Application-specific improvements on fast recovery 4.5kV press-pack rectifiers

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Application-Specific Improvements on Fast Recovery 4.5kV Press-Pack Rectifiers

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Zusammenfassung

Aufgrund der stetigen Forderung nach höheren Schaltfrequenzen benötigt die neue Generation der Leistungsschalter, wie der GCT (Gate-Commutated Thyristor, auch bekannt als hart angesteuerter Gate Turn-off Thyristor) und der IGBT (Insulated Gate Bipolar Transistor) verbesserte Diodenkonzepte. In diesen neuen Anwendungen gewinnen beschaltungsfreie Kommutierungsbedingungen an Bedeutung, welche sehr hohe di/dt und dv/dt Schalttransienten ermöglichen.


Zusammenfassung

Der Vergleich zweier 4500 V Dioden mit einer im Hinblick auf größere Zwischenkreisspannungen erhöhten SOA wird gezeigt. Um die Injektionseffizienz der Anode einzustellen, wurden zwei heute bereits gebräuchliche Technologien, die der Reduzierung der Emitterdotierung und die der Ionenbestrahlung in die p-dotierten Gebiete miteinander verglichen.


Desweiteren wurden 4500V Elemente mit einer neuen Bestrahlungstechnik gefertigt, bei der die Elektronenbestrahlung durch eine zweite Protonenbestrahlung ersetzt wurde. Die Tiefe des zweiten Protonen-Peaks befindet sich dabei inmitten der n⁻-Basis. Verglichen mit der kombinierten Ionen- und Elektronenbestrahlung, zeigen Dioden mit einem Doppel-Protonen-Peak einen kleineren maximalen Rückstrom und ein wesentlich weicheres Abkommutierverhalten. Das neue Element ist ausserordentlich robust, was sich in einem zerstörungsfreien Abschalten auch bei auftretenden Leistungsdichten von 1MW/cm² äussert.

Abstract

With increasing demand for higher switching frequencies, new power switches such as the Gate-Commutated Thyristor (formerly called hard-driven Gate Turn-off Thyristor) and the IGBT (Insulated Gate Bipolar Transistor) require improved diode concepts. Snubberless conditions in these applications are gaining ground, imposing switching transients with very high di/dt and dv/dt values. This leads to new challenges in diode development.

Besides the standard criteria of low static and dynamic losses, soft recovery under all application conditions (in particular at low turn-off forward current density and a high line voltage) and low reverse recovery current, the need for a large SOA (Safe Operating Area) has become most important. The optimum diode design depends on the specific application conditions. The electrical stress on fast recovery rectifiers is analyzed for two different applications, clamped inductive and resistive switching.

In order to improve the reverse recovery characteristic, the excess carrier concentration close to the anode during the on-state has to be reduced. Local lifetime control has proven to be very successful in optimizing the excess carrier distribution in a device. Therefore, computer simulations employing lifetime profiles were performed and compared to the measured results. An excellent agreement of simulated and measured recovery characteristics was achieved.

The comparison between two 4500 V devices with expanded SOA with regard to higher line voltages is shown. In order to control the injection efficiency of the anode, two state-of-the-art technologies, the
reduction of the emitter doping and the ion irradiation in the p-doped region, are compared.

The local lifetime control technique is shown to have major advantages compared to the emitter doping reduction technique, namely up to 50% lower switching losses at the same on-state losses due to a heavily reduced maximum reverse recovery current. Additionally, a softer switching behavior is observed for the ion-irradiated diodes. An explanation for this behavior, which was observed experimentally, is provided by calibrated computer simulations.

Furthermore, a 4500 V device was fabricated using a new ion irradiation technique, where electrons are replaced by protons in a second irradiation step. The second proton peak is located well within the n^-base. Compared to the combined ion and electron irradiation, diodes with a double proton peak show a smaller maximum reverse recovery current and a much smoother tail current behavior. The new device has an excellent ruggedness, being able to withstand a peak power density of 1 MW/cm^2.

Finally, a new approach to lifetime control in fast recovery power diodes, arbitrary axial lifetime profiling by single-step ion irradiation, is described. The principle, which invented by [1], is based on irradiation through a mask, which is inserted between the ion source and the device.
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Chapter 1

Introduction

1.1 Motivation of this Work

New power switches such as the Insulated Gate Bipolar Transistor (IGBT) or the Gate-Commutated Thyristor [2] (also known as hard-driven GTO) enable switching transitions with higher di/dt and dv/dt values. These devices permit the use of dramatically reduced snubber components or operate completely without snubber circuits. Because of this, the diode becomes the weakest component in a high power circuit and as such it limits the overall performance of the circuit. This leads to an increasing demand in the design of fast high power diodes. Computer simulation tools provide quick and accurate estimations of device performance, and allow drastically reduced development cycle times. Therefore, intensive use of numerical device design is also made in this thesis.

In addition to the standard criteria of low static and dynamic losses, soft recovery under all application conditions and a low reverse recovery current, the need for a large SOA (Safe Operating Area) has become most important[3]. Especially at small forward current densities and, depending on the lifetime control technique, at a specific temperature, a soft current decay at the end of the recovery process is an important requirement which is very hard to fulfill.
The critical power density at which device failure occurs depends on a large number of design parameters which influence the static and transient plasma distribution. The most important design parameters are the n\(^{-}\)-base thickness, the emitter injection efficiencies, and both, the axial and lateral carrier lifetime profiles.

A diode design with optimized axial lifetime profile is defined and achieved in this project. A comparison between devices with vertically structured lifetime profiles and diodes with reduced emitter doping is made.

### 1.2 Structure of the Thesis

**Chapter 2** : This chapter introduces the reader to the static and transient characteristics of modern high power rectifiers. The two static phases, on-state and blocking behavior, are described, followed by the two transition modes: forward and reverse recovery. The fundamental physical processes in these conditions are analyzed, providing the foundations for the following chapters.

**Chapter 3** : Two different device structures are introduced, the full wafer press-pack rectifier and the chip diode concept. In state-of-the-art industrial applications, the press-pack diode is used in power circuits together with Gate Turn-off Thyristors (GTO) and Gate-Commutated Thyristors (GCT). The 4500 V press-pack diode is the main point of interest of this thesis. Additionally, the basic structure of the chip diode with its planar junction termination is presented. This diode, with its device area in the range of 1-2 cm\(^2\), is used in Insulated Gate Bipolar Transistor (IGBT) modules.

**Chapter 4** : The differences in the device structure of the press-pack rectifier and the chip diode have significant impact on the electrical device characteristics. In this chapter, the consequences of the different junction terminations on the electrical switching characteristics are analyzed.

**Chapter 5** : The design concepts for diode optimization basically include the variation of emitter efficiency and lifetime control. Two technologies, the reduced emitter doping and the ion irradiation
are described and their influence on the reverse recovery performance are compared to each other.

Chapter 6: In this chapter, the effect of homogeneous and inhomogeneous lifetime engineering on high power rectifiers is introduced. The influence of the static excess carrier distribution on the electrical device characteristics, especially on the reverse recovery performance, is analyzed. A new method, the double proton irradiation, is used to optimize the static plasma distribution.

Chapter 7: With the technologies described in the previous chapters, the fast recovery devices are optimized for specific applications. The switching environment of the snubber diode is explained and the electrical stress in the circuit on the Device Under Test (DUT) is analyzed. The usage of the simplified resistive switching circuit, which is used in this thesis up to this point, is legitimized in this chapter.

Chapter 8: The second application-specific switching environment, the clamped inductive circuit, is of increasing industrial importance. The electrical stress on freewheeling diodes in this circuit is analyzed depending on their lifetime engineering (explanation see chapter 6).
Part I

Physics of High Power Diodes
Chapter 2

Device Structures

In this chapter, two different diode structures, the full-wafer GTO/GCT press-pack and the chip diode technology, are introduced. The junction termination of any high voltage semiconductor device has to be treated in a special way. The positive charges, which are typical for a silicon-silicon oxide interface, lead to a significant distortion of the space charge region. This is because of the establishment of a charge balance between the two sides of the junction. Without any further treatment of this junction termination, an up to 3 times higher electric field with respect to the peak field within the bulk occurs. To reach high blocking voltage capability of the devices, the maximum electric field at the edge has to be decreased to the level of the maximum bulk electric field.

Two possible technologies, leading to an optimized field distribution at the junction, are discussed in the following chapter: One is the bevel edge technology, commonly used in full wafer press-pack rectifiers for applications in stacks together with Gate Turn-Off thyristors (GTO) or Gate-Commutated Thyristors (GCT). A second possibility is the planar junction termination using field rings. The planar approach is implemented in state-of-the-art chip diodes used as freewheeling diodes in Insulated Gate Bipolar Transistor (IGBT) modules.
2.1 GTO/GCT Press-Pack Diode

In a full wafer press-pack rectifier, the electric field is forced to expand near the surface, due to the beveled edge junction termination. The increased spreading of the depletion layer causes a reduction in the electric field strength. In general, both the negative and the positive bevel are possible. With respect to manufacturability, the decision for the full-wafer rectifier was made in favor of the negative beveled junction termination, which is schematically illustrated in Fig. 2.1. The field reduction which is reachable in practice with this technology leads to an about 10% higher electric field at the edge compared to the bulk value.

![Diagram of junction termination](image)

**Figure 2.1:** Cross-section view of the junction termination of a modern full-wafer diode. The doping profile at the cross-section, marked with an arrow, is shown in Fig. 2.2.

In case of the negative bevel technology, it is necessary to place a deep p-diffusion below the bevel. The low acceptor doping lead to a wider spreading of the electric field on the p-side of the p-n junction compared to a steep (highly doped) junction. The bevel angle in these cases is very flat, between 1 and 5 degrees, depending on the doping concentration of the deep acceptor profile. It is possible to make the bevel steeper by driving the p-profile deeper. To contact the p-doped
2.2 IGBT Chip Diode

Figure 2.2: Schematic structure of the doping profile at the cross-section of the full-wafer rectifier in Fig. 2.1.

Silicon surface to the metalization of the anode contact, an additional shallow acceptor diffusion is necessary in the bulk. A schematic view of the corresponding doping profile is shown in Fig. 2.2. The anode of the device has a double profile consisting of a deep (≈ 80 μm) and a shallow acceptor (≈ 30 μm) diffusion.

The device which will be analyzed in the following chapters, is a 4500 V full-wafer press-pack fast recovery diode with a base resistivity between 200 Ωcm and 500 Ωcm, depending on the specific application (see chapter 3.1). The total thickness of the device, including the contact metalization is around 600 μm.

2.2 IGBT Chip Diode

An additional possibility to reduce the electric field at the junction edge is the usage of free floating field rings, as presented in [4]. This technology, leading to a planar junction termination, is schematically illustrated in Fig. 2.3.

