1. Internal Stress

*Internal* stress in deposited thin films is generally composed of *intrinsic* and *extrinsic* stress components. The intrinsic stress is hereby the stress inherently in the deposited material, for example originating from the incorporation of other interstitial atoms (e.g. from residual gases or chemical reactions in the deposition chamber), or from recrystallisation processes. *Extrinsic* stress is for example due to the differences in thermal expansion coefficients of the deposited material and the substrate during deposition (thermal mismatch stress). Theoretical explanations for intrinsic stress have been proposed and summarized in Ohring’s Materials Science of Thin Films [71], however, origins of intrinsic stress are still subject to discussion.

Nevertheless, intrinsic stresses can be measured experimentally. Such intrinsic stress measurements have shown that hard refractory metals with high melting points tend to have higher residual stresses than softer metals with a low melting point. In deposited thin metal films that have a low melting point, the thermal mismatch stress generally exceeds the intrinsic stress. In deposited thin metal films that have a high melting point it is the other way: the thermal mismatch stress is often less than the intrinsic stress.

Reported values for intrinsic stress are summarized in the review article by Koch [72]. The values for gold, copper and silver are reported by Abermann and Koch [73]. Extensive work on titanium film deposits has been carried out by Schneeweiss and Abermann [74]. These measurements of stress in thin films as a
function of thickness and time are reprinted in Figure 4-34. In the figure, the forces per unit width are depicted; the intrinsic stress is the force per unit width divided by the deposited thin film thickness. For metals with a rather low melting point such as gold and aluminum, the force response rises initially, peaks, and then reverses sign as a function of film thickness. Most interestingly, important changes in stress occur at room temperature after the film deposition is complete. It is suggested by Abermann and Koch [73] that this relaxation is a result of recrystallisation and annealing processes that occur in the deposited thin films.

For the metals with high melting points, titanium, iron and chromium, a constant intrinsic stress of 0.6 GPa, 1.3 GPa and 1.4 GPa respectively has been measured. The stress for these metals remains stable after deposition. Intrinsic stress in evaporated thin gold films is negligible in comparison with evaporated thin chromium films.

![Figure 4-34](image)

**Figure 4-34** – Literature stress values for evaporated thin metal films (after Koch [72]). The stresses in films of metals with a low melting point (a) are generally instable and lower compared to stresses in metals with a high melting point (b).

Taking into account the origins of intrinsic stress in deposited thin films, the important process parameters during deposition for a stress control include deposition rate, sample temperature, base pressure in the chamber, materials / impurities present in the chamber, target composition and quality, substrate surface composition, impurities on the substrate surface, etc. By adjusting these parameters, the intrinsic stress can be predicted and bimorph structures can be designed having a desired curvature.

Using standard thin film deposition equipment, the deposition conditions in sputter systems vary stronger than in evaporative systems. Stress in sputtered metal films is thus more difficult to control; sputtered thin films appear to exhibit generally
2-3 times higher stresses than similar evaporated metal films. Due to availability and better control of the process conditions, it was thus chosen to deposit thin metal films by evaporation. However, also other materials could be used and stress could be tailored in layers such as e.g. silicon nitride or silicon oxide films. Further references on the subject of stress in sputtered films, can be found in chapter 12.5 in the Materials Science of Thin Films by M. Ohring [71].

### 4.4.2. Analytical Model and Design

In order to model the mirror bow due to internal stress, a bimorph cantilever model can be used. In this simplified model, a thin metal film is deposited on a (thick) silicon beam structure of width \( w \), assumed to be in an initial rest position (Figure 4-35a). As soon as the bimorph structure is released, the internal stresses \( \sigma \) cause it to curl (Figure 4-35c).

![Figure 4-35](image)

\( t_{Si} / t_m \) Silic on / Metal Thickness  
\( E_{Si} / E_m \) Silicon / Metal Young’s Modulus  
\( \alpha_{Si} / \alpha_m \) Silicon / Metal thermal expansion coefficient  
\( w \) beam width  
\( r \) radius of curvature

**Figure 4-35** – Bimorph cantilever model (a), schematic representation of the forces and moments (b) and freestanding curved structure after release (c).

As the freestanding curved cantilever (Figure 4-35c) is not loaded at its ends, the sum of the moments \( M \) and the sum of the forces \( F \) acting on one end of the cantilever (Figure 4-35b) equal zero:

\[
\sum F = 0 \quad \sum M = 0 \tag{4.30}
\]

\[
\sum F = F_{Si} + F_m = 0 \quad \sum M = M_{Si} + M_m = 0 \tag{4.31}
\]
where the moments $M$ are relative to the interface between the two layers. Expressed with the internal stress $\sigma$, the conditions (4.30) become

$$\sum F = \int_0^{z_m} \sigma_m dz + \int_{-z_m}^0 \sigma_{Si} dz = 0 \quad \sum M = \int_0^{z_m} \sigma_m zdz + \int_{-z_m}^0 \sigma_{Si} zdz = 0 \quad (4.32)$$

Stress can be modeled as the forces $F$ acting on the cross sections as defined in Figure 4-35. Within the elastic domain of the materials, the strain is proportional to the stress:

$$\sigma = E \varepsilon \quad (4.33)$$

Where $\varepsilon$ is the strain, $E$ is the Young’s modulus. In order to extend the one dimensional cantilever model to two dimensions, a certain width $w$ can be assigned to the cantilever. Bending will also occur in the axis transverse to the cantilever direction. This biaxial flexion can be taken into account by introducing the Poisson coefficient $\nu$ into equation (4.33).

$$\sigma_{Si} = \varepsilon_{Si} \frac{E_{Si}}{1 - \nu_{Si}} \quad \sigma_m = \varepsilon_m \frac{E_m}{1 - \nu_m} \quad (4.34)$$

It follows from this, that, provided the material constants Young’s modulus and Poisson coefficient are known a priori, the equilibrium state can be expressed as a function of the strain. The strain in a film can be expressed as

$$\varepsilon_{film} = \varepsilon_{film}^* + \Delta \varepsilon - \frac{z}{r_{int}} \quad (4.35)$$

Where $\varepsilon^*$ is the mean strain depending on the process conditions (for the metal it is $\varepsilon_m^*$, and for the silicon membrane it is assumed to be negligible), $\Delta \varepsilon$ is the strain variation when the beam is released (not known a priori but equal for the two materials), $z/r_{int}$ is the strain from the bending moment and the flexural rigidity of the cantilever, and $r_{int}$ is the radius of curvature due to the bending of the structure as a result of internal stress as shown in Figure 4-35. This expression for the strain (4.35) can be inserted into the equations (4.34).

Using equations (4.32), a system of two linear equations with the two unknown $r_{int}$ and $\Delta \varepsilon$ results. This system can be solved (solution presented in the work of Schweizer [75]) and the radius of curvature can be expressed as:
This formula links the curvature radius to the material properties on the one hand (thicknesses $t$, Young’s moduli $E$, Poisson’s coefficients $\nu$), and to the strain on the other hand. The strain however can have different origins.

If we consider the case where the freestanding silicon membrane is much thicker than the metal layer and the respective material constants Young’s moduli $E$ and Poisson coefficients $\nu$ are of the same order of magnitude, we can simplify equation (4.36) to

$$r_{int} = \frac{E_{m}t_{m}^{3}(1-\nu_{m})}{E_{s}t_{s}(1-\nu_{s})} + 6t_{m}t_{s} + 4t_{s}^{2} + 4t_{m}^{2} \div 6(\varepsilon_{m}^{*} - \varepsilon_{s}^{*})(t_{m} + t_{s}) \quad (4.37)$$

Rewriting the intrinsic stress induced using equations (4.33) and (4.34) leads to

$$\sigma_{int} = E \varepsilon = \frac{E_{m}}{(1-\nu_{m})}(\varepsilon_{m}^{*} - \varepsilon_{s}^{*}) \quad (4.38)$$

Inserting (4.38) in (4.37) gives the approximate formula

$$r_{int} = \frac{E_{s}t_{s}^{2}}{6\sigma_{int}(1-\nu_{s})t_{m}} \quad (4.39)$$

This approximate formula was first published in 1909 by Stoney [76]. It relates the radius of curvature to the thicknesses of the silicon mirror membrane and the metal coating. The approximate formula is valid for thin metal films on a thick silicon membrane. For a deposit of some 100 nm on a 10 µm silicon membrane, this condition is fulfilled.

As the micromirror is used at low temperatures, the influence of the thermal stresses have to be considered. For this, the curvatures due to internal stress and due to thermal stress can be added [77]:

$$\frac{1}{r_{tot}} = \frac{1}{r_{int}} + \frac{1}{r_{th}} \quad (4.40)$$
The thermal stress can hereby be expressed with the difference in thermal expansion coefficients and the difference in temperature.

\[ \sigma_{th} = \frac{E_m}{(1 - \nu_m)} \left( \alpha_m - \alpha_{Si} \right) \Delta T \]  \hspace{1cm} (4.41)

The radius of curvature due to thermal stress can hence be expressed for thin metal layers

\[ r_{th} = \frac{E_{Si} t_{Si}^2}{6E_m t_m (1 - \nu_{Si})} \left( \frac{1}{\alpha_m - \alpha_{Si}} \right) \Delta T \]  \hspace{1cm} (4.42)

Combining (4.42) and (4.39) in (4.40), the total radius of curvature can be estimated for a certain metal thickness on the silicon membrane. The following hypotheses apply for this analytical model:

- the stress due to the weight of the structure can be neglected
- the beam width \( w \) is the same for metal and silicon layer
- the layers are isotropic and homogeneous (thicknesses, thermal expansion, etc.)
- the radius of curvature is constant over the cantilever (mirror) length

The parameters used for the calculation are summarized in Table 4-8. The elastic modulus for the thin metal film was estimated to be the same as for the bulk material. This assumption can generally be made for evaporated metal films as reported by Ohring [71].

