Large Area 6.5 kV Fast Recovery Diode with Cathode shorts for Very High Current Handling Capability

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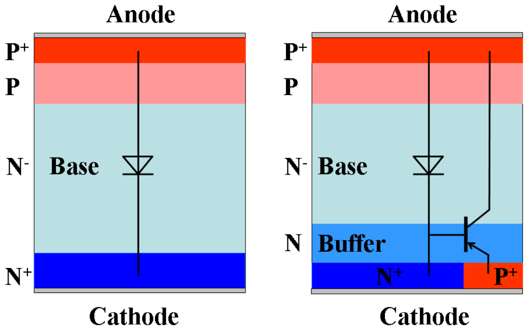
Abstract

Large-area silicon P-i-N diodes (V_{RRM} = 6.5 kV, I_{FAV} » 1.5 ¸ 2 kA, A > 53 cm^2) for the applications employing high power IGCTs were produced with cathode shorts. The aim is to conserve the softness under reverse recovery, while using thinner silicon for a better technology curve between the static and dynamic losses compared to existing designs. Since the new design can reduce around 10% of the original device thickness while achieving the same softness, fast recovery diodes with increased power handling capability can be achieved for the demanding applications with 4 kV DC link. A specific diode design with the cathode shorts is shown to provide a slightly better technology curve even for the same silicon thickness.

1. Introduction

To achieve breakdown voltages as high as 6.5 kV while matching the required cosmic ray withstanding capability, designers have to use a starting silicon with a high resistivity specification. In fast recovery diodes, also the wafer thickness must be sufficiently high to avoid voltage oscillations (snap-off). As a result, the ON-state and switching losses are much higher compared to lower voltage classes. As this reduces the maximal output current in the application and increases the associated reliability concerns, high-voltage diodes are less employed when compared to those of lower voltage classes. The aim of this work is to demonstrate that this paradigm can be shifted by using a diode with cathode shorts (Fig.1), which will allow us to reduce the silicon thickness and achieve a much better technology curve while maintaining other parameters at the same level.



a) Classic b) New

Fig.1: Classical PIN diode (a) and new PIN diode with the P^+ cathode shorts and N buffer (b).

The design of the new diode is based on the concept of the P^+ shorts at the cathode side, which was originally proposed in [1] and demonstrated for the chip diodes in [2]. The P^+ shorts inject additional holes through the PNP transistor action (Fig.1) at the tail phase of the reverse recovery. Depending on a particular design and operating conditions, the injected holes can prevent the current from a sudden fall-off, which would otherwise cause the voltage overshoots. Hence, the resulting device becomes softer.

Except for the choice of the starting silicon wafer, the whole design of state-of-the-art PIN diodes takes place at the anode [3]. The cathode shorts have brought a design instrument which can be employed independently of the anode design. Their application enables one to make an additional improvement of existing designs which is sufficient for a next generation device. The particular benefits are demonstrated below on the large-area fast recovery diode.

2. Experimental

Large area (A » 53 cm^2) PIN diodes with nominal breakdown voltage of 6.5 kV were processed from the (111) float zone neutron transmutation doped 4" silicon wafers. The double diffused anode doping profile was optimized to meet the overall demands on the static and dynamic parameters of both the classical and new diodes. The classical diode was processed with three different thicknesses, the new diode only with the lowest one. The higher thickness of the classical diode enabled us to achieve the same softness during reverse recovery as with the new device with cathode shorts.

The cathode of the classical PIN diode was made by a single diffusion from $POCl_3$. The cathode of the new PIN diode was provided with the P^+ shorts in an area which occupies less than 10 % of the total cathode area. The required blocking capability is secured by the N-type buffer (Fig.1). The role of this buffer is to prevent the electric field from reaching the P+ emitter of the PNP transistor at reverse bias. The buffer manifests itself in a lower leakage current at lower reverse voltages (Fig.2). A higher surface concentration of the buffer can reduce the leakage current at the nominal breakdown voltage. On the other hand, a too low surface concentration would lead to the loss of blocking capability. The actual breakdown voltage is given by the anode p-n junction and its termination. In this case it is 7.5 kV at room temperature for both the classical and new devices. This means that no reduction of breakdown voltage takes place due to the buffer in favour of the dynamic parameters (softness). The margin of 1 kV provides a sufficient reserve in blocking down to the lowest operation temperatures and against the process variations.