The potential difference between these field rings lead to a spreading of the space charge region and therefore to a lower electric field peak. This enhances the breakdown voltage of these devices up to values of the breakdown voltage of the bulk. The technology of free floating field
Figure 2.3: Schematic view of the junction termination of a modern planar chip diode. The doping profile at the cross-section, marked with an arrow, is shown in Fig. 2.4.

rings for junction termination is the preferred technique for lower current devices, where a large number is produced on one wafer. In this multi-device-per-wafer-approach the beveling technology of chapter 2.1 is impractical. A big advantage of the field rings is the possibility to fabricate this junction termination simultaneously with the main junction, because this can be achieved in the same processing step during fabrication. The spacing between the field rings is then adjusted together with the positioning of the extra diffusion window on the "anode" mask.

One consequence of this junction termination technology is a different structure of the anode in chip diode device compared to full-wafer diode ones. The doping profiles are shown in Fig. 2.4. The abrupt p-n junction leads to different electrical characteristics of the devices, compared to the devices with beveling technology. A comparison of these differences is shown in chapter 4.

In addition to the different junction terminations mentioned above, a passivation of the edge zones is necessary to enhance the blocking capability of the devices. The most common technology is a semi-insulating layer, deposited on the junction termination area, where high electric
Figure 2.4: Schematic structure of the doping profile at the cross-section of the planar chip rectifier in Fig. 2.3.

field reach the surface. With this layer, it is possible to avoid electrostatic charge onto the junction, which would especially decrease the long term blocking capability at higher temperatures. A new technology, expanding the application of the passivation even to higher temperatures, is the Diamond Like Carbon (DLC) technology, which is described in [5].
Chapter 3

Static and Transient Characteristics

In this chapter, the physics of operation and the corresponding electrical characteristics of fast high power diodes are explained. The two steady-state conditions, the forward conducting and the reverse blocking behavior are introduced in chapter 3.2 and 3.1, respectively. They are followed by the discussion of the transient characteristics, the forward and the reverse recovery of a fast high power diode in chapters 3.3 and 3.4.

3.1 Off-State

To enable a blocking voltage of 4500 V in power rectifiers, the $n^-$-base of a silicon device must have a donor concentration in the range of $10^{12}$ to $10^{13}$ cm$^{-3}$. The dopant distribution has to be very homogeneous, which usually requires neutron transmutation doped wafers at the mentioned doping concentrations. If the anode is set to a negative voltage with respect to the cathode, the p-n junction becomes reversed-biased. This leads to an increase of the built-in space charge region in the device. Because of the lower doping of the $n^-$-base as compared to the concentration of the deep acceptor profile of the anode, the main part of
the space charge and, hence, the electric field extends into the $n^-$-base. This effect is shown in Figs. 3.1 and 3.2 for two different device designs, the Non-Punch Through (NPT) and the Punch Through (PT) design, respectively.

![Diagram](image)

**Figure 3.1:** Electric field distribution at a static blocking voltage of 3000 V of a full-wafer diode with an $n^-$-base doping of 200 $\Omega$cm for Non-Punch Through (NPT) design.

The differences in the electric field distribution in case of a Non-Punch Through and a Punch Through design are illustrated in Figs. 3.1 and 3.2, respectively. In an NPT device, the electric field is reduced to zero within the $n^-$-base. This leads to a triangular electric field distribution instead of a trapezoidal distribution for the PT design.

The Poisson equation describes the dependence of the slope of the electric field $E(x)$ on the space charge concentration $N_{sc}$. Assuming that the charge distribution $N_{sc}(x)$ is independent of location, it follows:

$$\frac{d^2 \phi}{dx^2} = \frac{dE}{dx} = -\frac{q}{\varepsilon_s} N_{sc}$$

$$\rightarrow E(x) = -\frac{1}{\varepsilon_s} qN_{sc}x + C$$
3.1. Off-State

The effective space charge $N_{sc}(x)$ is the sum of the electrically active doping concentration and the mobile carriers within the $n^-$-base. The maximum electric field of the device can be reduced by lowering the $n^-$-base doping. On the other hand, the electric field reaches the cathode at a lower voltage in case of a lower doped $n^-$-base. The resistivity of the PT device (Fig. 3.2) is approximately doubled as compared to the NPT device in Fig. 3.1. In practice, the resistivity of the device is chosen to fulfill the cosmic ray criteria. This can be simplified to the demand that the maximum electric field should not exceed $100 \text{ kV/cm}$ at line voltage. A more detailed description of the failure mechanism induced by cosmic particles is given in [6].

The influence of the PT/NPT design on the electrical characteristics, especially on the reverse recovery, is discussed in chapter 3.4.1.

**Figure 3.2:** Electric field distribution at a static blocking voltage of $3000 \text{ V}$ of a full-wafer diode with an $n^-$-base doping of $500 \Omega \text{cm}$ for Punch Through (PT) design.
3.2 On-State

3.2.1 Excess Carrier Distribution

To analyze the physical processes during the on-state, forward recovery and reverse recovery a one dimensional simulation was performed.

In the on-state, the forward biasing of the p-n junction leads to a hole injection of the anode and symmetrically to an electron injection of the cathode. In this case, the cathode has negative potential with respect to the anode contact. The holes and electrons recombine in the p-n junction, and therefore a current flow is established through the device.

In Fig. 3.3, the simulated excess carrier or plasma concentration is plotted for three different forward current densities: 1, 10 and 100 A/cm$^2$.

![Simulated excess carrier distribution at forward current densities of 1, 10 and 100 A/cm$^2$ of a 4500 V full-wafer diode. The doping profile is given by the dashed curve.](image)

In thermal equilibrium conditions, there is a balance between the generation and recombination process of electrons and holes. The effective lifetime $\tau$ itself is a measure of the duration of the recombination
3.2. On-State

process:

\[ \tau = -\frac{n}{R} \]  

(3.3)

where \( n \) is the carrier concentration and \( R \) the recombination rate. The amount of stored charge in the device at a specified current level is depending on the electron and hole lifetime in the device. The excess carrier concentration in the element leads to a charge-modulated resistivity, and therefore to a decreasing on-state voltage drop with increasing high injection lifetime. In \([7]\) and \([8]\) a detailed description of the different recombination processes and the lifetime definition is given. As seen in Fig. 3.3, the plasma concentration at a forward current density of \( 100 \, \text{A/cm}^2 \) ranges between \( 10^{16} \) and \( 10^{17} \, \text{cm}^{-3} \), thus leading to a large conductivity modulation and low static on-state losses.

A high injection condition is reached when the carrier lifetime \( \tau \) is large enough that the ambipolar diffusion length \( L_a \) equals the \( n^- \)-base thickness \( d \):

\[ d \approx L_a = \sqrt{D_a \tau} \]  

(3.4)

where \( D_a \) is the ambipolar diffusion coefficient. In a thinner PT device the carrier lifetime can be lowered at the same static on-state losses, resulting in a smaller amount of stored charge in the \( n^- \)-base at a specific forward current density as compared to an NPT device. This results in a faster reverse recovery of the PT device with respect to the NPT device.

To describe the carrier transport in the low doped \( n^- \)-base of a PiN-diode, the basic equations for the carrier transport and the continuity are needed. The electron/hole current is given by the sum of the drift and the diffusion current

\[ j_n = q \mu_n n E + q D_n \frac{\partial n}{\partial x} \]  

(3.5)

\[ j_p = q \mu_p p E - q D_p \frac{\partial p}{\partial x} \]  

(3.6)

and the continuity equation is given by

\[ \frac{\partial n}{\partial t} = \frac{1}{q} \frac{\partial j_n}{\partial x} - R \]  

(3.7)

\[ \frac{\partial p}{\partial t} = -\frac{1}{q} \frac{\partial j_p}{\partial x} - R \]  

(3.8)
where $\mu_n$ and $\mu_p$ are the electron and the hole mobility, respectively. Inserting Eq. 3.5 in Eq. 3.7 and Eq. 3.6 in Eq. 3.8 leads to the ambipolar diffusion equation:

$$D_a \frac{\partial^2 n}{\partial x^2} = \frac{n - n_i}{\tau}, \quad (3.9)$$

assuming the condition of neutrality ($p = n$). The solution of this differential equation describes the distribution of the excess carrier concentration in the device:

$$n(x) = n_i + \frac{\tau j}{2qL} \left[ \frac{\cosh((x - \frac{d}{2})/L)}{\sinh(\frac{d}{2L})} - \frac{\mu_n - \mu_p}{\mu_n \mu_p} \frac{\sinh((x - \frac{d}{2})/L)}{\cosh(\frac{d}{2L})} \right].$$

### 3.2.2 Temperature Dependence of the J-V Curve

In Fig. 3.4, the simulated and measured J-V curves of a non-irradiated 4500 V full-wafer rectifier are shown for two different temperatures, 300 and 400K. To obtain the static losses of the different devices, the forward I-V curves are measured on an industrial diode tester (LEM Diode Tester type DS5060).

A homogeneous current distribution, especially in surge current conditions, is important in high power modules, where the diodes are connected in parallel, as well as in the full-wafer diode. A positive temperature coefficient of the diode’s forward voltage drop, leading to an increase of the voltage drop with rising temperature, improves the homogeneity of the current distribution. However, at low currents, the voltage drop of a power P-i-N diode always possesses negative temperature dependence, and changes to a positive one at a certain current level. The corresponding current level is referred to as the crossing point current. The temperature behavior is a consequence of two rival processes, the increase of lifetime with growing temperature dominating at low current densities, and the decrease of mobility with rising temperature at higher current densities. At higher current densities, the effect of the decreasing mobility with growing temperature takes over, and the crossing point appears.

Since a lower value of the crossing point current facilitates the above mentioned paralleling of devices, the design considerations should take
3.3. Forward Recovery Characteristics

Figure 3.4: Measured (symbols) and simulated (solid and dashed lines) J-V curves of the non-irradiated 4500 V full-wafer diode at 300 and 400 K. The crossing point occurs at a current density of 70 A/cm².

into account the impact of process parameters on the crossing point current. The influence of different lifetime treatments on the crossing point is presented in [9] and [10].

3.3 Forward Recovery Characteristics

In Fig. 3.5, the forward recovery of the 4500 V rectifier at a current rise of 300 A/(cm² µs) is illustrated. Beginning in the static blocking state, the current pulse leads to a rise of the anode voltage, which starts the conduction phase. Depending on the di/dt value, the device reacts with an over voltage of up to 300 V. This voltage overshoot arises because of the existence of the highly resistive n⁻-base region and the lacking conductivity modulation at the beginning of the turn-on process.

The anode and cathode side hole and electron injection during the forward recovery process leads to a rise of the excess carrier concentration in the device, which is shown in Fig. 3.6. The excess carrier concentration is increasing until the static on-state distribution as seen in chapter 3.2.1 is reached. During this process, the conductivity mod-
Figure 3.5: Measured (dashed line) and simulated (solid line) forward recovery of a non-irradiated full-wafer diode at a $\frac{di}{dt}$ of 300 $A/(cm^2\mu s)$ leading to a voltage overshoot of 175 V.

ulation is increasing and the voltage drop over the device is decreasing to its on-state value.