<table>
<thead>
<tr>
<th>Property / Material (crystal direction)</th>
<th>Silicon (100)</th>
<th>Chromium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Expansion Coefficient ( \alpha ) ( [10^6] )</td>
<td>2.6 [56]</td>
<td>4.9 [56]</td>
</tr>
<tr>
<td>Poisson Coefficient ( \nu ) [-]</td>
<td>0.28 [63]</td>
<td>0.21 [78]</td>
</tr>
<tr>
<td>Young’s Modulus ( E ) [GPa]</td>
<td>130 [63]</td>
<td>279 [78]</td>
</tr>
<tr>
<td>Intrinsic Stress on Silicon ( \sigma_{int} ) [GPa]</td>
<td>-</td>
<td>1.4 [71]</td>
</tr>
</tbody>
</table>
Figure 4-36 shows the relationship between the radius of curvature and the deposited metal coating thickness for a given silicon membrane thickness, calculated with the Stoney formula (4.39).

The metal chosen was chromium: chromium thin films can be obtained by evaporation, and give rise to stable tensile stress as shown in chapter 4.4.1. With a coating in the range of 100 nm thickness, a radius of curvature in the cm range can be achieved. In the same figure, the effect of thermal stress for a temperature difference of 200 K is shown. This is of interest when operating the device at low temperatures, as typically in the tunable optical infrared elements around 100 K. The radius of curvature will decrease, i.e. the mirror curls more, when cooled down. However, since the internal stresses exceed the thermal stresses, the radius of curvature will have a small variance.

**Figure 4-36** — Radius of Curvature for chromium coating (around 100 nm) on a 9 μm silicon membrane at 300 K and 100 K. A radius of curvature in the range of cm can be obtained with a chromium coating around 100 nm. The internal stresses exceed the thermal stresses when cooled down to 100 K, thus the curvature changes only a few percent.
Metal Deposition and Curvature Measurements

Metal coatings were deposited by evaporation through a shadow mask that has been aligned onto the micromirrors. The deposition was only performed on micromirrors with parallel plate electrostatic actuation. Curvature adjustment of the comb drive actuated micromirrors can be achieved in an analog manner. The radii of curvature were measured before and after deposition of the metal coating.

In order to compare the measured values to the simulations, the curvature before and after deposition have been added, resulting in the final curvature. The different sign before and after deposition takes into account the different bending directions before and after deposition (cf. Figure 4-36). Table 4-9 summarizes the measurements of 3 coated micromirrors.

<table>
<thead>
<tr>
<th>Device</th>
<th>Suspension Size [μm]</th>
<th>tCr [nm]</th>
<th>r before dep. [cm]</th>
<th>r after dep. [cm]</th>
<th>rCr meas. [cm]</th>
<th>rCr calc. [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1500</td>
<td>~200</td>
<td>-22.92</td>
<td>1.53</td>
<td>1.43</td>
<td>0.87</td>
</tr>
<tr>
<td>2</td>
<td>800</td>
<td>~200</td>
<td>-30.85</td>
<td>2.25</td>
<td>2.10</td>
<td>0.87</td>
</tr>
<tr>
<td>3</td>
<td>1500</td>
<td>~150</td>
<td>-45.50</td>
<td>2.00</td>
<td>1.92</td>
<td>1.16</td>
</tr>
</tbody>
</table>

The measured values are in the same order of magnitude as the simulations. However, the discrepancies between the simulated values (from Figure 4-36) and the measured values are due to uncertainties in the layer thickness (monitored during deposition process using a quartz resonator, not measured after deposition) and due to a misalignment of the shadow mask. That the values for the internal stress in the realized deposits may differ from the reported ones in literature, because they depend strongly on the deposition process conditions, must be considered. The misalignment can be seen in Figure 4-37.

In a subsequent step, the mirrors were coated with a 30 nm gold layer. The gold layer serves as high reflective coating. Measurements before and after the coating showed no significant difference in curvature. This is due to relaxation processes in the gold layer, which lead to almost stress free coatings as shown in section 4.4.1.
Figure 4-37 – White Light Interferometer recording (a) and a microscope photograph (b) of device 2 (cf. data in Table 4-9). The curvature adjustment after the chromium thin film deposit can be seen clearly in the WLI recording. The misalignment of the shadow mask can be seen in both images. In the microscope photograph, after the subsequent gold deposit, the 30 nm gold coating on top of the 200 nm chromium coating is visible due to higher reflectivity.

With the presented method exploring internal stress in a thin film deposit on the micromirror, the curvature of the micromirrors can thus be adjusted to a desired value. With a chromium thin film deposit in the range of some 100 nm, a curvature in the range of centimeters has been obtained for the parallel plate actuated micromirrors. For the comb drive mirrors, the same procedure can be applied. A precise curvature control is of importance for VECSEL applications as introduced in section 3.2.3. In theory, stress compensation in order to obtain flat mirrors without curvature is possible with the same method. In this case however, the stress compensation has to be designed for a specific temperature, as the thermal mismatch stress will dominate in such a stress compensated structure.
5. TUNABLE MID-IR RCEDs

The tunable Resonant Cavity Enhanced Detectors (RCEDs) are composed of two components; the movable micromirror and the detector part (cf. Figure 4-1). This allowed flexibility in the development of the two components separately. Additional flexibility is given in the assembly step for the integration of the separately developed diode and micromirror.

Three different tunable RCED variants have been fabricated accordingly: one using a piezo-actuated micromirror, and two using MEMS micromirrors. The MEMS micromirrors are based on electrostatic parallel plate actuation (cf. chapter 4.2) or based on electrostatic comb drive actuation (cf. chapter 4.3). The results of the optical measurement are presented in this chapter.

Only the specific design parameters for the fabricated detectors are introduced. The design of the diode and of the Distributed Bragg Reflector for the tunable RCEDs are presented in detail in the theses by Arnold [46] and Felder [79]. Further, the process steps for assembly of diode and micromirror are presented in this chapter.
5 Tunable mid-IR RCEDs

5.1. Design and Fabrication

5.1.1. Tunable Detector Design

In chapter 3.1, the tunable RCED working principle was introduced. Figure 5-1 shows the schematic working principle with a comb drive actuated micromirror.

Numerical simulations have been performed in order to determine the design parameters for the tunable RCED device. The simulations are based on the propagation of an electromagnetic wave in the RCED structure for different mirror distances using a transfer matrix method. The calculations have been performed in the Thin Film Physics Group. These numerical simulations, including details on the distribution of the electromagnetic field inside the cavity and the material parameters used for the specific design, are presented in detail in [79].

Figure 5-1 – Schematic representation of a tunable Resonant Cavity Enhanced Detector (RCED) using a comb drive actuated micromirror.

Table 5-1 – Numerical Simulation Results:
Tunable RCED design and expected performance [79].

<table>
<thead>
<tr>
<th>Property</th>
<th>Design Value</th>
<th>Property</th>
<th>Expected Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>DBR Reflectivity</td>
<td>~ 90 %</td>
<td>Selected Mode #</td>
<td>4 - 10</td>
</tr>
<tr>
<td>Tunable Range</td>
<td>4.6 µm to 5.5 µm</td>
<td>Linewidth (FWHM)</td>
<td>100 nm</td>
</tr>
<tr>
<td>Initial Airgap</td>
<td>0.5 µm</td>
<td>Cut-Off (@100K)</td>
<td>&gt; 5.5 µm</td>
</tr>
<tr>
<td>Mirror Movement</td>
<td>~ 2.5 µm</td>
<td>Buffer Absorption</td>
<td>&lt; 4.7 µm</td>
</tr>
<tr>
<td>SU8 Thickness</td>
<td>&gt; 8 µm</td>
<td>Diode/DBR Stack</td>
<td>~ 7.5 µm</td>
</tr>
</tbody>
</table>
Figure 5-2 shows the interdependency of the position of the micromirror and the detected wavelength. With an initial air gap of 0.5 μm, a micromirror movement of about 2.5 μm allows the wavelength to be tuned from approximately 4.6 μm to 5.5 μm for a specific design. The parameters used for this calculation and the resulting performance are summarized in Table 5-1. The required SU8 spacer layer thickness is calculated from the actual stack size plus the designed initial air gap.

![Figure 5-2](image)

**Figure 5-2** – Simulated detector quantum efficiency for different mirror positions. At a fixed mirror position, the detector is only sensitive at a single narrow wavelength band. Moving the micromirror allows changing this detected wavelength (from [A1]).

### 5.1.2. Diode and Bragg Reflector Design

The detailed layout for the detector simulated in Figure 5-2 is shown in Figure 5-3. The fixed DBR mirror is grown onto a Silicon (Si) single crystalline (111) substrate. It consists of 1.5 pairs of alternating layers with high (Pb_{0.99}Sr_{0.01}Te, \( n \approx 6 \)) and low (EuTe, \( n \approx 2.4 \)) refractive indices. With the high contrast in refractive index, mirror reflectivity is above 90% for wavelengths from 4 μm to 6 μm. The mirror is followed by a 3 μm buffer layer Pb_{0.99}Sr_{0.01}Te, which absorbs wavelengths below 4.7 μm (100 K) in order to select a single detection peak. This absorber layer can alternatively be grown directly onto the Si substrate, in order to reduce the total cavity length (for detailed presentation of the thin film layer stacks, cf. Felder [79]).
The active region is formed by a p(PbTe)–n+(PbSrTe:Bi) diode. Tellurium (Te) excess accounts for p-type semiconductor while Bismuth (Bi) doping ensures n+ type conductivity. The absorbing layer is only 0.3 μm thin. When compared to a bulk photodetector, the thin layer has a reduced volume where noise due to Shockley-Read generation and recombination of charge carriers can originate, which results in drastically increased device sensitivity [4].

