Large Area Fast Recovery Diode with Very High SOA Capability for IGCT Applications

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Abstract

A large area (>50 cm^2) fast recovery 4.5 kV silicon diode with very low leakage current and high SOA up to 140 ^{o}C was developed for IGCT applications. The silicon design and lifetime control has also been optimized for soft reverse recovery and high cosmic ray withstanding capability of 100 FIT at 2.8 kV. Furthermore, a defect peak of ion irradiation shielded from the reverse bias space charge region by anode buffer combined with electron irradiation were used for shaping the ON-state plasma and reduction of reverse recovery losses. In addition to low leakage currents, the new design provides a strong anode for high ruggedness during reverse recovery without a di/dt choke up to 10 kA/µs. The diode parameters are compared for low- and high-energy electron irradiations in terms of leakage current, temperature coefficient of the forward voltage drop, technology curve V_F vs. E_{rec}, softness of reverse recovery and surge current.

1. Introduction

High SOA IGCTs for state-of-the-art voltage source inverters have increased their current handling capability from around 3.5kA to over 5 kA at a 2.8 kV dc link voltage [1]. Since the IGCT have the potential to operate above 125 ^{o}C, the complementary free wheeling and neutral point clamping diodes have to follow this trend, if placed into a common stack. This requires to turn-off higher currents at the same di/dt and dc link voltage, and at higher temperatures. The placement of a diode into the common stack with IGCTs requires also the same package size with 85 mm pole piece. The size of the accompanying diodes can be then close to 4" (> 50 cm^2) and the fast recovery diode design has to cope with very large area scaling.

By increasing the size of a diode, the following parameters can be improved:

The forward voltage drop V_F, the thermal resistance R_{th}, the reverse bias safe operation area RBSOA (lower dynamic avalanche), the forward bias safe operation area FBSOA (lower forward recovery voltage V_{fr} and higher surge current).

Nevertheless, by increasing the size of a diode, the following parameters will be adversely affected:

The leakage current, the temperature coefficient of forward voltage drop V_F, the reverse recovery losses E_{rec}, charge Q_{rr}, and softness.

Fig. 1. Large area fast recovery diode with 85 mm pole piece.

In this paper we present the physical principles and design features one has to apply in order to cope with the deterioration of the electrical parameters when the diode area is increased significantly. By doing so, the electrical behaviour of the 4.5 kV fast recovery diode is shown to satisfy the needs of high-power IGCTs up to 140 ^{o}C.

2. Device parameters

2.1. Leakage Current

Fig.2 (left) shows the results from high-temperature reverse bias test (HTRB), in which a diode is biased at 3.6 kV at elevated temperature. The leakage current was registered for every 5 ^{o}C after several hours in order to determine, whether thermal run-away takes place (see failure point in red). The graph shows that for the free-floating silicon configuration employed with a diode area above 50 cm^2, the safe operation at a given temperature requires that the leakage current is not higher than 50 mA.