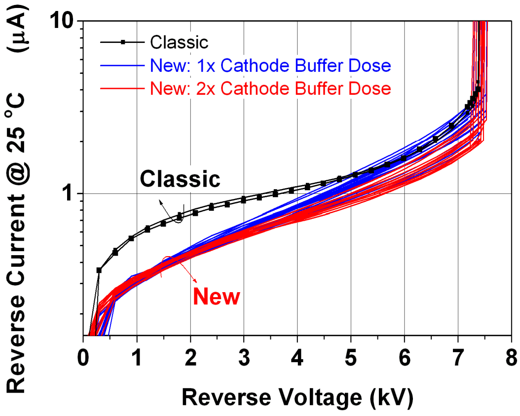


Fig.2: Reverse I-V curves of the classical and new diodes. N-buffer surface concentration is a parameter.

The local lifetime control by ion irradiation was used to reduce the peak power and to improve the softness during reverse recovery [4]. On top of that, four different doses of electron irradiation were selected to obtain a representative technology curve between the static and dynamic parameters. These doses represent multiples of the minimal dose denoted as “1x”. The same parameters of the lifetime control are used when the new and classical diodes are compared.

3. Results and Discussion

Since the P^+ shorts consume a portion of the cathode area, the forward voltage drop V_f of the new diode slightly increases (Fig.3). This difference grows with the increasing dose of electron irradiation. The higher V_f due to the reduced area of the N^+ region has been mentioned as a principal drawback of the concept with cathode shorts in [5]. However, it is not the forward voltage drop alone, but the technology curve between the ON-state V_f and reverse recovery losses E_{rec} which is the deciding technological factor. The technology curves for the classical and new diodes are compared in Fig.4, where the reverse recovery losses were evaluated for V_r = 3.8 kV, I_f = 2.5 kA, di/dt = 1 kA/ms and

T = 125 °C. The figure demonstrates that the cathode shorts can bring a slightly better technology curve, even if the same thickness of the starting silicon is used. For such an example, the difference in the recovery losses E_{rec} amounts to 9 % for V_f » 3V at 2.5kA and T = 140 °C. This trend is valid for the range of the electron irradiation doses for which is the forward voltage drop V_f below 4 V. This range is important for the circuits with the IGCTs which operate at the switching frequencies below f = 300 Hz.

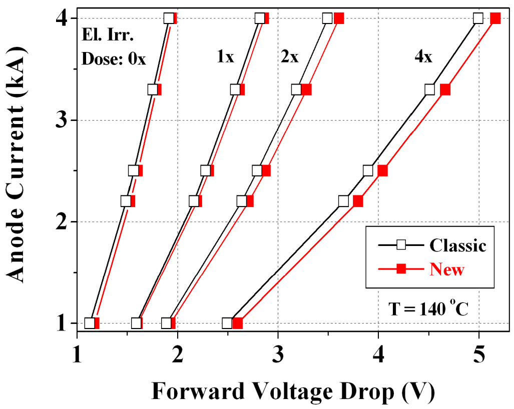


Fig.3: Forward I-V curves of the classical and new diodes measured at the devices with identical thicknesses. The dose of the electron irradiation is the varied parameter.

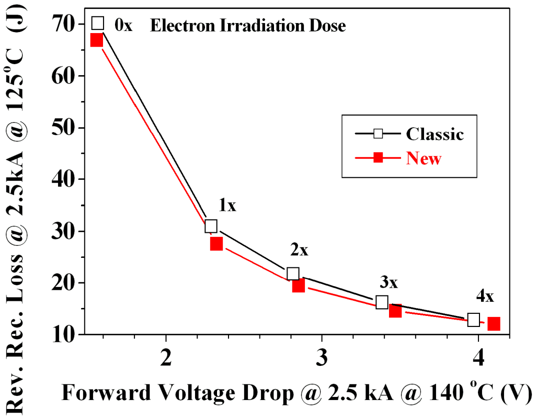


Fig.4: Technology curves E_{rec} vs V_f. of the classical and new diodes with identical silicon thicknesses. The measurement has been carried out at the free-wheeling position in the circuit with an IGCT.

Fig.5 shows that the slightly better technology curve of the new diode is given by a shorter tail time. In this period, the anode voltage is above the dc link voltage due to the operation of the clamping circuit and the contribution of a little tail current to the overall recovery losses is therefore not negligible. The longer tail time of the classical diode is given by a higher total amount of the electron-hole plasma at the cathode side. If this plasma is considerably reduced using a high dose of the electron irradiation, the difference between the classical and new diodes disappears. Their technology curves then merge into the common one as we can see in Fig.4 for the electron irradiation dose “4x”.