Figure 5-3 – Detailed schematic representation of the detector part layout as shown in the lower part of Figure 5-1, including the Distributed Bragg Reflector (DBR), the buffer layer and the photosensitive diode, as well as contacts and antireflection (AR) coating.

The Te transparent contact ensures the n+ side diode contact and an anti-reflective TiO₂ coating on top of the structure minimizes unwanted reflections at the diode / air gap interface. A p-n junction with transparent contacts has to be used for tunable detectors. In contrast, a Pb metal layer is employed in the RCED with a fixed cavity length [4]. This Pb layer acts as a Schottky diode contact and as fixed mirror at the same time. The detectors are designed for 100 K operating temperature, however, they can be used up to > 220 K or even room temperature using a proper design [A3]. The complete diode chip layout can be found in the appendix (cf. section 8.2.3).

5.1.3. Diode and Micromirror Integration

Diode chip and micromirror chip are assembled using a photostructurable SU8 polymer layer. The thickness of this SU8 layer defines the initial cavity length and thus the mode which the tunable RCED will be working at. By choosing an appropriate SU8, layers from less than 1 μm up to more than 100 μm can be achieved. In the realized devices, the fabricated SU8 layers were in the range of 10 μm. The SU8 is spun on the diode chip, exposed and developed.

On one diode chip, four different diodes are accommodated. Due to fabrication, the diodes differ in quality. A preliminary testing step allows selection of the best working diode. Alignment marks allow then positioning the micromirror...
above the previously selected best working of the four diodes arranged on one chip.
The chip alignment is performed using an alignment tool developed for this purpose,
which also allows fixation of the two chips under slight applied pressure with a
mechanical holder after alignment. The polymer curing is then performed at 110°C
for 3h (complete chip including the holder, which exerts a slight force on the aligned
chips). This results in an acceptable bond. Once the bond is performed, an epoxy
could eventually be cast around the device assuring overall stability.

For characterization, the assembled chip was glued on a Cu heat sink,
ensuring good thermal conductivity when cooled down to the operating temperature
at 100 K. On the Cu support, a printed circuit board is connected by wire bonding to
the chip contacts. The contact pads of the diode and the contact pads of the
micromirror are aligned in such a way, that they are accessible from two different
sides (top and bottom). Figure 5-4 shows the integration of the diode chip with the
micromirror chip schematically.

Figure 5-4 – Schematic representation of the fabrication process for joining the
micromirror and the detector parts. For characterization, the assembled device is
 glued on a Cu heat sink and wirebonded to a Printed Circuit Board (PCB) for
contacting.
5.2. Tunable RCED Performance

5.2.1. Experimental Setup

The spectral response of the fabricated tunable RCEDs was characterized using a commercial Bruker Vertex 70 Fourier Transform Infrared (FTIR) Spectrometer. The detector signal (p-n diode photocurrent at reverse bias) from the tunable RCED is connected to the external detector input at the FTIR. Scanning the internal movable mirror of the FTIR allows recording the interferogram at the external detector. With the Fourier Transformation of the recorded signal one obtains the spectral response of the detector.

The tunable RCED detectors are placed inside a vacuum chamber with an infrared window and cooled to approximately 100 K with liquid nitrogen. A voltage source connected to the tunable RCED movable mirror allows scanning through its movable range. For each applied voltage, i.e. each mirror position, the spectral response is recorded. The IR source has been assumed to have a homogeneous distribution over the investigated wavelength domain. For more accurate measurements, a background correction can be implemented additionally. The experimental setup is depicted in Figure 5-5.

![Figure 5-5 – Experimental setup for characterization of the tunable RCEDs.](image)

**Figure 5-5** – Experimental setup for characterization of the tunable RCEDs.
5.2.2. **Tunable RCED using external piezo-actuated micromirrors**

The first experiments have been carried out with a gold-coated silicon mirror plate mounted onto a piezo stage. This holder allows for tilting, and for a parallel movement of 10 μm. The experiments have been performed within the Master’s Thesis by Christian Ebneter [80]. The measurements showed single peak tunability of the RCED from 4.55 μm to 4.85 μm. The total reported wavelength shift was about 0.7 μm with a total mirror travel of roughly 6 μm at a cavity length of approximately 30 μm. This relatively large cavity length was due to the mounting setup of the mirror, resulting in multiple peak recordings. Representative recorded spectra are shown in Figure 5-6.

![Figure 5-6](image)

*Figure 5-6 – Measured spectral response versus piezo-actuated mirror displacement.*

5.2.3. **Tunable RCED using parallel plate electrostatic actuated micromirrors**

Several tunable RCEDs have been assembled using the parallel plate electrostatic actuated micromirrors presented in section 4.2. The measurements of the first of these devices are depicted in Figure 5-7 (published in [A2] and [46]). The optical resonance effect can be clearly distinguished over the background level (including noise). The detector spectral response at four micromirror positions is shown. Two resonance modes are visible at each mirror position. The tunable range is relatively small (about 4.95 μm to 5.05 μm). This is due to the relatively high total cavity length (~36 μm; leading to a higher resonance order). The high cavity length
is due to placement of the buffer layer inside the cavity (cf. section 5.1.2) and due to a conservative choice for the spacer layer thickness for this first device. At ~4.4 μm, a small sideband can be distinguished from the next resonance, which is slightly above the cut-off of the absorbing buffer layer. The detection minimum (below the background level) at ~4.2 μm is probably due to atmospheric CO₂ absorbance outside the cavity (between the detector and the FTIR output, outside the vacuum chamber). The increase in the signal strength at the peak around 4.6 μm is due to the not sharp band edge of the absorbing buffer layer. Similarly, above 5.0 μm, the diode cut-off is not sharp, resulting in a decrease of the quantum efficiency. This effect is visible in the measurements presented later in this section as well, and can be seen in the map representations of the measurements. In the curve representations however, it is not visible, as the individual measurement curves are normalized in the following.

![Figure 5-7](image)

**Figure 5-7** – Measured detector spectra for four different applied electrostatic actuation voltages, i.e. four different MEMS mirror positions, of the first realized tunable mid-infrared RCED. The peak detection wavelength is shifted from about 4.95 to 5.05 μm. The main characteristics of the device are displayed in the inset to the left.
5.2.4. Tunable RCED using comb drive actuated micromirrors

The recorded spectra of a tunable RCED employing a comb drive actuated micromirror as presented in section 4.3 are shown in Figure 5-8. Tunability of the detector was achieved from 4.7 µm to 5.4 µm approximately for a single detection mode. The mirror displacements were induced by an actuation voltage from about 30 V – 60 V. At lower actuation voltages, i.e. for a movable micromirror positioned further away from the diode, a second detection peak appears. This peak is due to the approximate adjustment of the SU8 spacer layer.

![Figure 5-8](image)

**Figure 5-8** – Measured detection spectra, for a) actuation voltages from 0 V to 62 V and for b) six selected actuation voltages corresponding to the respective different movable mirror positions. The position of the selected curves shown in b) are represented as horizontal lines in a). The measurements are corrected for common background and each detection curve in b) is normalized individually.

At a wavelength of 5 µm, a less pronounced detection peak can be distinguished independent from the mirror position. This can most probably be attributed to a misalignment of the micromirror above the diode, as the fixed comb drive fingers form in this assembly a partial fixed length resonant cavity. A microscope photograph of the assembled device showing the misalignment of the micromirror (square) with respect to the photodiode (octagonal) is shown in Figure 5-9. The misalignment is a technological issue which can be solved with an improved alignment tool.

A very narrow peak at exactly 5 µm can be distinguished. In later measurements with different devices with better alignment, similar observations were made at exactly the same wavelength. Therefore, most probably, this artifact can be attributed to an internal effect in the spectrometer, which the detectors are characterized with.
5 Tunable mid-IR RCEDs

Figure 5-9 – Misalignment of the micromirror on top of the octagonal photodiode after assembly.

5.3. Comparison of realized RCED variants

Tunable detectors for the mid-infrared have been realized with three different actuation mechanisms: With a gold coated silicon mirror mounted on an external piezo-actuator (not presented in detail in this thesis, cf. Master Thesis by Ebneter [80]), with electrostatically actuated MEMS micromirrors in a parallel plate configuration (cf. section 4.2), and in a comb drive configuration (cf. section 4.3). The piezo-actuated version allowed verification of the concept, but resulted in a bulky setup and needed a relatively high actuation voltage for displacements. Alignment of the mirror mounted on the piezo-actuator with respect to the fixed DBR mirror was achieved manually and required laborious manual adjustment steps. Only with the MEMS micromirrors, integrated detectors have been fabricated, requiring low actuation voltages for a comparable displacement.

In Table 5-2, the characteristics of each realized setup are compared. In all cases, a thin gold coating was used for the reflective coating on the movable mirror. Gold has a reflectance of >99% for the mid-infrared wavelength band (e.g. [81]).

The measured detector spectra for different actuation voltages, corresponding to different movable mirror positions, are shown in Figure 5-10 for each tunable detector type. For all three types, the curve representations (b, d, f) have been normalized for each measured spectrum, whereas the map representations (a, c, e) show the measured aspect ratios.
Table 5-2 – Characteristic data for fabricated tunable resonant cavity enhanced detectors using piezo-actuation or MEMS electrostatic actuation in a parallel plate or comb drive configuration as tuning actuation mechanisms.