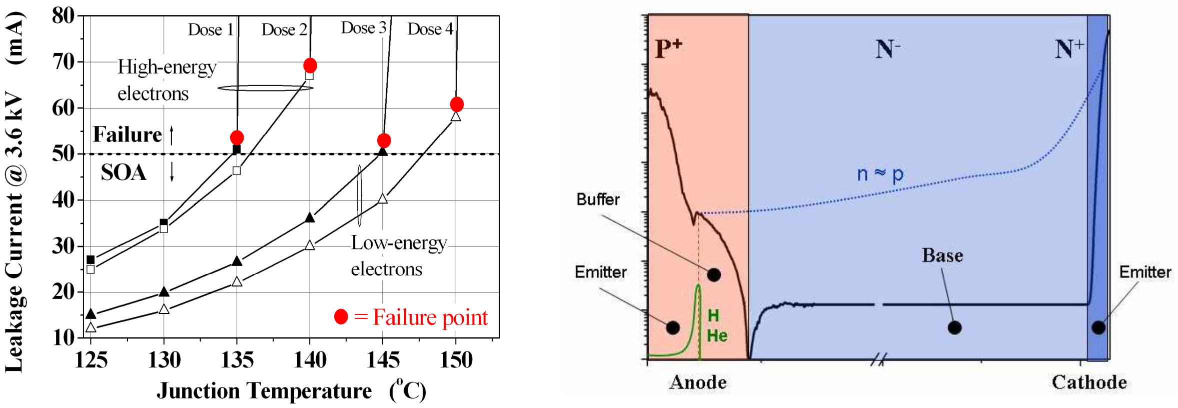


Fig. 2. Leakage current vs. junction temperature (left). Local lifetime control concept at anode (right).

Fast recovery P-i-N diodes require an intensive recombination lifetime control in order to reduce the reverse recovery losses E_{rec} and achieve high RBSOA capability. As a result, relatively high concentrations of deep levels are introduced into the silicon bulk with subsequent reductions of recombination lifetime levels and increased leakage currents. The impact of deep levels placed in the space charge region (SCR) of a reverse biased diode on leakage current is given by eq. (1)

$$I = A \cdot e \int_{0}^{SCR} N_T \cdot \frac{e_n \cdot e_p}{e_n + e_p} \quad , \qquad (1)$$

where A is the diode area, *e* is the electron charge, N_T the concentration of deep levels and e_n and e_p are the emission rates of electrons and holes, respectively. This means that the deep levels without any impact on the leakage current are the ones outside the SCR. Such levels are used for the local lifetime control of anode regions by ion irradiation in order to reduce reverse recovery peak power and voltage oscillations. This is due to the fact that they are shielded from the electric field by the anode buffer shown in Fig.2 (right). Practically, only the tail of the SCR is allowed to reach the peak defect region at the nominal breakdown voltage of 4.5 kV, so that the increase in leakage current after ion irradiation is minimized.

On the other hand, for setting the recombination lifetime in the bulk, electron irradiation is employed. In this case, the deep levels are placed in the whole SCR, and will therefore cause the dominant increase of leakage current. The minimization of the leakage current will then require careful consideration of the effective emission rates $(e_n.e_p)/(e_n+e_p)$ in eq.(1)) of the deep levels created by the electron irradiation. Since the annealing temperature after irradiation is below 300 ^{o}C, the dominant deep levels are the single acceptor level of divacancy V-V (E_C - 0.42 eV) and the acceptor level of vacancy-oxygen pair V-O (E_C - 0.16 eV). The divacancies, which control the lifetime at low-level injection, causes much higher leakage currents than the V-O pairs, which control the high-level lifetime. This can be compensated by taking into account the fact that the production rate of the V-V relative to that of the V-O decreases with decreasing irradiation energy [2, 3]. For lower energies of electron irradiation, the leakage current is lower in spite of the fact that a higher irradiation dose is needed in order to achieve the same reduction of recovery losses. This reflects in Fig.3, which compares the leakage current vs. electron irradiation dose for Low- (LEE) and High-Energy Electron irradiation (HEE) in the range of doses resulting in similar recovery losses. Thanks to a twofold reduction of the leakage current after the LEE compared to that of the HEE one, the diode with LEE can safely operate at 140 °C (see Fig.2).

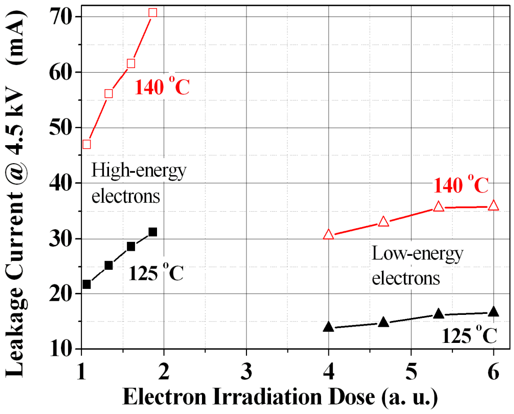


Fig. 3. Leakage current vs. electron irradiation dose for low- and high-energy electron irradiations.