At a fixed current rise $\frac{di}{dt}$ and a fixed turn-on current, the over-voltage peak Mostly depends on the temperature and on the thickness of the device. The first dependence is due to the decreasing electron and hole mobility with rising temperature leading to an increased over voltage. The second dependence is the thickness of the device. The thicker the device, the higher the over voltage peak. The over voltage is almost independent of the doping profile and the lifetime distribution of the diode. Therefore, this switching mode is ideal for calibrating the physical models of the device simulator and its parameters.

The forward voltage overshoot during the turn-on transient can be a serious problem in power circuits, especially in transistor applications: the voltage can appear at the emitter-base junction of the transistor, exceeding its forward breakdown voltage.
Figure 3.6: *Simulation of the increasing excess carrier concentration during the forward recovery of the non-irradiated full-wafer diode illustrated in Fig. 3.5 at the following points of time: 2.1μs, 2.5μs and 3 μs.*

### 3.4 Reverse Recovery Characteristics

In the reverse recovery process, the rectifier is switched from its on-state to its blocking state. When the diode voltage is reversed, the reverse recovery current starts to remove the stored excess carriers out of the deep p and the n⁻-base. At the point of time where the diode is able to sustain reverse voltage, the plasma concentration at the p-n junction is decreased to the value of the doping level. This results in a delay time of the voltage rise, compared to the reverse current decrease. All the reverse recovery processes presented in chapter 3 to 8 were obtained in the resistive switching mode. A detailed description of this switching environment can be found in chapter 7, where also the differences to the clamped inductive mode are described.

In Fig. 3.7, the reverse recovery process of a proton-irradiated diode (see chapter 6.2) at a forward current density of 11 A/cm² and a line voltage of 3000 V is illustrated. Additionally the results of a one dimensional device simulation can be seen in this figure.

In a resistive switching environment, the current decrease di/dt is accelerating during the recovery process because of its dependence on
the turn-on speed of the corresponding switch in this circuit. The $\text{di/dt}$ at current zero crossing in Fig. 3.7 is in the order of $100 \text{ A/(cm}^2 \text{ ms)}$. The dependences of the reverse recovery waveforms on the device temperature, the forward current densities from which the device is turned off, and the commutating $\text{di/dt}$ is explained in [11]. The reverse recovery current has to flow through the corresponding switch, thus adding to peak power dissipation and to total turn-on losses in the switch.

During the recovery process of the diode, holes are being extracted via the p$^+$ anode region and electrons via the n$^+$ cathode region. When the p-n junction is depleted, the voltage over the device starts to rise, leading to an increasing electric field in the n$^-$ base. Figure 3.8 shows the expansion of the electric field during the recovery process seen in Fig. 3.7 in chronological order, starting at 1 $\mu\text{s}$ in 0.1 $\mu\text{s}$ steps.

The current through the space charge region at the p-n junction is carried by holes only. The additional charge given by these holes increases the effective space charge density in Eq. 3.1, leading to a steeper field slope and a higher field maximum at the p-n junction compared to the static field distribution. If this amount of holes reaches a
certain level, the field peak approaches a critical value (approximately 200 kV/cm), where impact ionization starts to become significant. The holes and electrons generated by the so-called dynamic avalanche get separated in the high electric field, leading to an electron flow into the still remaining plasma in the n⁻-base and a hole flow to the anode contact. This additional electron current reduces the effective space charge density, leading to a reduced maximum electric field. Thus, dynamic avalanche does not necessarily have to be destructive. However, these additionally generated carriers increase the total amount of switching losses in the diode as well as in the corresponding switch.

The occurrence of a dynamic avalanche can also be seen in Fig. 3.7. Shortly after the reverse current maximum, an additional "rucksack" (bump in recovery current) occurs, in contrast to the recovery shown in Fig. 3.9. A detailed description of the dynamic avalanche process in high power Si diodes can be found in [12].
3.4.1 Tail-Current Behavior

In addition to the p-n junction space charge region, which occurs at the high electric field region illustrated in Fig. 3.8, a second one at the n-n+ junction may occur. The reason for this second depletion region is the fast extraction of electrons through the cathode in the case of high di/dt and high dv/dt during turn-off. During the recovery process the higher mobility of electrons compared to that one of holes results in a faster expansion of the space charge region at the p-n junction compared to the one at the n-n+ junction. Since the electron flow in the second depletion region compensates the charge of the ionized donors of the n−-base doping, the voltage drop via this second space charge region at the cathode can be neglected. The build up of a second space charge region is highly undesired, because it reduces the effective n−-base width. Before the recovery process of the device is completely finished, the reverse recovery current suddenly drops to zero, resulting in high voltage oscillations due to stray inductances in the circuit as can be seen in equation:

\[ v = -L_{stray} \frac{di}{dt}. \]  

(3.10)

The so called snap-off (or snap-back) of the diode current most likely occurs at low forward current densities (1...3 A/cm²) and high DC-link voltages. There is a much higher probability that this snap-off imposes problems on the neighboring circuitry than on the device itself.

Figure 3.9 illustrates the reverse recovery process of a homogeneously lifetime-engineered device (see chapter 6) at the same switching conditions as for the snap-free (soft) recovery process (diode with inhomogeneous lifetime engineering) shown in Fig. 3.7. From a forward current density of 11 A/cm² the device is turned off to a line voltage of 3000 V. At 3.1 µs, the reverse current suddenly drops to zero, leading to significant voltage/current oscillations in simulation and experiment. A turn-off consisting these oscillations in the current and voltage waveforms is called a snappy reverse recovery. The reason for this behavior is the reduced n−-base width due to the second space charge region at the cathode side seen in Fig. 3.10. The differences between simulated and measured voltage and current curves are due to the missing damping effect in the device simulation and the limited sampling frequency of the measurement equipment.
3.4. Reverse Recovery Characteristics

Figure 3.9: Measured (dashed curve) and simulated (solid) waveforms of a snappy reverse recovery of an electron only irradiated diode at a forward current density of 11 A/cm² and a line voltage of 3000 V.

Figure 3.10: Simulated electric field expansion during the snappy reverse recovery shown in Fig. 3.9.
The inhomogeneous lifetime engineering as one possibility for avoiding the cathode side space charge region is described in later chapters. Another possibility to reach a soft reverse recovery process is the add of a charge reservoir close to the cathode. The example of an additional deep n$^+$ diffusion at the cathode side is presented in [13].

### 3.4.2 Safe Operating Area

In contrast to the reverse recovery snap-back, the dynamic avalanche occurs during turn-off of a high forward current density and a high line voltage. The impact ionization leads to an increase in peak power dissipation in the device. This heat dissipation may result in local destruction of the device. In Fig. 3.11 an example of a diode with a high ruggedness is shown. The reverse recovery from a forward current density of 90 A/cm$^2$ and a line voltage of 3200 V yield to a significant impact ionization. The "ruck-sack" mentioned in chapter 3.4 is increased in a way that the maximum reverse recovery current $I_{rr}$ is dominated by the amount of charge generated by dynamic avalanche. The maximum reverse recovery current density of 270 A/cm$^2$ and the over voltage of 4000 V lead to a maximum peak power dissipation of 1 MW/cm$^2$. The maximum peak power a diode is able to withstand during turn-off gives a measure for the ruggedness (SOA) of the device.
3.4. Reverse Recovery Characteristics

Figure 3.11: Reverse recovery characteristic of a double proton-irradiated diode turned off at 125 °C from $I_F = 90 \text{ A/cm}^2$ to $V_{DC} = 3200 \text{ V}$. The resulting peak power is equal to 1 MW/cm$^2$ ($I_{rr} \approx 270 \text{ A/cm}^2$ and $V_{r_{\text{max}}} \approx 4000 \text{ V}$).
Part II

Performance Enhancing Technologies
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Chapter 4

Junction Terminations

In this chapter, the significant impact of the device structure on the electrical device characteristic is shown. The consequences of the different junction terminations on the electrical switching characteristics are analyzed.

The impact of different junction termination technologies on the electrical device performance, in particular on the losses of the reverse recovery process, will be defined in this chapter. The beveled edge technology and the planar junction termination, which were already introduced in chapter 2 will be compared to each other through simulation. Besides the electrical characteristics, the type of junction termination has other significant impacts, for example on the thermal properties (cooling of the edge of the device) or on the cosmic ray stability [6]. Omitting the other implications of different edge termination approaches, this chapter concentrates only on the variation of the reverse recovery waveforms determined by the edge technology.

Two one-dimensional rectifiers with the same n^-base and cathode structure, but with varying anode profiles were investigated with the device simulator [14]. Figures 4.1 and 4.2 depict these diode structures: a state-of-the-art press-pack rectifier and a hypothetical planar junction device, comparable with the chip diode of chapter 2.2.

The deep acceptor profile in the anode of a press-pack diode as
Figure 4.1: Doping concentration and lifetime distribution of a state-of-the-art 4500 V full-wafer diode.

Figure 4.2: Doping concentration and lifetime distribution of a hypothetic planar diode with a shallow anode, leading to a correspondingly reduced total device thickness at a constant $n^-$-base width compared to the device in Fig. 4.1.
described in chapter 2.1, leads to an increase of 60\,\mu m in the total device thickness as compared to a planar junction approach. The same n^-base width of the devices ensures an equal blocking capability of 5000 V. Both elements are processed with an inhomogeneous lifetime engineering to reduce the anode side injection efficiency (see Figs. 4.1 and 4.2).

The technology of lifetime engineering, which will be described in detail in chapter 5, was used in a way that the static losses of the two devices were exactly the same. This can be seen in Fig. 4.3, where the simulated J-V-curves of the full-wafer diode (deep anode) and the planar junction concept (shallow anode) are compared to each other.

![J-V curves](image)

**Figure 4.3:** Simulated I-V curves of the full-wafer diode shown in Fig. 4.1 (dashed curve) and the hypothetic planar diode (solid curve) shown in Fig. 4.2.

The reverse recovery of these devices with identical static losses was compared to each other in the same resistive switching environment. In Fig. 4.4 the simulated turn-off from a forward current density of 10 A/cm^2 and a line voltage of 2800 V with an di/dt of 100 (A/cm^2 \, \mu s) is shown. The deep anode diode shows a 20 A/cm^2 higher maximum reverse recovery current density but a softer return of reverse recovery current at the end of the tail-phase. Because of the overall thinner device structure of the shallow anode diode, the whole amount of extracted charge is smaller compared to the other device. Additionally, the less deep anode leads to a faster removement of the carriers at the p-n junction and consequently to a faster establishment of a space charge region. The resulting earlier rise
of voltage in case of the shallow junction device is shown in Fig. 4.4. The difference in the softness of the recovery waveforms is due to the electric field distributions of the two diodes. Since a small portion of the voltage drops off is in the deep-acceptor-diffused area, the full-wafer device shows a smoother current decay during recovery.