<table>
<thead>
<tr>
<th></th>
<th>Piezo-Actuation</th>
<th>MEMS Parallel Plate</th>
<th>MEMS Comb Drive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Approximate DBR Reflectance</td>
<td>80%</td>
<td>80%</td>
<td>90%</td>
</tr>
<tr>
<td>Calculated Finesse (w/o absorber)</td>
<td>10 (27)</td>
<td>10 (27)</td>
<td>13 (55)</td>
</tr>
<tr>
<td>FWHM δλ [nm] (δλ/λ)</td>
<td>~75 (1.5%)</td>
<td>~100 (1.9%)</td>
<td>~150 (3%)</td>
</tr>
<tr>
<td>Maximum Tuning Voltage [V]</td>
<td>128</td>
<td>25</td>
<td>62</td>
</tr>
<tr>
<td>Maximum Displacement [μm]</td>
<td>6</td>
<td>4.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Optical Cavity Length [μm]</td>
<td>44 - 50</td>
<td>28.5 - 33</td>
<td>14.5 - 17</td>
</tr>
<tr>
<td>Minimum Air Gap [μm]</td>
<td>20</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>Tuning Range λ_min - λ_max [μm]</td>
<td>4.55 - 4.85</td>
<td>4.85 - 5.15</td>
<td>4.7 - 5.4</td>
</tr>
</tbody>
</table>

The recorded signals show that the detection signal has been tuned in a range between 4.5 μm and 5.3 μm. The tuning range depends on the actuation type and configuration of the detector part. Absolute quantum efficiency was not measured; previous reported monolithic RCED exhibited a quantum efficiency of 35% [4].

The movement of the micromirror induced by an applied actuation voltage depends on the type of actuation. With increased actuation voltage, the MEMS parallel plate actuated mirror moves away from the DBR, the air gap increases and the detection wavelength is shifted to longer wavelengths. For the piezo-actuated mirror and the comb drive actuated MEMS mirror, the micromirror moves towards the DBR with increased actuation voltage, the air gap decreases and the detection wavelength is shifted to shorter wavelengths.

For the parallel plate actuated micromirror version, a distinct jump can be distinguished at 28 V, and a minor jump again at 33 V. These are due to a slight misalignment of the mirror with respect to the SU8 layer. A small part of one of the suspension legs stayed in contact with the SU8 layer at 0 V. Only at the jump, it detached, which resulted in a discontinuous spectra recording (Figure 5-10c).
Figure 5-10 – Measured spectral responses for micromirrors actuated with (a, b) piezoelectric actuators, (c, d) parallel plate electrostatic actuators, and (e, f) comb drive actuators for different actuation voltages corresponding to different positions of the movable mirror. The tuning range of each detector depends on its initial air gap between the movable mirror and the diode and on the mirror displacement. The detection peak irregularities for the MEMS micromirrors are due to a reduced finesse of the cavity. Operating temperatures were around 100 K.
The detection peaks of the piezo-actuated mirror are of a rather regular shape. The detected signals are less regular for the MEMS mirror cavities (both types). This is due to the increased number of technological process steps needed for fabrication which leads to an increased number of mirror plate defects, such as curvature of the mirror plate, mirror surface roughness and departure from parallelism to the DBR mirror. These defects may degrade the cavity as discussed in section 3.1.4. In case of the MEMS setups, a slight misalignment of the actuated mirror and of the reflective coating with respect to the fixed DBR mirror may further deteriorate the resonance peak. The curves shown in Figure 5-10 e) and f) were corrected for common background. The correction has no influence on the already deteriorated peak width.

Variations in the linewidth (full width at half maximum, FWHM) can be distinguished for all devices shown in Figure 5-10. All the devices showed a FWHM around 100 nm, which corresponds to the calculation presented in section 3.1.4. For the piezo setup, the limiting factor is the fine tuning of the parallelism of the two mirrors. The increased FWHM of detected signals recorded detectors using MEMS micromirrors on the other hand, especially of the comb drive sample, is mainly caused by a departure from parallelism, a misalignment of the gold layer on the micromirror, as well as a misalignment of the mirror and the diode. These are technological issues which can be solved by improving the assembly step performed with a custom built alignment tool. Additionally the finesse, and therefore the FWHM, depends on the absorption within the cavity.

The detectors were characterized at operating temperatures between 90 K and 135 K. Due to the temperature dependent bandgaps of the photodiode and the buffer layer, the tunable region is shifted.

With the integrated MEMS actuated versions, the air gap can be drastically reduced. This leads to a lower-order configuration of the detector, resulting in an increased free spectral range. The initial air gap distance can be chosen for a single detector during the process by adjusting the SU8 spacer layer thickness. The large optical cavity length in the first two configurations is due to the buffer layer placed within the cavity. Originally necessary for improved crystal quality of the active layer, it can now be grown outside of the cavity due to advances in crystal growth.
6. GAS DETECTION USING TUNABLE MID-IR DETECTORS

Gas detection is of interest in applications such as fire detection, safety systems, industrial process control or indoor air quality control. There are different methods for gas detection including chemical reactions, change in electrical properties in the presence of the analyte or optical detection. Most of the existing detectors using these concepts are designed for one specific analyte only. In miniaturized sensor systems, several of these detectors can then be combined to form a sensor, which can distinguish between different gases, as e.g. in fire detectors. Using a tunable RCED, one single device may allow detection of different gases. In such a system, a broadband infrared source illuminates the tunable RCED. In presence of a gas, the gas absorption at specific wavelengths reduces the IR radiation intensity at the detector. By analyzing the intensity of the recorded signal over a spectral bandwidth, the absorbing gases can thus be identified. A tunable RCED may thus essentially serve as single-chip IR spectrometer.
6.1. Infrared absorption spectroscopy using tunable RCEDs

The interaction of electromagnetic radiation with molecules in gases can be observed in the absorption at specific wavelengths. These absorption lines have their origin in excitation into higher energy states of the molecule by the impinging photons. Due to the quantized nature of the energy states, the absorption lines are narrow and of specific energy, corresponding to specific wavelengths, for each molecule.

The absorption bands of numerous gases lie in the wavelength range of the fabricated tunable RCED devices. Using the Matlab Spectrum Viewer [82] based on the HITRAN04 database [83], several gases having absorption bands in the wavelength range from 4 µm to 7 µm can be identified (see also [84, 85]). The absorption lines for CO, CO\textsubscript{2}, NO and NO\textsubscript{2} are depicted in Figure 6-1.

![Absorption lines CO, CO\textsubscript{2}, NO and NO\textsubscript{2} in the mid-IR range as obtained with the spectrum viewer [82] based on the database HITRAN04 [83].](image)

**Figure 6-1** – Absorption lines CO, CO\textsubscript{2}, NO and NO\textsubscript{2} in the mid-IR range as obtained with the spectrum viewer [82] based on the database HITRAN04 [83].

One of the fabricated tunable RCED devices has been used to measure the carbon monoxide absorption at 4.6 µm and 4.75 µm. Reference measurements of the gas cell were performed at the Physical Chemistry Laboratory of ETH Zurich using a
Bruker step scan FTIR spectrometer, at resolutions of 0.25 cm\(^{-1}\) and 10 cm\(^{-1}\). The measurements with high resolution provide accurate measurement results of the absorption lines. The reduced resolution allows an estimate for the detected signal, where the absorption lines are convoluted with the detector function. As shown in Figure 6-2, the overall intensity reduction due to absorption is strongly reduced due to the limited resolution in the detection. With a partial pressure of 6 mbar, the overall maximum intensity reduction can be expected around 2% at 10 cm\(^{-1}\) resolution (instead of highest absorption peaks of 20% at 0.25 cm\(^{-1}\) resolution). With increased partial pressure to 250 mbar, an overall maximum intensity reduction of almost 15% can be expected at 10 cm\(^{-1}\) resolution. The additional absorption bands of some percent that appear at 250 mbar partial pressure are isotopic and hot bands.

![Figure 6-2](image)

**Figure 6-2** - Carbon monoxide absorption spectra for 6 mbar (a,b) and 250 mbar (c,d) CO at .25 cm\(^{-1}\) (a,c) and 10 cm\(^{-1}\) (b,d) in a gas cell (5 cm length). Reference measurements using a Bruker FTIR spectrometer.
6.2. Experimental Setup

The tunable RCED gas detection capabilities were characterized with a Bruker Vertex 70 Fourier Transform Infrared (FTIR) Spectrometer. The tunable RCED was connected as external infrared detector (Figure 6-3). In a first step, the detector was characterized without absorbing gas, by tuning through the micromirror positions in the same fashion described in section 5.2.1. For the absorption measurement, a gas cell (5 cm length, NaCl IR-windows) filled with the analyte at a defined partial pressure was introduced in the optical path of the spectrometer test beam. For this purpose, the spectrometer test chamber was used. For simplicity, the reference spectral detector response was recorded without the empty gas cell, assuming reflections and signal deterioration below the detector limits. The FTIR spectral resolution was set to 10 cm\(^{-1}\), which is below the detector detection linewidth (~100 nm, corresponding to 40 cm\(^{-1}\) at 5 \(\mu\)m). At lower resolutions, better identification of the individual absorption lines of the analyte can be obtained, however, due to the detector layout, the Si substrate generates high order resonances, which are flattened with these resolution settings. The detector responses of the two measurements with and without the presence of the absorbing gas were then compared and the absorbing bands were identified.

**Figure 6-3** – Experimental setup for the gas detection using a tunable mid-IR RCED. For each tunable RCED movable mirror position, a complete spectrum is recorded with and without absorbing gas in a gas cell in the FTIR sample chamber.
6.3. CO detection using a tunable mid-IR RCED

The spectral response of a tunable RCED for measurements both with and without CO are presented in Figure 6-4. The device is tunable from 4.55 μm (0 V) to 5.2 μm (65 V). The mirror is a 400 μm x 400 μm parallel plate actuated micromirror in an 800 μm frame. The diode chip consists of a 2.5 pair DBR (Pb_{0.99}Sr_{0.01}Te / EuTe, 98.9% at 4.9 μm) and a 20 nm thin active layer. The CO absorption lines around 4.6 μm and 4.75 μm can be distinguished. At higher mirror displacements (more than 1 μm), the next resonance appears.

The figure shows the measured quantum efficiency for different mirror positions. The displacements have been measured before assembly for actuation voltages from 0 V to 65 V (steps of 1 V). As presented in section 3.1.6, the detection curve should ideally be straight. The figure shows however rather a S-shaped detection curve. This is most probably due to the DBR phase shift. The figure has been corrected for common background per recorded spectrum (minimum per line subtracted).