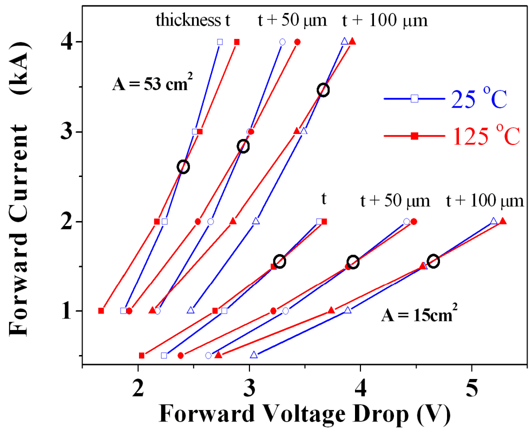


Fig. 4. Forward I-V curves of combined ion and electron irradiated diodes measured at 25 and 125 °C for different areas A and thicknesses t .

2.2. Temperature Coefficient of Forward Voltage Drop V_F

The purpose of increasing the diode area is to decrease the forward voltage drop V_F. The dominant portion of V_F is that of the thick electron irradiated low-doped n-base, where mobility μ and lifetime τ are the dominant temperature dependent components according to the following formula [4, 5]

$$V_{base} \approx \frac{1}{\mu(T,n) \cdot \tau(T,n)} \quad . \qquad (2)$$

While μ(T, n) always monotonously decreases with increasing temperature and carrier concentration, τ(T, n) can increase or decrease with increasing temperature and carrier concentration according to the specific behaviour of the introduced deep levels. The mutual behaviour of the functions μ(T, n) and τ(T, n) determines the point at which the low temperature forward I-V curve crosses the high temperature curve. Below and above the crossing point, the temperature coefficient of the forward voltage drop V_F is negative and positive, respectively. In principal, the crossing point current is at higher level with increasing n-base thicknesses t and larger areas A (see Fig.4). Note that the increase of the crossing point with increasing thickness is much stronger in the large area diode. In these diodes, the crossing point is already very high before irradiation as is illustrated in Fig.5. After ion irradiation into the anode buffer, the crossing point decreases, and subsequently becoming higher again after the electron irradiation.

On one hand, the μ(T, n) decreases with increasing temperature independently of deep levels in the range of applied irradiation doses. On the other hand, the τ(T, n) rises more strongly with increasing temperature when a higher concentration of shallower deep levels (e.g. V-O instead of V-V) is present. This occurs for example when diodes are annealed above 300 °C or when the energy of electron irradiation is decreased from the HEE level to that of LEE. Higher concentrations of shallower (lower leakage current) levels will then result in the temperature coefficient V_F becoming more negative, i.e. it takes up the crossing point current to higher currents. At high doses of the LEE, the crossing point disappears as is shown in Fig.5 (right), which is drawn for the HEE and LEE devices with equal reverse recovery losses. This means that the large area devices subjected to the LEE, which have very low leakage currents up to higher temperatures, are not suitable for paralleling. On the other hand, this issue is not a problem of low area diodes, such as in the case of chip diodes with $A \approx 1\ cm^2$, which have in principle a low crossing point current level.