The 30% lower reverse recovery losses of the hypothetic planar diode, resulting from the differences in the maximum reverse recovery current and the tail-phase behavior, can also be seen in the technology curve of Fig. 4.5. At an on-state voltage of 3.5 V at 420 A/cm², the turn-off switching losses were calculated from the reverse recovery waveforms depicted in Fig. 4.4 and transferred to the trade-off curves of Fig. 4.5. The complete trade-off curve between static and dynamic losses was attained by varying the bulk lifetime by means of electron irradiation (homogeneous lifetime distribution), which will be explained in chapter 6.1.

In this chapter the impact of the differences in the device structure of the press-pack rectifier and the chip diode have been analyzed. The potential reduction of the device thickness in case of the planar junction termination leads to significant reduced static and dynamic losses.

**Figure 4.4:** Simulated reverse recovery of the deep (dashed curve) and the shallow (solid curve) anode diode. \( j_F = 10 \, \text{A/cm}^2, V_{DC} = 2800 \, \text{V} \) and \( dj/dt = 100 \, \text{A/(cm}^2 \, \text{µs)} \).
Figure 4.5: Simulated technology curve of the deep (dashed curve) and the shallow (solid curve) anode diode. Switching parameters for the calculation of the turn-off losses were \( j_F = 10 \, A/cm^2, V_{DC} = 2800 \, V \) and \( \frac{dj}{dt} = 100\, A/(cm^2\mu s) \).
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Chapter 5

Anode Emitter Injection Efficiency

Today it is generally recognized that one of the most efficient concepts for an improved diode performance is the appropriate control of the on-state excess carrier distribution. As already mentioned in chapter 3.4, a common technology for optimizing the reverse recovery characteristic of fast high power rectifiers is to reduce the injection efficiency of the anode. Such a reduction leads to a lower on-state excess carrier concentration at the p-n junction, which manifests itself as a lower maximum reverse recovery current ($I_{rrm}$) during the diode turn-off. This leads to a decrease of the peak power density. Because of the lower $I_{rrm}$ and the comparable higher storage of excess carriers at the cathode compared to the concentration on the anode, the softness behavior of the current and voltage waveforms at the end of the tail phase gets improved.

Adjusting the anode emitter injection efficiency and with it the excess carrier distribution can be done either by varying the doping profiles or by local lifetime control [15]. Local lifetime control is achieved either by exposing the diode to ion beams (helium or protons) or by doping with heavy transition metals (gold or platinum).

Additionally, several new device structures for fast high power diodes have been introduced ([16, 7]). The schematic structures of the different concepts are illustrated in Fig. 5.1: First, the transparent anode emitter
Figure 5.1: Schematic drawing of different diode structures: PiN diode with recombination centers, P-iN diode, Self adjusting P Emitter Efficiency Diode (SPEED), Static Shielding Diode (SSD), Merged PiN Schottky (MPS) diode and Soft and Fast recovery Diode (SFD).
5.1. SPEED Concept

diode with a homogeneous reduction of the anode doping (in other words the P–iN diode) and second the Merged PiN/Schottky diode (MPS), which was proposed in 1987. The uncompleted shielding of the Schottky regions in reversed bias lead to weaker blocking capability and higher leakage currents of the MPS devices. The Static Shielding Diode (SSD), reported in 1984, also had only low blocking capability, because the inhomogeneities in the blocking junction resulting in higher electric field peaks. The Soft and Fast Recovery Diode (SFD), with an additional alloying process, where the anode aluminum metalization is alloyed to the silicon, was reported in 1991. The most promising technology was the Self adjusting P-Emitter Efficiency Diode (SPEED) proposed in 1989.

The PiN diode is still the dominating rectifier in the field of high power conversion. Within this work, the original PiN diode was optimized resulting in an enlarged Safe Operating Area (SOA) in terms of an expansion to higher line voltages. To control the injection efficiency of the anode, two state-of-the-art technologies, the reduction of the emitter doping and the ion irradiation into the p-doped region, are compared to each other.

5.1 SPEED Concept

The anode of the SPEED diode, which Schlangenotto invented in 1989 [16], consists of a p layer with embedded p+ islands. The p+ regions in the p layer represent a high injection efficiency in a p region of low injection efficiency. Both regions are connected to the aluminum metal layer of the anode contact (see Fig. 5.2).

By varying the lateral distances of the p+ regions, the injection efficiency can be easily adjusted to the needed value. The self adjusting effect becomes important at higher current levels only. Due to the different built-in potentials of the p+–p–n and p–n junctions, the electrons preferably flow to the anode contact via the low doped p-region. At high current densities, this inhomogeneity in electron current density will lead to a non-neglectable potential difference between the p+ and p− regions as seen in Fig. 5.3, leading to increased injection from the p+ islands.
Figure 5.2: Schematical figure of the Self adjusting P-Emitter Efficiency Diode (SPEED).

Figure 5.3: Electron current density in a SPEED diode at a total forward current density of 40 A/cm².
5.1. SPEED Concept

The simulated result of a forward biased SPEED diode at a current density of 40 A/cm² in Fig. 5.3 illustrates the shrinking effect of the electron current. At the interface of the metalization/p⁻ contact the current density rises beyond 100 A/cm², whereas in the middle of the p⁺ islands, the current density decreases to a value below 40 mA/cm². The driving force for this current division is the difference in the built-in potential of the two p regions of the anode. It results in a potential difference of 4.3 and 4.7 V for the p and p⁺ regions at the silicon surface, respectively. The higher potential at the p⁺ islands leads to an enhanced hole injection of the p⁺ regions which increases the excess carrier concentration at the anode. The higher the current level, the higher the potential difference between the p regions. This leads to an increasing rise of the hole injection. As a consequence of this self adjusting injection efficiency effect, the I-V curves of common SPEED diodes are much steeper compared to homogeneous device structures.

![Figure 5.4: Comparison of the simulated on-state behavior of a SPEED diode (solid curve) and a PiN rectifier (dashed curve).](image)

Figure 5.4 compares the on-state losses of the two different diode structures. Whereas the on-state voltage drop at lower current densities is more or less equal in both devices, the voltage drop of the SPEED diode rises significant slower at higher current densities compared to the homogeneous p doped PiN diode. This advantage results in a better surge current capability of the devices.
The self adjusting effect has also some positive effects on the softness of the reverse recovery characteristic. At lower current densities, the injection efficiency of the anode is relatively weak. This leads to a reduced plasma concentration at the p-n junction and, consequently to a reduced current snap-off behavior at the end of the tail phase.

The drawbacks of the SPEED technology are additional mask steps and, compared with homogeneous structures, a lower peak power capability of these devices. The latter may result from a local heat generation at places of higher current densities during turn-off, which would increase the local peak power dissipation at these points. During turn-off at high current densities, a local punch-through because of holes compensating the p- doping would also result in device destruction.

5.2 Weak Emitter

Another approach to limit the excess carrier concentration at the p-n junction is to decrease the injection efficiency by homogeneous reduction of the anode doping. This weak or even transparent emitter is implemented through a reduction of the boron doping in its maximum value and its diffusion depth as illustrated in Fig. 5.5.

\[ \text{Figure 5.5: Doping profile of the emitter-reduced structures. Three variations of boron depth and peak value were simulated.} \]
5.2. Weak Emitter

The minimal necessary p-dopant concentration for an ohmic contact at the silicon/metal interface limits the amount of doping concentration reduction of the weak emitter (see [8]). In the following, the diodes with the reduced boron doping of the anode are termed "emitter-reduced devices". For two different anode dopant reduced structures (see Fig. 5.5), the simulated excess carrier distribution is shown in Fig. 5.6 for a current density of 100 A/cm².

Additionally, the relative values of the free carrier absorption measurement of one of the elements are compared to the simulation, where the correspondence between the simulated and the experimental data can clearly be seen. To check the lifetime calibration, two different approaches were investigated: the recording of the waveforms of the electrical characteristic and the Free Carrier Absorption measurements (FCA, [17]; done at the Royal Institute of Technology in Stockholm). The significant decrease of the plasma concentration in the anode side half of the emitter-reduced device is demonstrated in measurements as well as in simulations in Fig. 5.6.

This variation of the plasma distribution has the following influences on the static and dynamic electrical characteristics: because of
the smaller conductivity modulation as described in chapter 3.2, the on-state voltage rises with decreasing excess carrier concentration. In Fig. 5.7, the simulated I-V curves for the different boron implantation doses are shown.

![Simulated J-V curves](image)

**Figure 5.7:** Simulated J-V curves of the emitter-reduced structures seen in Fig. 5.5.

At a current density of 50 A/cm², the on-state voltage rises with falling injection efficiency from 3 V to more than 5 V, which is a high value depending on the practical application.

In Fig. 5.8, the simulated reverse recovery waveforms for a very low forward current density of 1 A/cm² are illustrated for the three different device structures shown in Fig. 5.5. The decreased plasma density close to the anode (seen in Fig. 5.6) leads to a lower reverse recovery current and a much smoother tail current behavior. At a line voltage of 3000 V, the diode with the highly efficient anode shows a significant current snap-off with a high di/dt. By the stray inductance in the circuitry this abrupt current change leads to a high over voltage. This can destroy the device itself or other components in the circuit. It can also be seen in Fig. 5.8 that the over voltage is substantially reduced for devices with weakened anodes. The lower carrier concentration at the p-n junction in the on-state plasma distribution leads to a smaller maximum reverse recovery current $I_{rrm}$ during turn-off in case of the weakened anode devices. The comparable higher carrier concentration at the cathode side (related to the value at the p-n junction) leads to a
smoother current decay at the end of the reverse recovery process.

![Graph](image)

**Figure 5.8:** Simulated reverse recovery characteristic of the emitter-reduced structures (seen in Fig. 5.5) at a forward current density of 1A/cm² and a line voltage of 3000 V.

In Fig. 5.9, the free carrier absorption measurement of the open circuit decay (OCD) [18] is shown. In the OCD, the on-state excess carrier distribution (t=0µs) is followed by a carrier decay. This is given only by recombination and diffusion, i.e. there is no current through the contacts (see the captions of Figs. 5.9 and 5.14). These FCA measurements were used to extract the lifetime properties of the fabricated devices and to calibrate the simulation.

The open circuit decay of the weak emitter diode shows the expected carrier concentration reduction close to the anode (x≈10µm at t=0µs) and a homogeneous decay of the carrier concentration (for t>0µs) due to the almost constant lifetime throughout the device. The differences to the OCD of an ion-irradiated diode will be discussed in section 5.3.
Figure 5.9: Free Carrier Absorption (FCA) measurement of the emitter-reduced device at a forward current density of 100 A/cm$^2$. For $t = 0\mu s$ the on-state carrier distribution is shown; for $t > 0\mu s$ the open circuit decay occurs.
5.3 Ion Irradiation

Ion irradiation is intended to reduce the anode emitter efficiency and hence the plasma density close to the anode, thus leading to a lower maximum reverse current and a "softer" recovery behavior.