![Figure 6-4](image)

**Figure 6-4** – Measured quantum efficiency for different movable mirror positions for the same device without (a) and with (b) presence of carbon monoxide. The gas absorption results in lower signal intensity around 4.6 μm and 4.75 μm.

In order to make the difference more clearly visible, the difference between the two measurements has been plotted in Figure 6-5a. Both the absorption maxima around 4.6 μm and 4.75 μm are clearly visible. A substructure in the absorption lines can be distinguished. A more detailed model has to be investigated in order to determine the origin of this substructure.
Figure 6-5 – a) Difference between the recorded quantum efficiency for different mirror positions with and without carbon monoxide. The absorbance peaks can be distinguished clearly. b) The off-resonance response has been set artificially to zero simulating a higher spectral contrast.

Once the detector is characterized, the detection of CO can be performed by measuring the detector response at each mirror position while illuminated by a broadband IR source. Experimental verification has not been carried out with a separate setup, since the detector response can be deduced from the measured difference (shown in Figure 6-5a): the detector response will be the integral over all contributions from all wavelengths. In Figure 6-6a, the line by line sum is shown, corresponding to the overall detector response for different movable mirror positions, i.e. different wavelengths.

Figure 6-6 – Summed detector response at different wavelengths (movable mirror positions) for a) low spectral contrast and b) artificially augmented spectral contrast.
It can be seen, that the signal recorded outside the resonances contributes to this sum in a significant way. The detection peaks can hardly be distinguished. However, assuming a much higher signal to noise ratio (spectral contrast), the detection peaks can be found. This has been verified by artificially setting the detector response outside the resonances to zero. Figure 6-6b shows the line by line sum of the adjusted data. The detection peaks can be seen at 4.6 μm and 4.7 μm. The limited resolution due to the wide linewidth results in a shift to lower wavelengths of the second detection peak (which lies clearly around 4.73 μm in Figure 6-5b). Spectral contrast and linewidth can be improved by increasing the detector finesse.
7. **Conclusions and Outlook**

Design, process development and fabrication of micromirrors for the use in tunable integrated optical devices have been presented in this thesis. Two variants have been realized, which rely on electrostatic actuation, one in a parallel plate configuration, the other using comb drive actuators. Both micromirror types showed displacements around 3 μm at 30 V actuation voltage.

First vertically moving micromirrors were fabricated based on double side polished (DSP) silicon wafers using a parallel plate electrostatic actuation. Changing to silicon on insulator (SOI) wafers allowed fabrication of improved versions, one using parallel plate electrostatic actuation and one using electrostatic comb drive actuators. The fabrication process for the parallel plate electrostatic actuated micromirrors proved to be reliable with a high yield. Improvements can be achieved through a cleaner dicing process, and by temperature and stress control e.g. during anodic bonding, that reduces curvature for RCED applications. The fabrication process for the comb drive actuated micromirrors showed a comparatively low yield. This is due to geometry issues that can be addressed by proper layout adjustments,
e.g. taking into account aspect ratio dependent etching. In the comb layout, the fabrication limits were exploited, making the devices relatively fragile. For laboratory handling, the parallel plate actuated micromirror proved to be more robust.

Reflectivity of the movable mirror was obtained with a thin gold coating, evaporated on the micromirror through a shadow mask. The alignment of the shadow mask proved to be delicate with the equipment at hand, but can be optimized with adequate adjustments.

The mechanical resonance frequencies occur above a few kHz, and may be adjusted by the design of the mirror geometry and the suspensions. Exploiting a vertical mechanical resonance mode, tunable detectors could be operated at a high sampling rate in spectroscopic applications for example. Other resonance modes like the tilting movements can possibly be exploited for barcode reader or displaying applications. At atmospheric pressure, the mechanical resonances are strongly degraded by squeeze-film air damping, reducing Q-factors typically below 100. At low pressures, below 1 μbar, Q-factors increase typically over 3'000. For applications in mechanical resonance, the micromirrors have thus to be operated at low pressures, which can be achieved with an adequate housing of the devices.

Curvatures have been measured in some tens of centimeters for the parallel plate actuated micromirrors, and around one meter for the comb drive actuated micromirrors. This is due to the increased stiffness by fabricating the micromirror much thicker than the suspensions. The curvature could be precisely adjusted in the range of centimeters and separated actuation electrodes allowed tilting of the micromirrors in order to achieve a parallel alignment inside the resonant cavity.

For the first time, such micromirrors have been integrated with a photodiode in order to form a tunable, integrated Resonant Cavity Enhanced Detector (RCED). Mirrors, using electrostatic parallel plate actuation or comb drive actuation, have both been assembled to very compact detector systems, a spectrometer-on-chip so to speak. A wide wavelength tuning range of up to 0.7 μm has been achieved. With such a tunable RCED, carbon monoxide detection has been demonstrated. However, the resolution of the tunable RCED is limited due to the degraded cavity finesse. The detector bandwidth was about 100 nm around 5 μm detection wavelength (~40 cm⁻¹). Coarse absorption measurements are possible with this resolution. Higher resolution can be obtained by improving the cavity finesse, thus narrowing the linewidth, while even higher resolution can be obtained with laboratory spectrometers.

The cavity finesse can be improved by increasing parallelism and reducing the curvature, but the linewidth is then still limited to about 10 nm by the effects of
surface roughness and reflectivity (at low order resonances). A linewidth in this order of magnitude will limit the detection possibilities in a spectroscopic absorption measurement, as the absorption measured is the convolution of the (narrow) absorption peaks and the detector function. For the use of a tunable RCED in a spectroscopic intracavity absorption system, the limited detector linewidth and its influence on the absorption measurement has to be investigated in detail. For spectroscopic absorption measurements, an external broadband infrared source may be accommodated, and an external absorption cavity exploited for the gas detection. An extended tunable range may be exploited to cover several absorption gases with one single detector. Such an arrangement addresses the issue of low operating temperatures as well. To date, the detectors are operated at 100 K, in order to lower noise. Operation at higher temperatures is generally possible, typically up to 250 K, but noise increases. These temperatures are accessible with Peltier cooling. Improving the diode thin film crystal quality, the signal to noise ratio can be improved.

In a further step, the realization of tunable Vertical External Cavity Surface Emitting Lasers (VECSEL) is envisioned. The developed micromirrors are suitable for these applications without modification in the fabrication process. Depositing a stress controlled thin metal film on top of the micromirrors, the curvature of the micromirrors can be adjusted for transversal mode selection, in the range of millimeters to centimeters, depending on the application. VECSELS can be used in intracavity absorption spectroscopy. Due to the very narrow linewidth of the emission peak, typically in the range of nanometers, high resolution measurements can be expected. However, power consumption has to be addressed, and optical pumping may to be replaced by electrical pumping for integration. In an intracavity absorption system, depending on the applications, analyte filtering may be considered in order to protect the sensor system.

Both SOI based fabrication processes for the parallel plate actuated and for the comb drive actuated micromirror can be extended to wafer-scale production. However, inhomogeneities in the dry etching steps will need compensation or characterization for each individual device. This can be achieved for example with on chip CMOS electronics integration. Several detectors can further be placed in arrays, either by placing several active components under one micromirror, or by fabricating arrays of micromirrors. Reduction in size is possible in general, but will demand better fabrication tolerances.
8. APPENDIX

8.1. Dynamic Measurement Results – Measured Data

a) Mirror frame length 1500 µm and mirror square length 400 µm

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<th>Device c)</th>
<th>Device d)</th>
<th>Device e)</th>
<th>Device f)</th>
<th>Mean</th>
<th>St.Dev.</th>
<th>Sim. t=10</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.87</td>
<td>11.61</td>
<td>11.61</td>
<td>11.20</td>
<td>12.39</td>
<td>12.39</td>
<td>11.35</td>
<td>1.30</td>
<td>15.18</td>
</tr>
</tbody>
</table>

(continued)

e) Mirror frame length 800 μm and mirror square length 500 μm

<table>
<thead>
<tr>
<th>Mode #</th>
<th>Device a)</th>
<th>Device b)</th>
<th>Device c)</th>
<th>Device d)</th>
<th>Device e)</th>
<th>Mean</th>
<th>St.Dev.</th>
<th>Sim. t=10</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.38</td>
<td>9.38</td>
<td>-</td>
<td>10.02</td>
<td>8.87</td>
<td>9.41</td>
<td>0.47</td>
<td>11.94</td>
</tr>
</tbody>
</table>
f) Resonance frequencies in dependence of the surrounding pressure of the measurements depicted in Figure 4-22; mirror frame length 1500 μm and mirror square length 400 μm.

