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Single-Mode, Broadband, Near Infrared Light Emission from Metal-Oxide-Semiconductor Tunnel Junctions in Silicon Photonics

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Achieving electrically driven light sources on a silicon substrate is one of the great challenges in integrated optics. For low-power applications, one possible candidate could be Light Emitting Tunnel Junctions (LETJs) [1]. Unlike many semiconductor light sources that rely on direct-bandgap materials, the emission characteristics of LETJs are not strongly dependent on the material choice, but are determined by the electrical and optical environment of the tunnelling interface. While most electrons tunnel elastically from one electrode to the other, some can couple to and excite electromagnetic modes in a broad range of frequencies, spanning the microwave to the visible [1–3].

Here, we demonstrate the first direct LETJ emission into a single mode waveguide by utilizing a metal-oxide-semiconductor (MOS) tunnel junction, where the tunnelling process primarily excites a long-range hybridized plasmonic mode (Fig. 1a). By incorporating the MOS junction within a Fabry-Pérot cavity, we shape the local density of optical states (LDOS) to achieve the narrowest spectral emission observed to date for optical LETJs, with $Q_{\max} = 47 \pm 3$ [1, 2]. This is made possible by utilizing the lower losses of the hybrid TM₀₀ mode ($l_{\text{prop}} = 9.6 \mu\text{m}$) compared to those of the fundamental mode of a metal-insulator-metal LETJ ($l_{\text{prop}, \lambda=1.4 \mu\text{m}} \approx 0.6 \mu\text{m}$). Further, the lower losses enable μm^2 -sized tunneling areas emitting similar powers as reported for MIM LETJs ($\sim \text{pW}$), even though such MIM junctions feature a LDOS which is larger by about one order of magnitude.

Fig. 1: (a) A LETJ in a colored SEM. The insert shows the cross-section with the fundamental TM₀₀ mode qualitatively overlaid in red. (b) The band structure of the MOS-LETJ is shown under positive bias. (c) The TM filtered emission spectrum of the 2 μm long device from (a) shows the longitudinal resonances of the cavity between M₁ and M₂. (d) The linearly polarized emission is shown in dependence of the polarizer angle. The error bars denote the uncertainties in fitting the imaged emission with a 2d Gaussian profile.

The frequency continuum of the long-range hybridized plasmonic mode (Fig. 1a) is determined by the band structure and applied bias (Fig. 1b). By inclusion of reflectors M₁ and M₂ at the respective ends of the tunnel area, the longitudinal resonant modes of the TM₀₀ resonator are enhanced and show up clearly in the edge-coupled, TM filtered electroluminescence emission spectrum (Fig. 1c). Five of the Lorentzian-shaped emission peaks can be attributed to the resonant modes of the 2 μm long emitter, with the highest Q-Factor ($Q = 47$) coinciding with the highest reflectivity of the hybrid-mode to photonic-mode interface (M₁). In addition, the emission is strongly TM polarized (Fig. 1d), i.e. the electric field is perpendicular to the tunneling direction. This is expected from the tunnelling transition, which can be modelled with a dipolar approximation [4]. However, it is evident that a non-TM component of the emission remains, which we attribute to radiative recombination in silicon. This is also visible in the TM filtered emission spectrum of Fig. 1(c) as a much broader emission peak ($Q = 18$) centered around 266 THz. In TE filtered spectra (not shown), only this silicon emission is visible.

Electroluminescence emitted from LETJs certainly is of interest due to the freedom of choice of the materials and thus the possibility for monolithic integration into SOI platforms, e.g. by exchanging the gold for copper. In the future, stronger shaping of the emission by the design of the optical environment could be of interest to further elucidate the detailed mechanism of light-matter interaction of tunneling electrons.

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