![Diagram](image)

**Figure 5.10:** Simulated lifetime profiles of the proton-irradiated devices (solid and dot-dashed lines). Only the first 100 μm of the anode side are illustrated in this graph. For comparison, the lifetime profiles of the unirradiated (dotted line) and electron-irradiated (dashed line) diodes are shown.

The distribution of the irradiation induced traps and their capture cross sections were taken from a work carried out by Vobecky et al. [19] and used to calculate the excess carrier lifetime. A linear approximation of the trap concentration and distribution for different proton doses and energies turned out to be acceptable. The resulting lifetime profiles can be seen in Fig. 5.10. For a current density of 100 A/cm², the calculated excess carrier distribution is compared to the FCA-measurements in Fig. 5.11. The simulated excess carrier distributions show a good agreement with the measured plasma curves. In contrast to the homogeneous electron irradiation, which leads to an overall decreased plasma concentration, the exposure to proton irradiation of defined energy facilitates a more precise and local tailoring of the plasma.

The static and dynamic losses are shown in Figs. 5.12 and 5.13,
respectively. In this case the on-state voltage increase of the exclusively proton-irradiated devices is relatively small compared to the electron-irradiated devices.

The reverse recovery shown in Fig. 5.13 was measured under the same switching conditions as the electron irradiated diode in Fig. 3.9 (chapter 3.4). The simulated (solid lines) and measured (dashed lines) switching transients of the proton-irradiated diode (dose 2xA) show a soft recovery similar to the one in Fig. 3.7, where the proton dose is reduced to half. But the influence of the dynamic avalanche in the recovery process is even increased compared to the reduced dose. Due to the steeper gradient of the remaining plasma after the I_{rrm} during the recovery, the diffusion of holes into the anode side space charge region is higher. This additional charge of the holes is adding to the charge of the ionized dopant impurities, leading to a steeper electric field distribution. This results in a higher peak field value, which increases impact ionization. Because of the separation of the generated electrons and holes in the high electric field area, the electrons will partly compensate the positive charge of the dopant/holes and therefore reduce the gradient of the field. This compensation of the positive charge results in a non-destructive effect of the dynamic avalanche. A detailed description on the physics of impact ionization during reverse recovery is given in
5.3. Ion Irradiation

Figure 5.12: Simulated (lines) and measured (symbols) J-V curves of the electron- and proton-irradiated structures.

Figure 5.13: Simulated (solid line) and measured (dashed line) reverse recovery of the proton-irradiated device with dose 2xA, see Fig. 5.11. Forward current density of 11A/cm²; line voltage of 3000 V.
Figure 5.14: FCA measurement of the proton-irradiated device at a forward current density of 100 A/cm². For $t = 0 \mu s$, the on-state carrier distribution is shown; for $t > 0 \mu s$, the open circuit decay occurs. Local lifetime control results in a faster decay of the carrier concentration at the p-n junction ($x \approx 80 \mu m$) and a slower one close to the cathode ($x > 300 \mu m$) compared to the emitter-reduced diode (see Fig. 5.9).

In Fig. 5.14, the open circuit decay of the excess carrier distribution for a proton-irradiated device is shown. Compared to the emitter-reduced diode (see Fig. 5.9), the ion-irradiated diode has an anode with a high emitter efficiency; in this case, the on-state plasma reduction (at $t=0\mu s$) is achieved by a higher recombination rate near the p-n junction ($x \approx 80 \mu m$). This leads to the illustrated inhomogeneous carrier decay in the OCD in Fig. 5.14.

Summarizing, both the emitter reduction and the ion irradiation technology lead to the desired reduction of the plasma density at the anode side of the rectifier, thus lowering the maximum reverse recovery current. However, the onset of impact ionization even at relatively low forward current densities of 11 A/cm² (see Fig. 5.13 and 3.7) requires further lifetime engineering which will be shown in chapter 6).
5.4 Comparison of Technologies

In this chapter, an experimental and numerical comparison of diodes with different emitter injection efficiencies is presented. The approach of the local lifetime control by ion irradiation and the reduction of the anode emitter efficiency by means of reducing the emitter doping are both leading to an enlarged Safe Operating Area (SOA) in terms of an expansion to higher line voltages. First, the measured results (chapter 5.4.1) will be discussed, then the simulated ones (chapter 5.4.2). Finally, the different physical processes involved will be presented (chapter 5.4.3).

5.4.1 Measurements

With the technology described in chapter 5.3, the dose of the proton irradiation was chosen such that the same on-state characteristics are obtained for the ion-irradiated device and for the emitter-reduced diode. The j-V curves in Fig. 5.15 show that the two different diodes have the same on-state characteristic and that the temperature dependence of the curves is similar, e.g. the crossing points (see chapter 3.2.2 and [9]) for the two temperatures 300 K and 400 K are the same for both diodes.

Figure 5.16 illustrates the measured reverse recovery characteristics in an Undeland/McMurray circuit (see chapter 7.1 and [20]) for the two different diodes at a temperature of 400 K. A low forward current and a high line voltage were chosen because this increases the probability of snap-off of the diode reverse recovery current (see chapter 3.4.1).

In order to see the differences in softness during the tail phase, a very small forward current density of 2 A/cm² and a high line voltage of 3100 V were chosen. For the ion-irradiated device a reduction of more than 30 A/cm² in the maximum reverse recovery current density (J_{rr}) is observed as compared to the emitter-reduced diode. This results in a 50 percent decrease in the peak power density, mainly due to the earlier rise of the reverse voltage over the device. The higher peak power for the emitter-reduced diode is accompanied by the onset of impact ionization (t=2μs) shortly after I_{rr} is reached. The extracted charge Q_{rr} during the recovery process differs more than 100 percent between the ion-irradiated and the emitter-reduced diode. The physical
Figure 5.15: Measured J-V curves of the two different diodes at 300 K and 400 K.

Figure 5.16: Measured reverse recovery characteristics in an Undeland/McMurray circuit at 400 K with a forward current density of 2 A/cm² and a line voltage of 3100 V. The maximum reverse recovery current density of the ion-irradiated device (dashed curves) is reduced by 30 A/cm² compared to the value of the emitter-reduced diode (solid curves).
5.4. Comparison of Technologies

Figure 5.17: Measured reverse recovery characteristics in an Undeland/McMurray circuit at 300 K with a forward current density of 2 A/cm² and a line voltage of 3100V. The emitter-reduced diode (solid curve) shows harder current snapping at 3.1 μs.

Explanation for this substantial difference in the extracted charge will be given in chapter 5.4.3. At 300 K, the comparison shows the differences in softness between the devices (Fig. 5.17) measured with the same switching parameters as for the 400 K measurements. The ion-irradiated element has a soft current decay while the emitter-reduced diode shows a significant current snap-off, which is accompanied by large voltage oscillations at the end of the tail phase current. Additionally, the peak power density of the ion-irradiated diode is reduced to 46 percent and the extracted charge during turn-off is limited to 55 percent of the value of the emitter-reduced diode.

5.4.2 Simulations

Figure 5.18 displays simulated J-V curves at 300 K, showing equal on-state voltage drops for both types of diode technologies in agreement with the measurements (see Fig. 5.15). In Fig. 5.19, the simulated free charge carrier distributions for current densities of 1 and 10 A/cm² are shown for both diodes. In the proton-irradiated diode, a significantly
lower plasma density can be seen close to the junction (indicated by the arrow) compared to the emitter-reduced one.

At a current density of 1 A/cm² the difference in carrier concentration is approximately 30 percent.

![Simulated J-V curves of the emitter-reduced (solid curve) and the ion-irradiated (dashed line) diode at 300 K.](image)

**Figure 5.18:** Simulated J-V curves of the emitter-reduced (solid curve) and the ion-irradiated (dashed line) diode at 300 K.

At the proton-induced trap density maximum, the excess carrier distribution exhibits a sharp knee (arrow in Fig. 5.19). In the simulation, a conversion from electron to hole current can be seen in this region. Figure 5.20 illustrates at current densities of 30, 55 and 85 A/cm² an increase of the hole current density close to the anode of almost a factor of two for the ion-irradiated diode as compared to the emitter-reduced device. The corresponding electron current density shows a sharp decrease around 50μm in the case of the ion-irradiated device (see Fig. 5.21).

The proton-irradiated diodes display the same voltage drop, e.g. the same static losses, but a significantly reduced excess carrier concentration at the p-n junction for small current densities as compared to the emitter-reduced devices. The impact of the different on-state plasma distributions for the two types of diodes on the dynamic reverse recovery characteristics is simulated in the Undeland/McMurray circuit discussed in chapter 7.1 (see Fig. 7.3). Because of missing damping effects in the simulated circuit, the current snap-off occurs in the sim-
Figure 5.19: Simulated carrier distribution at two current densities 1 and 10 A/cm$^2$ for the ion-irradiated (dashed curves) and for the emitter-reduced (solid curves) diode, respectively.

Figure 5.20: Simulated hole current density for total current densities of 30, 55 and 85 A/cm$^2$ for the ion-irradiated (dashed curves) and the emitter-reduced (solid curves) diode. At the depth where the traps of the proton-irradiation are located, the hole current density is increased for the ion-irradiated diode.
Figure 5.21: Simulated electron current density for total current densities of 30, 55 and 85 A/cm\(^2\) for the ion-irradiated (dashed curves) and the emitter-reduced (solid curves) diode. At the depth where the traps of the proton-irradiation are located, the electron current density is decreased for the ion-irradiated diode.

ulation at lower line voltages and higher forward current densities. For this reason, Fig. 5.22 shows the simulated reverse recovery waveforms at 400 K for both diodes with a forward current density of 11 A/cm\(^2\) and a line voltage of 2800 V. The main difference between the two types of diodes is the earlier voltage rise and the smaller maximum reverse recovery current density of the ion-irradiated device in correspondence with the measurements (see Fig. 5.16). In Fig. 5.23, the same recovery process was simulated at a temperature of 300 K. Like in the measurement shown in Fig. 5.17, the tail phase current of the emitter-reduced diode has a current snap-off at about 4.2\(\mu\)s.

5.4.3 Discussion

Both measurements and simulations show that the ion-irradiated device has a better trade-off between static and dynamic losses than the emitter-reduced one. For devices with a homogeneous lifetime like the emitter-reduced diode, the optimum plasma distribution for the best trade-off between on-state and turn-off losses is flat. Unfortunately,
Figure 5.22: Simulated reverse recovery characteristics in an Undeland/McMurray circuit at 400 K with a forward current density of 11A/cm\(^2\) and a line voltage of 2800V. For the different points of time (1-6) the hole distribution is shown in Fig. 5.24.