<table>
<thead>
<tr>
<th>Pressure [mbar]</th>
<th>Mode 1</th>
<th>Mode 2.3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>f [kHz]</td>
<td>Δf [kHz]</td>
</tr>
<tr>
<td>&gt; 1000</td>
<td>4.1</td>
<td>6.133</td>
</tr>
<tr>
<td>800</td>
<td>4.2</td>
<td>6.100</td>
</tr>
<tr>
<td>460</td>
<td>4.3</td>
<td>6.232</td>
</tr>
<tr>
<td>350</td>
<td>4.6</td>
<td>6.959</td>
</tr>
<tr>
<td>10</td>
<td>5.1</td>
<td>0.917</td>
</tr>
<tr>
<td>1</td>
<td>5.1</td>
<td>0.105</td>
</tr>
<tr>
<td>0.1</td>
<td>5.0</td>
<td>0.012</td>
</tr>
<tr>
<td>0.0012</td>
<td>5.0</td>
<td>0.006</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pressure [mbar]</th>
<th>Mode 7</th>
<th>Mode 8.9</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>f [kHz]</td>
<td>Δf [kHz]</td>
</tr>
<tr>
<td>&gt; 1000</td>
<td>35.8</td>
<td>0.946</td>
</tr>
<tr>
<td>800</td>
<td>35.9</td>
<td>1.031</td>
</tr>
<tr>
<td>460</td>
<td>35.9</td>
<td>0.966</td>
</tr>
<tr>
<td>250</td>
<td>36.0</td>
<td>0.950</td>
</tr>
<tr>
<td>100</td>
<td>36.1</td>
<td>0.710</td>
</tr>
<tr>
<td>10</td>
<td>36.1</td>
<td>0.191</td>
</tr>
<tr>
<td>1</td>
<td>36.1</td>
<td>0.032</td>
</tr>
<tr>
<td>0.1</td>
<td>36.0</td>
<td>0.014</td>
</tr>
<tr>
<td>0.0012</td>
<td>36.0</td>
<td>0.011</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pressure [mbar]</th>
<th>Mode 11</th>
<th>Mode 13,14</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>f [kHz]</td>
<td>Δf [kHz]</td>
</tr>
<tr>
<td>&gt; 1000</td>
<td>87.0</td>
<td>0.653</td>
</tr>
<tr>
<td>800</td>
<td>87.1</td>
<td>0.806</td>
</tr>
<tr>
<td>460</td>
<td>87.2</td>
<td>0.429</td>
</tr>
<tr>
<td>250</td>
<td>87.2</td>
<td>0.381</td>
</tr>
<tr>
<td>100</td>
<td>87.2</td>
<td>0.388</td>
</tr>
<tr>
<td>10</td>
<td>87.2</td>
<td>0.177</td>
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<tr>
<td>1</td>
<td>87.2</td>
<td>0.102</td>
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<td>0.1</td>
<td>87.2</td>
<td>0.051</td>
</tr>
<tr>
<td>0.0012</td>
<td>87.1</td>
<td>0.186</td>
</tr>
</tbody>
</table>

Actuation [V] 0.3*50 0.1*50 0.4*50 0.3*50
Signal periodic chirp periodic chirp periodic chirp
8.2. Mask Designs

8.2.1. Parallel Plate Actuated Micromirror

Figure 8-1 – Parallel plate actuated micromirror mask designs for one individual chip. The chip size is 7.2 mm x 12 mm. A close-up of the mirror area is shown in the upper part of the picture. Due to size constraints, the 2 upper electrodes and the 2 lower electrodes in Mask 3 (electrodes on glass wafer) were connected together in this mask version, making tilting only possible in one direction.

Mask 1: Mirror frames (sizes 800 μm and 1500 μm)
ICP Etch 1 - defining electrostatic actuator air gap

Mask 2: Suspension and mirror (mirror square lengths 400μm, 500μm and 600μm)
ICP Etch 2

Mask 3: Aluminum counter electrodes on glass wafer
With/Without contact ring around the 4 electrodes for silicon contacting
Table 8-1 – Overview of all realized meander type geometries with the SOI based fabrication process.

<table>
<thead>
<tr>
<th>Realized Mirror Geometries</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mirror Frame Length $f$ [μm]</td>
<td>1500</td>
<td>1500</td>
<td>1500</td>
<td>800</td>
<td>800</td>
</tr>
<tr>
<td>Mirror Square Length $s$ [μm]</td>
<td>400</td>
<td>500</td>
<td>600</td>
<td>400</td>
<td>500</td>
</tr>
<tr>
<td>Suspension Leg Width $b$ [μm]</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Outer Suspension Leg Length $l_1$ [μm]</td>
<td>930</td>
<td>980</td>
<td>1030</td>
<td>580</td>
<td>630</td>
</tr>
<tr>
<td>Inner Suspension Leg Length $l_2$ [μm]</td>
<td>440</td>
<td>390</td>
<td>340</td>
<td>115</td>
<td>65</td>
</tr>
<tr>
<td>Design Thickness $t$ [μm]</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Spring Constant $k$ [N/m]</td>
<td>6.48</td>
<td>6.16</td>
<td>5.82</td>
<td>38.79</td>
<td>35.81</td>
</tr>
<tr>
<td>Mirror Mass $m$ [μg]</td>
<td>3.73</td>
<td>5.83</td>
<td>8.39</td>
<td>3.73</td>
<td>5.83</td>
</tr>
<tr>
<td>Fundamental Resonance $f_0$ [kHz]</td>
<td>6.64</td>
<td>5.18</td>
<td>4.19</td>
<td>16.23</td>
<td>12.48</td>
</tr>
<tr>
<td>Pull-in Voltage (for $d=10$) $U_p$ [V]</td>
<td>36.8</td>
<td>35.9</td>
<td>34.9</td>
<td>90.0</td>
<td>86.6</td>
</tr>
<tr>
<td>Single Electrode Square Length [μm]</td>
<td>175</td>
<td>200</td>
<td>250</td>
<td>175</td>
<td>200</td>
</tr>
</tbody>
</table>

Figure 8-2 – Micromirror layout and design variables in a cross section (a) and a top view of geometries with meander type suspension (b) that were fabricated using the SOI based fabrication process. The suspensions are described as indicated with the mirror square length $s$, the thickness $t$ and the outer ($l_1$) and inner ($l_2$) suspension leg lengths of a single micromirror suspension leg.
8.2.2. Comb Drive Actuated Micromirror

Figure 8-3 – Comb drive actuated micromirror mask designs for one individual chip. The chip size is 7.2 mm x 12 mm. A close-up of the mirror area is shown in the upper part of the picture.

**Mask 1:** Fixed combs and mirror (mirror square lengths 300 µm and 400 µm)
ICP Etch 1 – fixed (high height) comb drive fingers and mirror

**Mask 2:** Suspension and movable comb finger (‘self-alignment’, pattern transfer)
ICP Etch 2 – movable comb drive fingers and suspension (low height)

**Mask 3:** Backside etch (mirror backside release and chip separation)
ICP Etch 3 – backside
Figure 8-4 – 3 suspension types have been realized: with 4 folded suspensions (A), with 8 straight suspensions (B), and with 4 straight suspensions (C).

Table 8-2 – Realized micromirror geometries with comb drive actuators.

<table>
<thead>
<tr>
<th>Suspension Version</th>
<th>Type (Finger Gap / Finger Length) [μm]</th>
<th>Mirror square length [μm]</th>
<th>Number of fingers</th>
<th>Simulated Displacement @ 50V [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Type 1 (2/75)</td>
<td>300</td>
<td>100</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>Type 2 (2/100)</td>
<td>300</td>
<td>100</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td>Type 3 (3/100)</td>
<td>300</td>
<td>80</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>Type 4 (3/120)</td>
<td>300</td>
<td>80</td>
<td>2.8</td>
</tr>
<tr>
<td>A, $k = 1.47 \text{ N/m}$</td>
<td>Type 1 (2/75)</td>
<td>400</td>
<td>140</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td>Type 2 (2/100)</td>
<td>400</td>
<td>140</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Type 3 (3/100)</td>
<td>400</td>
<td>116</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Type 4 (3/120)</td>
<td>400</td>
<td>116</td>
<td>3.2</td>
</tr>
<tr>
<td>B, $k = 1.39 \text{ N/m}$</td>
<td>Type 1 (2/75)</td>
<td>300</td>
<td>108</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>Type 2 (2/100)</td>
<td>300</td>
<td>108</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>Type 3 (3/100)</td>
<td>300</td>
<td>92</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>Type 4 (3/120)</td>
<td>300</td>
<td>92</td>
<td>3</td>
</tr>
<tr>
<td>C, $k = 1.5 \text{ N/m}$</td>
<td>Type 1 (2/75)</td>
<td>400</td>
<td>148</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>Type 2 (2/100)</td>
<td>400</td>
<td>148</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td>Type 3 (3/100)</td>
<td>400</td>
<td>124</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td>Type 4 (3/120)</td>
<td>400</td>
<td>124</td>
<td>3.3</td>
</tr>
</tbody>
</table>
8.2.3. Diode Layout

Figure 8-5 – Diode layout. Contact pad sizes in millimeters, all other sizes in micrometers. The light gray indicates the 4 different positions of the SU8 layer, depending on which diode (octagons in the center) is chosen. The red SU8 spacer layer position is for example chosen when the lower left octagonal diode is chosen.
8.3. List of Acronyms and Abbreviations