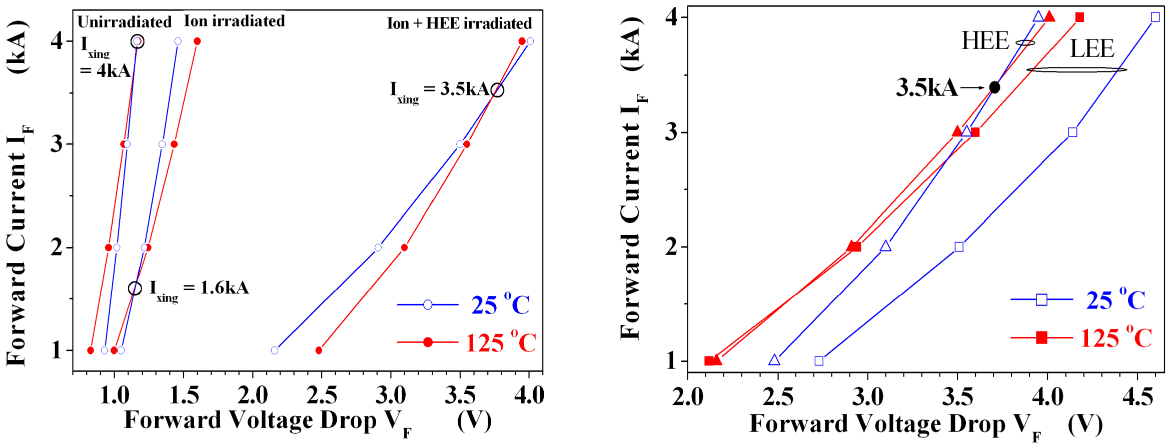
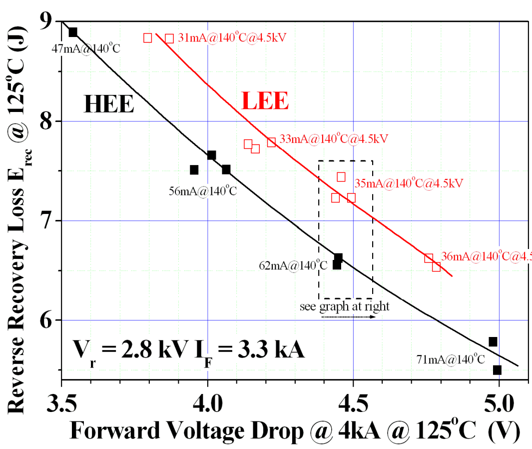


Fig. 5. Forward I-V curves of unirradiated, ion irradiated and combined ion and HEE diodes of the same area $A = 53\ cm^2$ (left). Forward I-V curves of combined ion and electron irradiated diodes with different energies of electron irradiation, namely HEE and LEE (right).

2.3. Reverse recovery

The diode for high power IGCT applications has to withstand the currents levels above 6 kA with subsequent turn-off at a 2.8 kV dc link voltage. In addition, at the same dc link voltage, the diode has to safely turn-off at current densities well below $1\ A/cm^2$. Since the guarantee of cosmic ray withstanding capability of 100 FIT at 2.8 kV dictates the usage of the starting silicon specification with a relatively high resistivity, excessive demands are laid on the design for soft recovery. For this purpose, the lifetime control and n-base thickness had to be optimized at the same time.



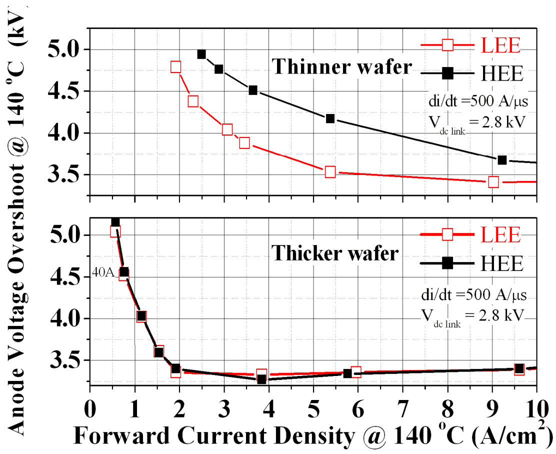


Fig. 6. Technology curve of combined ion and HEE vs. LEE irradiated diodes. Leakage current measured at 4.5 kV @ 140 °C is labeled for every group.