Figure 5.23: Simulated reverse recovery characteristics of the ion-irradiated (dashed curves) and the emitter-reduced (solid curves) devices in an Undeland/McMurray circuit at 300 K with a forward current density of 11A/cm\(^2\) and a line voltage of 2800V.
such a distribution leads to very snappy behavior of the reverse recovery current. Improving the softness and reducing the maximum reverse recovery current requires a lower excess carrier concentration at the p-n junction compared to the n$^+$-n$^-$ junction. This is achieved for both the ion-irradiated and the emitter-reduced devices, but to different extents. In order to explain why the on-state losses are equal for both types of diodes, although the overall plasma density is lower for the ion-irradiated diode, one has to distinguish between the drift current (electric field is the driving force) and the diffusion current (the gradient of the plasma distribution is the driving force). Due to the conversion of electron to hole current in the area of high recombination (Figs. 5.20 and 5.21), additional diffusion of excess carriers because of steep gradients lowers the on-state voltage in the ion-irradiated diode. Up to the location of the irradiation induced recombination centers of the device, the gradient of the carrier distribution enhances the current carried by holes. For low current densities, this leads to a smaller excess carrier concentration at the p-n junction for the same amount of static losses. In the dynamic turn-off characteristic, this difference in the on-state plasma level leads to a smaller $I_{rr}$ and a softer turn-off behavior for the proton-irradiated diode. Due to the decreasing lifetime at lower temperatures, the excess carrier concentration at room temperature is reduced and the current snap-off oscillations occur more significantly compared to 400 K (see Figs. 5.16 and 5.17).

The simulated hole density distribution at different points of time during the reverse recovery process is plotted in Fig. 5.24. The lower plasma concentration at the p-n junction combined with additional recombination due to the irradiation-induced traps lead to a faster expansion of the anode-side space charge region for the proton-irradiated diode in the beginning of the turn-off process (time points 2 and 3). Because the reverse blocking voltage of the ion-irradiated diode is established faster, the reverse recovery current is correspondingly limited earlier, i.e. a lower $I_{rr}$ is obtained. In addition, the depletion region at the n$^+$-n$^-$ junction, having less time to expand, is smaller at every time point for the ion-irradiated diode. At time point 5, the reverse recovery current is comparable for the two devices, although less charge has been extracted from the ion-irradiated diode. The remaining charge is now helping to keep the two depleted zones from meeting, allowing a soft recovery of the ion-irradiated diode; i.e. the closer the remaining carriers are located to the cathode, the softer the device behaves. At time point
6, the space charge region of the emitter-reduced diode has overtaken that of the ion-irradiated device due to the lower amount of charge left in the emitter-reduced diode. It can, therefore, be concluded that the lower on-state excess carrier distribution of the proton-irradiated diode leads to a faster establishment of the reverse voltage over the diode and consequently to a lower reverse recovery current maximum as compared to the emitter-reduced device. In addition, a softer reverse recovery behavior is achieved for the ion-irradiated diode due to the larger amount of stored charge, which remains in the diode during the tail-current stage. A broader range of forward current densities with related maximum $I_{rr}$ is shown in Fig. 5.25. Differences in the maximum reverse recovery current density up to 45 percent between the two technologies can be identified. At forward current densities greater than 5 A/cm$^2$ at a line voltage of 3100V, impact ionization dominates the recovery characteristic including the maximum $I_{rr}$. 

**Figure 5.24:** Simulated hole density distribution during the reverse recovery process shown in Fig. 5.22. The ion-irradiated device (dashed curves) shows a faster depletion of the p-n junction (points 2 and 3) and more remaining plasma towards the end of the recovery process (point 6).
Figure 5.25: Simulated (filled symbols) and measured (open symbols) dependence of the maximum reverse recovery current density on the forward current density from which the recovery process is started. The emitter-reduced (rhombi and solid line) and the ion-irradiated (circle and dashed line) diodes were turned off against a line voltage of 3100 V at 300 K.
Chapter 6

Carrier Lifetime Control

6.1 Homogeneous Electron Irradiation

Exposing the Si wafer to electron irradiation with an energy between 2.5 and 10 MeV lowers the electron and hole lifetime homogeneously in the device. At the same forward current density, the total amount of excess carriers decreases, leading to a lower carrier density and higher static losses. The higher the electron irradiation dose is chosen, the less carriers need to be swept out during the recovery process. This results in lower switching losses with increasing electron dose.

For this reason, electron irradiation is the most common technique used to adjust the trade-off between static and dynamic losses. Figure 6.1 shows an example of a trade-off curve (static and dynamic loss dependence) for a deep junction device of chapter 4. In addition to the trade-off, another important design criteria is the softness of the recovery process. By studying different devices in the trade-off characteristics, it was found that the best device from the trade-off point of view shows a snappy turn-off behavior. Therefore, it is not sufficient to focus only on the trade-off performance in device optimization. The reason for the low power dissipation of the snappy devices is a low blocking voltage when the maximum reverse recovery current occurs. Additionally, a reduction of the total switching losses occurs at steeper current
Figure 6.1: Scheme of the trade-off between switching losses and static losses.

decrease after the $I_{rrm}$. For this reason, the element with the snappiest recovery would seem to be the preferred element. Furthermore, the trade-off curve is also depending on the circuit in which the different elements are observed. In the Undeland/McMurray circuit (see chapter 7.1), used so far, the maximum reverse recovery current occurs when the voltage starts to rise (see turn-off process in Fig. 5.16). Therefore, the voltage times current product remains low during a large portion of the stored charge extraction process. As a result, the diode losses remain low. Even at a high reverse recovery current this leads to a relatively small portion of the total diode losses. On the other hand, the large over-current leads to high losses in the switch.

Using electron irradiation as the only lifetime engineering, the result is a snappy recovery of the tail phase current during reverse recovery. This is illustrated in chapter 3.4.1. The recovery process in Fig. 3.9 shows a significant current snap-off at the same switching conditions as for the soft recovery of the lifetime tailored device in Fig. 3.7. But due to the homogeneous carrier lifetime reduction both in the $n^-$-base and cathode area of the diode, electron irradiation causes no heavy impact ionization (dynamic avalanche) during the tail phase (see Fig. 3.7).
6.2 Inhomogeneous Irradiation

Inhomogeneous lifetime control has proven to be very successful and is achieved either by heavy metal doping or by exposure to ion beams (protons or α particles) in combination with electron irradiation [3, 15]. Additionally, a new irradiation technique, the multi-proton irradiation was developed to enhance the softness of fast recovery diodes.

The principle of these lifetime engineering techniques is shown in Fig. 6.2. The corresponding plasma distributions and the consequences on the dynamic characteristics of the devices are described in chapter 6.2.1 for the combined electron and proton irradiation, and in chapter 6.2.2 for the double proton irradiation.

Figure 6.2: Doping (dot-dashed curve) and lifetime profiles of the combined $p^+e^-$ (solid curve) and the double proton-irradiated (dashed curve) diode.
6.2.1 Combined Proton and Electron Irradiation

The combination of proton and electron irradiation is the state-of-the-art technology of today. Using the local lifetime engineering technique, it is possible to control the injection efficiency of the anode, which ensures a soft recovery performance. The additional homogeneous lifetime killing with electrons suppresses the dynamic avalanche by reducing the bulk plasma density in the device. Figure 6.3 shows the reverse recovery of a combined proton- and electron- lifetime engineered diode at switching conditions like the ones for the devices in Figs. 3.7 and 3.9. The recovery process is soft and the total amount of charge generated by impact ionization is reduced compared to the recovery in Fig. 3.7. The overtime variation of the electric field expansion during the turn-off, the expanse of the anode side space charge region, and the suppression of the cathode side electric field can be seen in Fig. 6.4.

![Graph showing reverse recovery](image)

**Figure 6.3:** Measured (dashed curve) and simulated (solid curve) reverse recovery of a proton- and electron-irradiated diode from a forward current density of 11A/cm² against a line voltage of 3300V and a dj/dt of 120A/(cm²µs).
6.2. Inhomogeneous Irradiation

6.2.2 Double Proton Irradiation

In the double proton irradiation technique, electrons are replaced by protons in a second irradiation step. The second proton peak is located well in the middle of the n⁻-base as shown in Fig. 6.2. The new ion irradiation technique leads to a lower lifetime in the anode part of the device and a higher lifetime close to the cathode. The resulting excess carrier distribution is schematically shown in Fig. 6.5.

This results in a favorable excess carrier distribution with lower concentration at the anode and a higher concentration at the cathode side as compared to a device with combined proton and electron irradiation.

In Fig. 6.6, the simulated and measured reverse recovery waveforms of two diodes with the same on-state voltage drop but different lifetime profiles are compared. Both diodes were turned off from a forward current density of 16A/cm² against a line voltage of 3800 V. The double proton-irradiated diode has a soft recovery, i.e. a smooth decay of the diode current without abrupt changes. This diode also has a smaller maximum reverse recovery current and, consequently, a lower maximum peak power density. By contrast the conventional diode with combined e⁻ & p⁺ irradiation shows a greater reverse peak current and a significant
Figure 6.5: Doping profile (dot-dashed curve) and on-state plasma distributions of the conventionally $p^+&e^-$ (solid curve) and of the double proton-irradiated (dashed curve) diode.

Figure 6.6: Simulated and measured reverse recovery characteristics of a double proton-irradiated (dashed curves) and a $p^+&e^-$-irradiated (solid curves) device. Forward current density = 16 A/cm$^2$, line voltage = 3800 V.
6.2. Inhomogeneous Irradiation

snap-off at \( t \approx 2.6 \mu s \). In order to understand the physical processes of the reverse recovery of devices with different lifetime profiles, one-dimensional device simulation was employed. To increase the maximum applied voltage of a proper device, the behavior of the electric field and the carrier distribution during recovery are of fundamental interest. Figure 6.7 illustrates the simulated electrical field of the double \( p^+ \)-irradiated diode compared to that of the \( p^+e^- \)-irradiated device.

![Simulated electric field distribution](image)

**Figure 6.7:** Simulated electric field distribution of a double proton-irradiated (dashed curves) diode compared to a conventionally \( p^+e^- \)-irradiated (solid curves) device during turn-off.

During reverse recovery, the carriers in a diode are extracted through the anode and cathode immediately after the voltage is reversed. As a consequence, in the device with combined proton and electron irradiation, a depletion region is formed not only across the p-n junction, but also across the n+-n~ junction under the applied recovery conditions. This results in a virtual reduction of the usable n~ base region (right arrow in Fig. 6.7) and in a snap-off of the reverse current at the moment when the two depletion regions meet at voltages lower than the static punch-through voltage. There is almost no voltage drop possible across this second depletion region at the cathode side as explained in chapter 3.4.1. In contrast, the field on the anode side is governed
by the minority carriers. Due to the lower recombination rate close to the cathode of the double-energy proton irradiated device, the excess carrier concentration is increased compared to the electron irradiated one. During recovery, at the point of time when a depletion region is being established, a stronger diffusion of holes into the base-region of the device with profiled lifetime as obtained by double-energy proton irradiation is observed. Consequently, the slope of the electric field is steeper compared to that of the device with a lifetime profile as obtained by single-energy proton irradiation combined with electron irradiation. This in turn also delays the "punch through" of the space charge region towards the cathode stopping layer and, therefore, supports "soft recovery" even up to voltages beyond the static punch-through voltage.