8.3.1. General Acronyms and Abbreviations

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFPA</td>
<td>Adaptive Focal Plane Arrays</td>
</tr>
<tr>
<td>AR</td>
<td>Antireflection (Coating)</td>
</tr>
<tr>
<td>ARDE</td>
<td>Aspect Ratio Dependent Etching</td>
</tr>
<tr>
<td>BOX</td>
<td>Buried Oxide Layer of a SOI wafer</td>
</tr>
<tr>
<td>BS</td>
<td>Backside</td>
</tr>
<tr>
<td>BTJ</td>
<td>Buried Tunnel Junction</td>
</tr>
<tr>
<td>CMI</td>
<td>Center of Micronanotechnology at EPFL</td>
</tr>
<tr>
<td>CMOS</td>
<td>Complementary Metal–Oxide–Semiconductor</td>
</tr>
<tr>
<td>DBR</td>
<td>Distributed Bragg Reflector</td>
</tr>
<tr>
<td>DL</td>
<td>Device Layer of a SOI wafer</td>
</tr>
<tr>
<td>DLP</td>
<td>Digital Light Processor (by TI)</td>
</tr>
<tr>
<td>DRIE</td>
<td>Deep Reactive Ion Etching</td>
</tr>
<tr>
<td>DSP</td>
<td>Double Side Polished</td>
</tr>
<tr>
<td>EPFL</td>
<td>École Polytechnique Fédérale de Lausanne</td>
</tr>
<tr>
<td>ETH</td>
<td>Eidgenössische Technische Hochschule, Zürich</td>
</tr>
<tr>
<td>Evap.</td>
<td>Evaporation</td>
</tr>
<tr>
<td>FE</td>
<td>Finite Element</td>
</tr>
<tr>
<td>FIRST</td>
<td>Frontiers in Research: Space &amp; Time (Laboratory at ETH Zürich)</td>
</tr>
<tr>
<td>FP</td>
<td>Fabry-Pérot</td>
</tr>
<tr>
<td>FSR</td>
<td>Free Spectral Range</td>
</tr>
<tr>
<td>FTIR</td>
<td>Fourier Transform Infrared</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full Width at Half Maximum</td>
</tr>
<tr>
<td>HL</td>
<td>Handle Layer of a SOI wafer</td>
</tr>
<tr>
<td>ICP</td>
<td>Inductively Coupled Plasma</td>
</tr>
<tr>
<td>IMES</td>
<td>Institute for Mechanical Systems at ETH Zürich</td>
</tr>
<tr>
<td>IR</td>
<td>Infrared</td>
</tr>
<tr>
<td>Max. Displ.</td>
<td>Maximum Displacement</td>
</tr>
<tr>
<td>MBE</td>
<td>Molecular Beam Epitaxy</td>
</tr>
<tr>
<td>MCT</td>
<td>Mercury Cadmium Telluride (HgCdTe)</td>
</tr>
<tr>
<td>MEMS</td>
<td>Micro Electromechanical Systems</td>
</tr>
<tr>
<td>mid-IR</td>
<td>Mid Infrared</td>
</tr>
<tr>
<td>MIR</td>
<td>Mid Infrared</td>
</tr>
<tr>
<td>MOEMS</td>
<td>Micro Opto-Electromechanical Systems</td>
</tr>
<tr>
<td>MOS</td>
<td>Metal Oxide Semiconductor</td>
</tr>
<tr>
<td>MST</td>
<td>Microsystem Technology</td>
</tr>
<tr>
<td>NIR</td>
<td>Near Infrared</td>
</tr>
</tbody>
</table>
8 Appendix

PCB  Printed Circuit Board  
PL  Photolithography  
QW  Quantum Well  
RCED  Resonant Cavity Enhanced Detector  
RF  Radio Frequency  
RIE  Reactive Ion Etching  
RMS  Root Mean Square  
ROC  Radius of Curvature  
SEM  Scanning Electron Microscope  
SOI  Silicon on Insulator  
Sputt.  Sputtering  
TEM₀₀  fundamental Transversal ElectroMagnetic mode  
TFP  Thin Film Physics Group at ETH Zürich  
TI  Texas Instruments  
VCSOA  Vertical Cavity Semiconductor Optical Amplifier  
VCSELs  Vertical Cavity Surface Emitting Lasers  
VECSEL  Vertical External Cavity Surface Emitting Laser  
WDM  Wavelength Division Multiplexing  
WLI  White Light Interferometer

8.3.2. Materials

Al  Aluminum  
AlAs  Aluminum Arsenide  
AlGaAs  Aluminum Gallium Arsenide  
Au  Gold  
BaF₂  Barium Fluoride  
Bi  Bismuth  
CaF₂  Calcium Fluoride  
CO  Carbon Monoxide  
CO₂  Carbon Dioxide  
Cr  Chromium  
Cu  Copper  
Eu  Europium  
Eu₄Te  Europium Telluride  
GaAs  Gallium Arsenide  
Ge  Germanium  
HF  Hydrofluoric Acid  
HgCdTe  Mercury Cadmium Telluride (MCT)
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>InAs</td>
<td>Indium Arsenide</td>
</tr>
<tr>
<td>InGaAs</td>
<td>Indium Gallium Arsenide</td>
</tr>
<tr>
<td>InGaAsP</td>
<td>Indium Gallium Arsenide Phospide</td>
</tr>
<tr>
<td>InP</td>
<td>Indium Phospide</td>
</tr>
<tr>
<td>InSb</td>
<td>Indium Antimonide</td>
</tr>
<tr>
<td>NaCl</td>
<td>Sodium Chloride</td>
</tr>
<tr>
<td>NO</td>
<td>Nitric Oxide</td>
</tr>
<tr>
<td>NO₂</td>
<td>Nitrogen Dioxide</td>
</tr>
<tr>
<td>PbEuSe</td>
<td>Lead Europium Selenide</td>
</tr>
<tr>
<td>PbSe</td>
<td>Lead Selenide</td>
</tr>
<tr>
<td>PbSnSe</td>
<td>Lead Tin Selenide</td>
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<tr>
<td>PbSrTe</td>
<td>Lead Strontium Telluride</td>
</tr>
<tr>
<td>PbSrTe:Bi</td>
<td>Lead Strontium Telluride doped with Bismuth</td>
</tr>
<tr>
<td>PbTe</td>
<td>Lead Telluride</td>
</tr>
<tr>
<td>Si</td>
<td>Silicon</td>
</tr>
<tr>
<td>SiO₂</td>
<td>Silicon Dioxide</td>
</tr>
<tr>
<td>Sn</td>
<td>Tin</td>
</tr>
<tr>
<td>Sr</td>
<td>Strontium</td>
</tr>
<tr>
<td>SU8</td>
<td>commonly used epoxy-based negative photoresist</td>
</tr>
<tr>
<td>Te</td>
<td>Tellurium</td>
</tr>
<tr>
<td>TiO₂</td>
<td>Titanium Oxide</td>
</tr>
<tr>
<td>TiPtAu</td>
<td>Titanium / Platinum / Gold (3 layer system)</td>
</tr>
<tr>
<td>ZnO</td>
<td>Zinc Oxide</td>
</tr>
<tr>
<td>ZnSe</td>
<td>Zinc Selenide</td>
</tr>
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</table>
### 8.4. List of Symbols