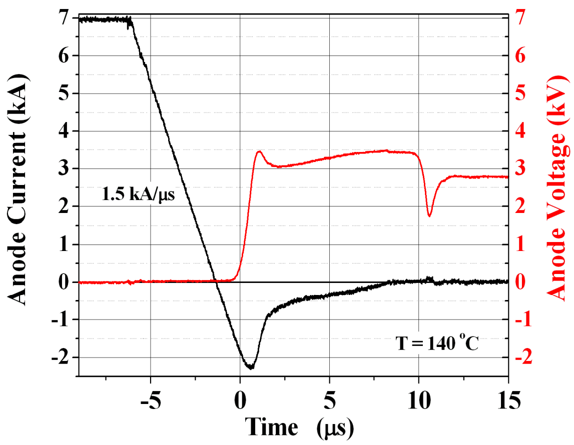
Fig. 7. Voltage overshoot vs. current density. Bottom: devices highlighted by dashed rectangle in Fig.5. Top: thinner devices with softer behavior of LEE ones.

The ion irradiation into the anode buffer (Fig.2 right) is a very efficient mean for making the diode recovery softer without decreasing SOA and with only a very little increase in V_F. To suppress the dynamic avalanche and reduce the reverse recovery loss E_{rec}, the electron irradiation is used. The low-energy electron irradiation gives a slightly worse technology curve (see Fig.6), but then it also provides much lower leakage currents and improved softness, especially if thinner devices are used. This is due to the fact that low energy irradiation controls the carrier lifetime locally and leaves more excess carriers prior to turn-off at the cathode side. Fig.7 shows the peak anode voltage (voltage overshoot) versus the anode current density. For the dc link voltage of 2.8 kV at high current densities, overshoot voltages are observed between 3.4 and 3.5 kV (see Fig.8), which are given by the clamping diode circuit. In addition, we have additional overshoots caused by the snap-off of the diode current at lower current densities, which cause unwanted oscillations of voltage and current. For the devices from Fig.7 (top) they take place below 5 A/cm^2 and from Fig.7 (bottom) below 1.5 A/cm^2.

Although the thicker n-base increases V_F, it can provide improved softness with less lifetime killing. For the same softness, the V_f of a thicker device can be then lower than that of the thinner one. In such a case, both the HEE and LEE give similar softness as shown in Fig.7 (bottom) for the devices depicted by the dashed line in the Fig.6. Fig.7 represents the worst case in terms of di/dt and temperature. Below 100 ^{o}C and towards higher di/dts the oscillations start only below 0.5 A/cm^2 at 2.8 kV dc voltage.

3. Device performance

Using the design principles mentioned above, diodes were processed on 4-inch silicon wafers and cut to the diameter of 91 mm. The leakage current was obtained below 40 mA at 140 ^{o}C thus giving sufficient margin for reliable operation, if any short-term temperature excursion above this limit occurs. The forward voltage drop is that of the technology curve in Fig.6. The diode has a rectangular single-pulse SOA of 3.2 kV and 7 kA up to 140 ^{o}C and di/dt ≈ 1.5 kA/µs (see Fig.8 left). The measurements above 7 kA were not performed due to the limitation of current source.



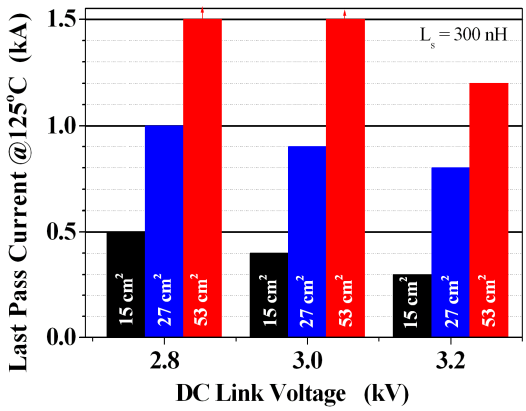


Fig. 8. Reverse recovery at 2.8 kV from I_F = 7 kA at 140 ^{o}C. (left). SOA under reverse recovery with di/dt→ 8 -10 kA/µs limited only by IGCT and L_S vs. dc link voltage with diode area as a parameter (right).

The prominent advantage of a large diode area is the very high maximal turn-off current during reverse recovery without a di/dt choke, when the di/dt grows with an increasing forward current towards 10 kA/µs. Fig.8 (right) shows this capability versus diode area and dc link voltage. All the diodes have the same doping profiles and differ only in the size of the active area. Since the diode presented in this paper has the largest area A ≈ 53 cm^2, it achieves the last pass turn-off current above 1.5 kA at 2.8 – 3.0 kV dc link voltage.