Figure 6.8: Simulated reverse recovery characteristics of a double proton-irradiated (dashed curves) and a $p^+\&e^-\$-irradiated (solid curves) device. $I_f = 16\,\text{A/cm}^2, V_{DC} = 3800\,\text{V}$ (same as in Fig. 6.6). The numbers indicate the different point of times of the plotted hole distribution in Fig. 6.9.

Figure 6.9 compares the plasma distributions during the reverse recovery process shown in Fig. 6.8. The voltage rise over the double proton-irradiated device leads to a comparatively faster propagation of the depletion region into the $n^-$-base until time point 2 (Fig. 6.9) as compared to the $p^+\&e^-\$-irradiated diode. However, towards the end of the recovery phase the situation changes. The different speeds at which
the depletion regions are built up, are illustrated in Fig. 6.9. Here, the expansion of the depletion region at low voltage is much higher (Fig. 6.9, points 1→2) in the double proton-irradiated device than in the \( p^+&e^- \)-irradiated diode, which results in a reduced \( I_{rr} \). However, at high voltage towards the end of the recovery phase (Fig. 6.9, points 3→4), the space charge region moves more slowly in the double proton-irradiated diode, resulting in a softer recovery. This is due to the higher amount of carriers close to the cathode in the double \( p^+ \)-irradiated device.

The improved peak power handling capability of the double proton-irradiated diode is illustrated in Fig. 3.11. It shows the turn-off waveforms of a double proton-irradiated diode at a forward current of 90 A/cm\(^2\) and a reverse supply-voltage of 3200 V which results in a peak power dissipation of 1 MW/cm\(^2\) without destruction of the device. This is a significantly improved capability as compared to previously tested devices with either electron or combined \( p^+&e^- \)-irradiation, where the destruction of the diodes was observed at peak power levels between 150 and 250 kW/cm\(^2\) [3].
Screened-Irradiation

The multiple-energy irradiation by two or more consecutive single-energy irradiation steps is expensive. This limits practical usage of this novel lifetime control technique.

A novel concept capable to replace the combination of different lifetime engineering techniques by one single irradiation step is presented in [21]. This method is based on the ion irradiation through a single mask which is inserted into the beam line between the ion source and the device as seen in Fig. 6.10.

![Image of mask and device](image)

**Figure 6.10:** Principle of the lifetime profiling by a single-step ion irradiation as invented in [1].

The density of the mask and its lateral structure (with its well-defined holes) determine the energy distribution of the ions entering the device. In the simplest case, the resulting defect profile is composed of two peaks. The deeper defect profile is given by the primary energy $E_0$ (ions getting through the holes), the shallower one by $E_0$ minus the energy loss in the screen (determined by the density and thickness of the foil).

Figure 6.11 shows the simulated defect distributions resulting from
6.2. Inhomogeneous Irradiation

Figure 6.11: Simulated defect distributions of a double-energy proton irradiation with the double-step (solid curve) and with the screened irradiation technique (dashed curve).

The capability of the new mask irradiation to substitute the double-step ion irradiation was further proven by the comparison of static and dynamic parameters of diodes irradiated with both techniques.

After irradiation, both diodes exhibited identical on-state characteristics. The reverse recovery waveforms of irradiated diodes measured under resistive snubberless switching conditions, with $V_{DC} = 2700\, V$, $J_f = 10\, A/cm^2$ are shown in Fig. 6.12. Furthermore, both current and voltage waveforms were found to be identical under different turn-off.
Figure 6.12: Measured reverse recovery characteristic of the double-energy proton-irradiated diodes from a forward current density of 10 A/cm$^2$ against a line voltage of 2700 V at 300K: comparison between the double-step (solid curve) and the screened irradiation (dashed curve) technology.

conditions. This confirms that the new single-step method can fully replace the standard multiple-energy ion irradiation.
Part III

Optimized Power Diodes for Specific Applications
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Chapter 7

A Snubber Diode

In order to optimize the behavior of the high voltage rectifier during turn-off, the circuit needs to be taken into consideration in particular with respect to "inductive" and "resistive" switching. The differences in stress that the diode experiences will be explained in chapter 7.1 for the resistive switching environment and in chapter 8.1 for the inductive switching environment.

7.1 The Undeland/McMurray Snubber Circuit

Until now, all the reverse recovery characteristics of the implemented diode structures have been analyzed in the Undeland/McMurray circuit. The Undeland/McMurray circuit is a snubberless, unclamped resistive switching environment, where the diode is nevertheless clamped to the source voltage until the switch is fully turned-on. During the switching transients, there is little or no energy storage in the whole circuit (low inductance circuit).

Figure 7.1 shows the Undeland/McMurray snubber of a two-phase bridge as proposed in [20]. In its simplest form, it includes the resistance $R_s$, the $di/dt$ limiting inductance $L$ and a capacitance $C_0$. 
To simulate the resistive recovery of the snubber diodes (black diodes in Fig. 7.1) the circuit can be simplified as seen in Fig. 7.2. Each phase-leg (e.g. phase-leg A) consists of a switch (S_A), which can be an IGCT or an IGBT, and a corresponding anti-parallel diode (DFA). In order to save calculation time, the GTO switches used in the measurements were replaced for the simulations by time-dependent resistors with an exponential decay. The two freewheeling diodes (DFA and DFB) and the switches (S_A and S_B) were snubbeder with a circuit consisting of two snubber diodes (Dsl_A, Ds2_A) and one capacitance (Cs_A) per phase-leg. The additional larger capacitance (C_0) together with the resistor R_S can be shared with the other phase-legs of the converter system.

A resistive recovery of a snubber diode occurs, when the current is switched from one phase-leg to the other one. Supposing that during turn-off of switch S_B the corresponding snubber diodes Ds1_B and Ds2_B turn on and, therefore, open the path to transfer the stored energy into the snubber capacitance C_SB and C_0. After turn-off of S_B, the current through the devices Ds1_B and Ds2_B is decreasing very slowly.
7.1. The Undeland/McMurray Snubber Circuit

Figure 7.2: Simulated circuit of the "reduced" two phase-leg Undeland/McMurray-Snubber.

afterwards (with a time constant in the millisecond range), depending on the value of the resistance $R_s$ and of the capacitance $C_s$. If the switch $S_A$ undergoes a turn-on while the the snubber diodes $D_{s1B}$ and $D_{s2B}$ are still conducting, the diode $D_{s1B}$ has to turn-off with an $di/dt$ limited only by the turn-on of switch $S_A$. The direction of the reverse recovery current is illustrated by a dashed line in Fig. 7.2. The snubber circuit is described in detail in [20].

Because of the small stray inductance $L_s$ in the circuit, the recovery of the snubber diode in the Undeland/McMurray switching circuit is only controlled by the turn-on behavior of the switch. This means that the rise of current ($di/dt$) is determined by the time-dependent resistance of the switch ($R_r$) rather than by the stray inductance $L_s$.
To avoid extensive simulation for snubber diode turn-off, the circuit in Fig. 7.2 was further simplified as illustrated in Fig. 7.3 and implemented in a mixed-mode circuit simulator. In this mode, the commutation $di/dt$ is controlled by the active switch and is typically in the range of 50 to 100 A/(μs cm$^2$) at zero current crossing, accelerating towards the maximum reverse recovery current $I_{rr}$ (see [3]).

![Figure 7.3: Snubberless Undeland/McMurray circuit for the simulation of snubber diode turn-off in a resistive switching environment.](image)

Since the inductance in the Undeland/McMurray circuit is comparable to the stray inductance in IGBT modules, this circuit is also an adequate test environment for IGBT freewheel diodes. One difference between IGBT and GTO/IGCT switches is that for the IGBT, the voltage decays more slowly towards the end of turn-on.

The schematical current and voltage waveforms of a diode in a snubberless, unclamped resistive recovery are shown in Fig. 7.4. Additionally, the softness-factor $S$ of the current decay is defined as the ratio of time interval $t_b$ to time interval $t_a$.

### 7.2 Optimized Diode for Resistive Switching

Different anode structures in chapter 5 and different lifetime profiles in chapter 6 were analyzed in the snubberless, unclamped resistive switch-
7.2. Optimized Diode for Resistive Switching

Figure 7.4: Current and voltage waveforms for a snubber diode in a snubberless, unclamped resistive switching environment.

The optimized double proton-irradiated diode and its superiority compared to the proton- and electron-irradiated diode was extensively discussed in chapter 6.2.2.

Another example is illustrated in Fig. 7.5, where the reverse recovery waveforms of two diodes with the same on-state voltage drop of 7.1V at 420 A/cm² (T=300K), but different lifetime profiles are compared. The double proton-irradiated diode shows a soft recovery, i.e. a smooth decay of the diode current without abrupt changes, even at forward current densities as low as 1 A/cm² and at line voltages as high as 3600 V. This diode also has a smaller maximum reverse recovery current and, consequently, a lower maximum peak power density. The conventional diode with combined p⁺&e⁻-irradiation shows a greater reverse recovery peak current and a significant snap-off by contrast. The physical processes of the reverse recovery of diodes with different lifetime profiles are described in chapter 6.2.2.
Figure 7.5: Measured reverse recovery waveforms of the double proton-irradiated diode (dashed curve) compared to the waveforms of a combined $p^+e^-$-irradiated diode (solid curve). Switching conditions: $J_f = 1\text{A/cm}^2$, $U_{DC} = 3600\text{ V}$. 
Chapter 8

Freewheeling Diode

8.1 Clamped Inductive Circuit

The clamped inductive switching operation is of growing importance in Voltage Source Inverters (VSI) without dv/dt protection circuits of IGCT switches and free wheel diodes. Also, the Neutral Point Clamping (NPC) diodes in the multi-level inverters are used in a clamped inductive circuit configuration in industrial applications. In this snubberless switching circuit, the di/dt is constant and determined by the snubber inductor L (see Fig. 8.2). Figure 8.1 shows the snubberless, clamped inductive switching circuit implemented in the mixed-mode device simulator.

Under these switching conditions, the $I_{rrm}$ is reached exactly at the same time when the voltage over the device reaches the DC-link level $V_R$, allowing the clamp diode to conduct. This can be seen in the reverse recovery waveforms in Fig. 8.2.

The voltage across the diode increases to its maximum value, while the full reverse current flows through the device. The maximum reverse current $I_{rrm}$, forced by the current source L, cannot decline until $V_{DUT} = V_R$ is reached (see Figs. 8.1 and 8.2). Once the clamp becomes effective, the recovery current declines, while the diode voltage remains constant. However, the additional stray inductance $L_S$ in the snubber
Figure 8.1: *Snubberless, clamped inductive switching circuit.*

Figure 8.2: *Current and voltage waveforms for a freewheeling diode in a snubberless, clamped inductive switching environment.*
8.1. Clamped Inductive Circuit

circuit itself leads to the over-voltage $V_{rr}$.