<table>
<thead>
<tr>
<th>Latin Symbol</th>
<th>Description</th>
<th>Base Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>aperture</td>
<td>[m]</td>
</tr>
<tr>
<td>$a$</td>
<td>exponential law fit parameter</td>
<td>[-]</td>
</tr>
<tr>
<td>$A_{el}$</td>
<td>electrode surface</td>
<td>[m$^2$]</td>
</tr>
<tr>
<td>$b$</td>
<td>exponential law fit parameter</td>
<td>[-]</td>
</tr>
<tr>
<td>$b$</td>
<td>suspension leg width</td>
<td>[m]</td>
</tr>
<tr>
<td>$B$</td>
<td>rectangular plate width</td>
<td>[m]</td>
</tr>
<tr>
<td>$c$</td>
<td>coefficient of the damping force caused by the surrounding air</td>
<td>[kg]</td>
</tr>
<tr>
<td>$c$</td>
<td>exponential law fit parameter</td>
<td>[-]</td>
</tr>
<tr>
<td>$C$</td>
<td>capacitance</td>
<td>[F]</td>
</tr>
<tr>
<td>$d$</td>
<td>active region thickness</td>
<td>[m]</td>
</tr>
<tr>
<td>$d$</td>
<td>initial distance between the electrodes</td>
<td>[m]</td>
</tr>
<tr>
<td>$d_0$</td>
<td>distance between the fixed and movable fingers (gap size)</td>
<td>[m]</td>
</tr>
<tr>
<td>$d_0$</td>
<td>initial mirror elevation (si surface to top point curved mirror)</td>
<td>[m]</td>
</tr>
<tr>
<td>$E$</td>
<td>electric field amplitude</td>
<td>[V m$^{-1}$]</td>
</tr>
<tr>
<td>$E$</td>
<td>energy</td>
<td>[J]</td>
</tr>
<tr>
<td>$E$</td>
<td>Young’s modulus</td>
<td>[Pa]</td>
</tr>
<tr>
<td>$E_{el,lin}$</td>
<td>energy for an applied voltage for one single comb finger</td>
<td>[J]</td>
</tr>
<tr>
<td>$E_{in}$</td>
<td>amplitude of the electric field arriving into the cavity</td>
<td>[V m$^{-1}$]</td>
</tr>
<tr>
<td>$E_{Si}$, $E_m$</td>
<td>silicon / metal Young’s modulus</td>
<td>[Pa]</td>
</tr>
<tr>
<td>$E_{tot}$</td>
<td>total energy</td>
<td>[J]</td>
</tr>
<tr>
<td>$f$</td>
<td>mirror frame length</td>
<td>[m]</td>
</tr>
<tr>
<td>$f_0$</td>
<td>fundamental resonance frequency</td>
<td>[Hz]</td>
</tr>
<tr>
<td>$F_A$</td>
<td>finesse degradation due to a finite aperture</td>
<td>[-]</td>
</tr>
<tr>
<td>$F_{DG}$</td>
<td>finesse degradation due to the roughness of the mirror surface</td>
<td>[-]</td>
</tr>
<tr>
<td>$F_{DP}$</td>
<td>finesse degradation due to a departure $t_P$ from parallelism</td>
<td>[-]</td>
</tr>
<tr>
<td>$F_{DS}$</td>
<td>finesse degradation due to a spherical bow of the mirror plate</td>
<td>[-]</td>
</tr>
<tr>
<td>$F_e$</td>
<td>electrostatic force</td>
<td>[N]</td>
</tr>
<tr>
<td>$F_{el,lin}$</td>
<td>force per unit finger length</td>
<td>[Pa m$^{-1}$]</td>
</tr>
<tr>
<td>$F_m$, $F_{Si}$</td>
<td>force acting on the metal layer / silicon layer</td>
<td>[N]</td>
</tr>
<tr>
<td>$F_R$</td>
<td>reflectivity finesse</td>
<td>[-]</td>
</tr>
<tr>
<td>$F_{spring}$</td>
<td>restoring force of the spring</td>
<td>[N]</td>
</tr>
<tr>
<td>$F_{tot}$</td>
<td>total force exerted onto the micromirror</td>
<td>[N]</td>
</tr>
<tr>
<td>$h_0$</td>
<td>movable finger and suspension height</td>
<td>[m]</td>
</tr>
<tr>
<td>$h_1$</td>
<td>fixed finger and comb drive actuated mirror height</td>
<td>[m]</td>
</tr>
<tr>
<td>$k$</td>
<td>suspension spring constant</td>
<td>[N m$^{-1}$]</td>
</tr>
<tr>
<td>$l$</td>
<td>single comb drive finger length</td>
<td>[m]</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Unit</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td>------</td>
</tr>
<tr>
<td>$l$</td>
<td>total length of one suspension leg (straight type)</td>
<td>[m]</td>
</tr>
<tr>
<td>$l_1$</td>
<td>outer length of one suspension leg (meander type)</td>
<td>[m]</td>
</tr>
<tr>
<td>$l_2$</td>
<td>inner length of one suspension leg (meander type)</td>
<td>[m]</td>
</tr>
<tr>
<td>$L$</td>
<td>rectangular plate length</td>
<td>[m]</td>
</tr>
<tr>
<td>$L$</td>
<td>total cavity length</td>
<td>[m]</td>
</tr>
<tr>
<td>$L_0$</td>
<td>initial total cavity length</td>
<td>[m]</td>
</tr>
<tr>
<td>$L_1$</td>
<td>partial cavity length</td>
<td>[m]</td>
</tr>
<tr>
<td>$L_2$</td>
<td>partial cavity length</td>
<td>[m]</td>
</tr>
<tr>
<td>$m$</td>
<td>longitudinal mode number ($m=1, 2, 3 ...$)</td>
<td>[-]</td>
</tr>
<tr>
<td>$m$</td>
<td>mirror mass</td>
<td>[kg]</td>
</tr>
<tr>
<td>$M_m, M_{Si}$</td>
<td>moment acting on the metal layer / silicon layer</td>
<td>[N m]</td>
</tr>
<tr>
<td>$N$</td>
<td>Fresnel number</td>
<td>[-]</td>
</tr>
<tr>
<td>$n$</td>
<td>index of refraction</td>
<td>[-]</td>
</tr>
<tr>
<td>$n$</td>
<td>number of fingers</td>
<td>[-]</td>
</tr>
<tr>
<td>$p_e$</td>
<td>electrostatic pressure</td>
<td>[Pa]</td>
</tr>
<tr>
<td>$p_{zi}$</td>
<td>increment i of the electrostatic pressure</td>
<td>[Pa]</td>
</tr>
<tr>
<td>$Q$</td>
<td>quality factor</td>
<td>[-]</td>
</tr>
<tr>
<td>$r$</td>
<td>radius of curvature</td>
<td>[m]</td>
</tr>
<tr>
<td>$r_1, r_2$</td>
<td>amplitude reflectivities at the mirrors</td>
<td>[-]</td>
</tr>
<tr>
<td>$r_{Cr}$</td>
<td>radius of curvature with a chromium deposit</td>
<td>[m]</td>
</tr>
<tr>
<td>$r_{int}$</td>
<td>radius of curvature due to the bending of the structure</td>
<td>[m]</td>
</tr>
<tr>
<td>$r_{th}$</td>
<td>radius of curvature due to thermal stress</td>
<td>[m]</td>
</tr>
<tr>
<td>$P_A$</td>
<td>power absorbed inside the active region</td>
<td>[W]</td>
</tr>
<tr>
<td>$P_I$</td>
<td>infrared radiation power impinging on the detector</td>
<td>[W]</td>
</tr>
<tr>
<td>$R_1, R_2$</td>
<td>mirror intensity reflectivities</td>
<td>[-]</td>
</tr>
<tr>
<td>$R_{Cr1}, R_{Cr2}$</td>
<td>mirror radii of curvature</td>
<td>[m]</td>
</tr>
<tr>
<td>$s$</td>
<td>mirror square length</td>
<td>[m]</td>
</tr>
<tr>
<td>$t$</td>
<td>suspension and mirror thickness</td>
<td>[m]</td>
</tr>
<tr>
<td>$t_{Cr}$</td>
<td>thickness of the deposited chromium layer</td>
<td>[m]</td>
</tr>
<tr>
<td>$t_m$</td>
<td>maximum excursion from the plane surface</td>
<td>[m]</td>
</tr>
<tr>
<td>$t_m, t_{Si}$</td>
<td>thicknesses of the metal layer and the silicon membrane</td>
<td>[m]</td>
</tr>
<tr>
<td>$t_p$</td>
<td>departure from parallelism</td>
<td>[m]</td>
</tr>
<tr>
<td>$t_{RMS}$</td>
<td>root-mean-square surface roughness</td>
<td>[m]</td>
</tr>
<tr>
<td>$t_{Si}, t_m$</td>
<td>silicon / metal thickness</td>
<td>[m]</td>
</tr>
<tr>
<td>$T$</td>
<td>temperature</td>
<td>[K]</td>
</tr>
<tr>
<td>$U$</td>
<td>applied voltage between the electrodes</td>
<td>[V]</td>
</tr>
<tr>
<td>$U_0$</td>
<td>fixed applied voltage</td>
<td>[V]</td>
</tr>
<tr>
<td>$U_P$</td>
<td>pull-in voltage</td>
<td>[V]</td>
</tr>
<tr>
<td>$w$</td>
<td>beam width</td>
<td>[m]</td>
</tr>
<tr>
<td>$w$</td>
<td>comb drive finger width</td>
<td>[m]</td>
</tr>
<tr>
<td>$w_0, w_1, w_2$</td>
<td>beam waists / spot sizes at the positions 0, 1, 2</td>
<td>[m]</td>
</tr>
<tr>
<td>Greek Symbol</td>
<td>Description</td>
<td>Base Unit</td>
</tr>
<tr>
<td>-------------</td>
<td>-------------</td>
<td>----------</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>linear thermal expansion coefficient</td>
<td>[-]</td>
</tr>
<tr>
<td>$\alpha_{Si}$, $\alpha_{m}$</td>
<td>linear silicon / metal thermal expansion coefficient</td>
<td>[-]</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>absorption coefficient in the active region</td>
<td>[-]</td>
</tr>
<tr>
<td>$\alpha_{ex}$</td>
<td>absorption coefficient in the cavity outside the active region</td>
<td>[-]</td>
</tr>
<tr>
<td>$\alpha_{c}$</td>
<td>average absorption coefficient in the cavity</td>
<td>[-]</td>
</tr>
<tr>
<td>$\beta$</td>
<td>geometry factor depending on the ratio of $B/L$. For a square plate, $\beta = 0.42$</td>
<td>[-]</td>
</tr>
<tr>
<td>$\beta$</td>
<td>propagation constant of the electromagnetic wave $= \frac{2n\pi}{\lambda}$</td>
<td>$[m^{-1}]$</td>
</tr>
<tr>
<td>$\delta_z$</td>
<td>beam tip movement</td>
<td>[m]</td>
</tr>
<tr>
<td>$\delta\lambda_m$</td>
<td>linewidth for mode number $m$</td>
<td>[m]</td>
</tr>
<tr>
<td>$\Delta\varepsilon$</td>
<td>strain variation when the beam is released</td>
<td>[-]</td>
</tr>
<tr>
<td>$\Delta L$</td>
<td>cavity length variation</td>
<td>[m]</td>
</tr>
<tr>
<td>$\Delta\lambda$</td>
<td>differences between the maximum and minimum wavelength</td>
<td>[m]</td>
</tr>
<tr>
<td>$\Delta T$</td>
<td>temperature difference</td>
<td>[K]</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>dielectric constant of air</td>
<td>$[F \text{ m}^{-1}]$</td>
</tr>
<tr>
<td>$\varepsilon_{film}^<em>$, $\varepsilon_{m}^</em>$, $\varepsilon_{Si}^*$</td>
<td>mean strain (in the thin film, metal layer or silicon membrane)</td>
<td>[-]</td>
</tr>
<tr>
<td>$\varepsilon_{m}$, $\varepsilon_{Si}$</td>
<td>strain in the metal / silicon layer</td>
<td>[-]</td>
</tr>
<tr>
<td>$\zeta$</td>
<td>damping ratio</td>
<td>[-]</td>
</tr>
<tr>
<td>$\eta$</td>
<td>quantum efficiency (current flux / photon flux)</td>
<td>[-]</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>vacuum wavelength</td>
<td>[m]</td>
</tr>
<tr>
<td>$\lambda_c$</td>
<td>center wavelength</td>
<td>[m]</td>
</tr>
<tr>
<td>$\mu$</td>
<td>the coefficient of viscosity</td>
<td>[Pa s]</td>
</tr>
<tr>
<td>$\nu_{m}$, $\nu_{Si}$</td>
<td>metal / silicon Poisson coefficient</td>
<td>[-]</td>
</tr>
<tr>
<td>$\rho$</td>
<td>resistivity</td>
<td>[$\Omega \text{ m}$]</td>
</tr>
<tr>
<td>$\sigma_{m}$, $\sigma_{Si}$</td>
<td>internal stress acting on the metal layer / silicon layer</td>
<td>[Pa]</td>
</tr>
<tr>
<td>$\sigma_{int}$</td>
<td>intrinsic stress</td>
<td>[Pa]</td>
</tr>
<tr>
<td>$\Psi_1$, $\Psi_2$</td>
<td>phase shift at the mirrors</td>
<td>[rad]</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>solid angle of the cone of rays passing through the FP cavity</td>
<td>[rad]</td>
</tr>
<tr>
<td>$\omega$</td>
<td>resonance frequency</td>
<td>[rad s$^{-1}$]</td>
</tr>
</tbody>
</table>
8.5. Publications

8.5.1. Journal Articles


8.5.2. Conference Talks


8.5.3. Conference Poster Contributions


8.5.4. Related Publications Thin Film Physics Group


8.6. Curriculum Vitae

The CV is included in the print version only.

Contact: niels@quack.ch
8.7. References