The fact that the temperature coeffcient V_F of large area diodes is negative up to high current levels (see Fig. 5) might become an issue since large-area devices could have problems under surge current conditions due to a stronger current localization. The counter-clockwise rotation of the I-V locus supports this assumption (see Fig.9 left), especially because it was also measured for devices with crossing point current levels down to 2.5 kA. However, Fig.9 right shows the value of the last pass surge current to be independent of the irradiation technology used and strongly correlating with the value of V_F. This means that the surge current capability is driven by the overall power losses (heat) generated during overloading and not by the temperature coefficient V_F. More detailed explanation of this feature was provided by a visual inspection of the wear-out pattern of aluminium metallization when approaching the failure current. The investigation shows that the surge current is evenly distributed along the whole device perimeter at its inner side. The localisation of current takes place only during failure and always in the bulk. A straightforward way to increase the maximal surge current I_{FSM} in a diode is therefore to decrease the V_F. The increase of device thickness while keeping the same or even lower V_F would bring an additional improvement as illustrated in Fig.9.

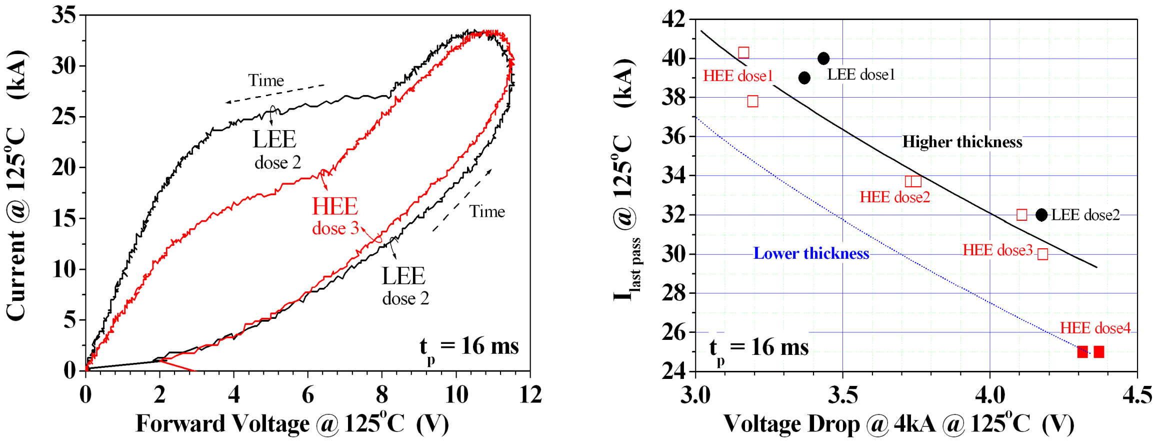


Fig. 9. I-V locus of HEE and LEE devices with equal V_F measured with a half-sine pulse width t_p = 16 ms at 125 °C during failure (left) Last pass surge current vs. forward voltage drop V_F for LEE and HEE devices with different thicknesses and irradiation doses (right).

4. Conclusions

A new large area fast recovery diode with low leakage currents, soft recovery behaviour, high current handling capability and cosmic ray withstanding capability of 100 FIT at 2.8 kV was presented. The improved performance will enable the diode to operate in a common stack with high SOA IGCTs without compromising the operating temperature. Common scaling design challenges of large area silicon diodes, such as excessive leakage current levels and limited softness of reverse recovery, have been overcome by using optimized carrier lifetime control and device dimensions. The RBSOA with constant di/dt in the range between 0.5 and 1.5 kA/µs is rectangular up to 7 kA and 3.2 kV @ 140 °C. In addition, the strong diode anode profile in terms of injection efficiency and sufficient softness during reverse recovery provides the rectangular RBSOA with di/dt capabilities up to 10 kA/µs up to 1.5 kA @ 3.0 kV @ 125 °C.

5. References

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