With the help of numerical device investigations, the physical stress on the DUT, especially the differences between those of clamped inductive and resistive commutation were analyzed. Figure 8.3 shows the different reverse recovery processes for the same double proton-irradiated device with an initial current density of $6 \text{ A/cm}^2$ and a clamp/line voltage of $3000 \text{ V}$.

![Graph](image)

**Figure 8.3:** Reverse recovery of a double proton-irradiated diode in a resistive (dashed curves) and a clamped inductive (solid curves) circuit ($V_{DC}/V_{clamp} = 3000 \text{ V}, J_F = 6\text{ A/cm}^2$). The corresponding widths of the space charge region is shown on the right axis. For the indicated points of time Fig. 8.3 shows the corresponding electric field distribution.

An obvious difference between the two commutation modes lies in the value of the voltage at the peak value of the reverse recovery current. For clamped, inductive commutation, the maximum reverse recovery current and the maximum voltage occur simultaneously (see Fig. 8.3). This results in a higher peak power compared to the resistive switching mode. In this case, the full clamp voltage is applied over a reduced space charge region width. Due to this smaller field expansion into the base-region of the device, the slope of the electric field is steeper as compared to that in case of the resistive commutation.
The different field distributions are shown in Fig. 8.4 for both commutation modes, at the points of time where the voltage starts to rise (point 1), where the DC-voltage is reached (point 2) and at zero current (point 3). Additionally, the extension of the space charge region during the recovery phase is plotted in Fig. 8.3. Concerning the snappiness criteria, the design rules for clamped inductive switching applications are similar to those for the resistive mode. The increased excess carrier concentration at the cathode prevents the formation of a second depletion region on the cathode side, which results in a smooth tail phase of the reverse recovery current.

8.2 Optimized Diode for Snubberless Operation

The circuit as depicted in Fig. 8.1 was implemented in the device simulator. The same virtual device structures as investigated under resistive snubberless conditions were simulated and compared to the corresponding measured waveforms. Figure 8.5 shows the good agreement of the
simulated and the measured data without further calibration of the freewheeling diodes. For both simulation and measurement, the clamped inductive switching conditions are: \( I_F = 6 \, \text{A/cm}^2, L = 50 \, \mu \text{H}, V_{\text{clamp}} = 2900 \, \text{V} \) and \( \frac{\text{di}}{\text{dt}} = 60 \, \text{A}/(\mu\text{s cm}^2) \).

**Figure 8.5:** Measured (dotted curves) and simulated (solid curves) reverse recovery characteristic of a double proton-irradiated device in a clamped inductive switching mode \((V_{\text{clamp}} = 2900 \, \text{V}, I_F = 6 \, \text{A/cm}^2)\).

In Fig. 8.6, the measured reverse recovery waveforms of a conventional \( p^+\&e^-\)-irradiated device are shown in the clamped inductive circuit.

The diode exhibits a snappy recovery behavior at a forward current density of \( 6 \, \text{A/cm}^2 \) and a clamp voltage of \( V_{\text{clamp}} = 2800 \, \text{V} \). In contrast, the diode with double proton irradiation technique in Fig. 8.7 shows the on-set of snap-off at a clamp voltage between 3800 and 3900 V for the same forward current density. This is an increase of more than 1000 V for a 4500 V diode. The peak power dissipated by the diode during turn-off under this inductive clamped condition can be approximated by multiplying the peak reverse recovery current with the clamp voltage: \( V_{\text{clamp}} \cdot I_{\text{rr}} \approx 90 \, \text{kW/cm}^2 \).

The multiple proton irradiation technique as described in chapter 6.2.2 brings a significantly improved diode performance with respect to snappiness under both resistive and inductive switching conditions in
Figure 8.6: Measured reverse recovery characteristic of a conventional $p^+\& e^-$-irradiated device in a clamped inductive switching mode with a snappy recovery at $V_{\text{clamp}} = 2800\, V, I_F = 6\, A/cm^2$.

Figure 8.7: Measured reverse recovery characteristics of a double proton-irradiated device in a clamped inductive switching mode ($V_{\text{clamp}} = 3800\, V$ and $3900\, V, I_F = 6\, A/cm^2$).
comparison to the combined proton and electron irradiation. Additionally, as already mentioned in chapter 6.2.2, the safe operating area of the double proton-irradiated device shows an increase - by a factor of 2 to 4 - in peak power handling capability as compared to devices with combined p⁺&e⁻ irradiation as can be seen in Fig. 3.11.
Chapter 9

Conclusion

9.1 Major Results

It has been demonstrated that the multiple proton irradiation technique leads to a significantly improved diode performance with respect to snappiness under both resistive and inductive switching conditions in comparison to the classical lifetime engineering, namely the combined proton and electron irradiation. In addition, the safe operating area of the double proton-irradiated device shows an increase - by a factor of 2 to 4 - in peak power handling capability as compared to devices with combined p⁺&e⁻-irradiation.

It has been shown that a 1-dimensional computer simulation employing lifetime profiles can be used to model the device performance and to explain the physical processes of a diode undergoing turn-off. The excellent agreement of simulated and measured turn-off characteristics allows a reliable prediction of the device performance and avoids extensive trial-and-error experimentation.

In addition, two different diode technologies to enhance the reverse recovery performance especially in the demanding conditions of small forward currents, low temperatures and high line voltages have been compared in this thesis. The chosen technologies were the p⁺-emitter reduction and the ion irradiation, both applied on 4500 V full wafer
press-pack diodes. In experimental studies, the ion-irradiated device shows a much better trade-off between static and dynamic losses. At identical static losses, the maximum reverse recovery current is reduced by up to 50% compared to the emitter-reduced structures. Additionally, a softer reverse recovery process at increased line voltage enhances the SOA of the proton-irradiated diode. The physical analysis of the investigated technologies was performed by calibrated mixed-mode computer simulations. It is shown that the ion-irradiated devices have an optimized on-state excess carrier distribution which leads to a faster establishment of the blocking voltage, a lower reverse recovery current and a softer tail phase behavior at the commutation process as compared to the emitter-reduced devices.

Furthermore, a novel concept for lifetime control in fast recovery power diodes was described. The concept is based on ion irradiation through a screen, leading to a well defined partitioning of the energy distribution of the ions. The new technology is capable to create arbitrary lifetime profiles by a single-step ion irradiation. By using a single accelerator arrangement only, the cost demands decrease significantly compared to the double-step ion irradiation. The results of static and dynamic measurements on irradiated fast power diodes show that the new method is fully capable to replace the technique of multiple single-energy ion irradiation.

The new ion irradiation technology guarantees a superior diode performance in terms of a larger SOA and a softer reverse recovery behavior.

9.2 Outlook

There are two major issues which should guide the direction of further work. First, the improvement of the numerical device simulation tool, and secondly, the optimization of the concept of the single-step irradiation technology.

As mentioned above, the device simulation employing lifetime profiles leads to a very good agreement with the measured turn-off characteristics. A further improvement would be an additional simulation tool which computes the respective lifetime distribution only from the
input of the dose and energy of protons and helium ions, the annealing
temperature and the material properties. This tool should addition¬
ally include the data base of the different defect centers resulting from
the ion bombardment and subsequent annealing, as well as the corre¬
sponding temperature-dependent capture cross-sections for holes and
electrons.

Another point is the further optimization of the single-step ion¬
irradiation technology, which should include a more complex geo¬
metry of the dispersion screen (see Fig. 6.10). A higher complexity of
the mask would enable a completely arbitrary lifetime distribution up
to the maximum depth, which would be limited only by the highest
achievable acceleration energy. The arbitrary lifetime profile lays the
basis for a continuous improvement of the device performance for the
respective specific application conditions.
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# Appendix A

## Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$P^+$</td>
<td>Anode region of a P-i-N diode.</td>
</tr>
<tr>
<td>$N^+$</td>
<td>Cathode region of a P-i-N diode.</td>
</tr>
<tr>
<td>$n^-$</td>
<td>Base region of a P-i-N diode.</td>
</tr>
<tr>
<td>$n_i$</td>
<td>Intrinsic carrier concentration.</td>
</tr>
<tr>
<td>$n, p$</td>
<td>Concentration of electrons, holes.</td>
</tr>
<tr>
<td>$\tau_e, \tau_h$</td>
<td>Electron, hole lifetime in the base region in case of high injection.</td>
</tr>
<tr>
<td>$d$</td>
<td>Total device thickness.</td>
</tr>
<tr>
<td>$V_{on}$</td>
<td>On-state voltage drop.</td>
</tr>
<tr>
<td>$V_{fr}$</td>
<td>Forward Recovery Voltage.</td>
</tr>
<tr>
<td>$I_F$</td>
<td>Forward current.</td>
</tr>
<tr>
<td>$I_{rr}$</td>
<td>Reverse recovery current.</td>
</tr>
<tr>
<td>$I_{rrm}$</td>
<td>Maximum reverse recovery current.</td>
</tr>
<tr>
<td>$i_n, i_h$</td>
<td>Electron, hole current density.</td>
</tr>
<tr>
<td>$t_a$</td>
<td>Time period from current zero-crossing to the maximum reverse current.</td>
</tr>
<tr>
<td>$t_b$</td>
<td>Time period from the maximum reverse current to a reverse current density of 10% of $I_{rrm}$.</td>
</tr>
<tr>
<td>$t_{rr}$</td>
<td>Reverse recovery current time ($t_{rr} = t_a + t_b$).</td>
</tr>
<tr>
<td>$S$</td>
<td>Softness factor calculated as $S = \frac{t_h}{t_a}$.</td>
</tr>
<tr>
<td>$Q_{rr}$</td>
<td>Extracted charge during turn-off.</td>
</tr>
<tr>
<td>$\mu_n, \mu_h$</td>
<td>Mobilities of electrons and holes, respectively.</td>
</tr>
<tr>
<td>$\phi$</td>
<td>Electrostatic Potential.</td>
</tr>
<tr>
<td>$\varepsilon_s$</td>
<td>Dielectric constant.</td>
</tr>
<tr>
<td>$E$</td>
<td>Electric field.</td>
</tr>
</tbody>
</table>
Bibliography


Curriculum Vitae

I was born in Munich, Germany, on May 24, 1972. After finishing high school at the Burkhart-Gymnasium in Mallersdorf-Paffenberg in 1991, I enrolled in Technical Physics at the Technical University Munich. In 1996 I worked on my thesis paper at the German Aerospace Research Establishment in Oberpfaffenhofen, Germany. In the spring of 1997, I received a M.Sc. in Physics (Diplom-Physiker Univ.) and then joined the Integrated Systems Laboratory of the Swiss Federal Institute of Technology, Switzerland. At the ETH Zurich I was employed as a research and teaching assistant in the area of high power semiconductor devices. During three years I worked on a joint project with ABB Semiconductors Ltd. dealing with Fast Recovery High Power Rectifiers.