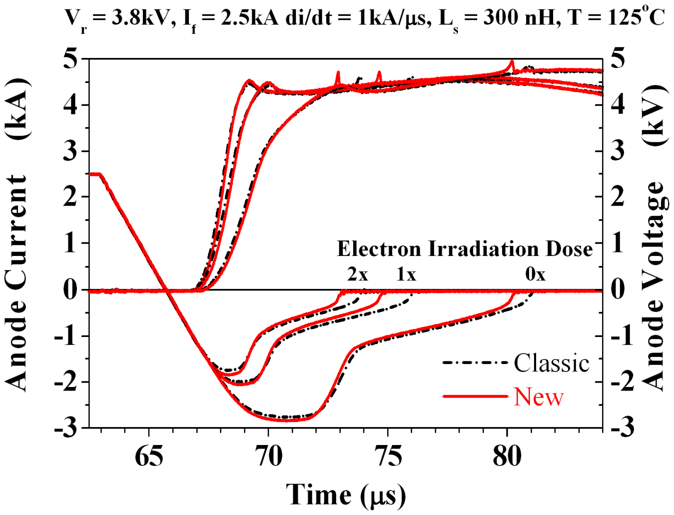


Fig.5: Reverse recovery of the classical and new diodes of equivalent thicknesses measured at T=125 °C.

Figs.6a) and b) compare the classical and new diodes of the same thickness and size during reverse recovery under low current densities (J_f » 5 A/cm^2). The beneficial effect of the cathode shorts on diode softness is obvious. The classical device provides soft recovery only for the very low doses of electron irradiation, for which the reverse recovery losses E_{rec} are too high (dose “1x” in Fig.4). For the highest dose of the electron irradiation, the voltage overshoot is already approaching the breakdown voltage specification. An operation at lower currents is dangerous for the diode itself and for the other parallel connected components as well. Contrarily, the new diode shows only a negligible oscillations of current. The voltage overshoots caused by the chop-off of the anode current at the end of the tail phase remain at the level of the overshoot given by the maximal reverse recovery current. In addition, the influence of the electron irradiation is small.

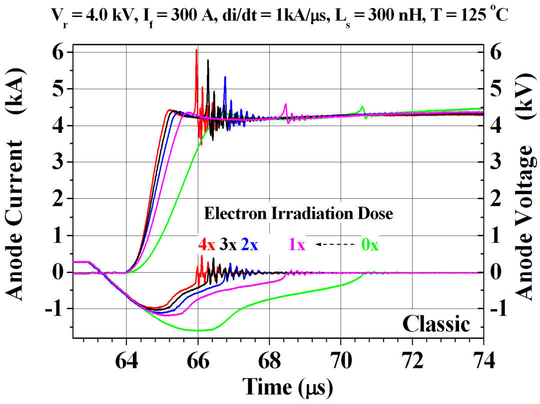


Fig.6a: Reverse recovery of the classical diode. The dose of the electron irradiation is the varied parameter.

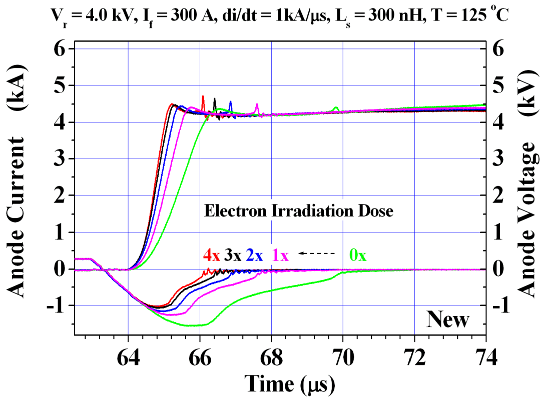


Fig.6b: Reverse recovery of the new diode. The dose of the electron irradiation is the varied parameter.

The snappy behavior of the classical diode can be eliminated only by the increased device thickness. Fig.7 shows the improvement of the softness of the classical diode when the original thicknesses t from Fig.6 is increased two times by 6.5 %. The dose of the electron irradiation "2x" represents the minimal dose for which a reasonable recovery loss of »20 J can be achieved. The comparison of the voltage overshoot at the tail phase between the classical and new diodes shows, that the classical one must be at least by 10% thicker than the new one in order to achieve the same softness. Fig.8 then shows how this reflects on the technology curves. For the equivalent softness and a typical value of V_f » 3 V at I_f = 2.5 kA, the recovery losses E_{rec} of the new diode can be reduced by »40%.

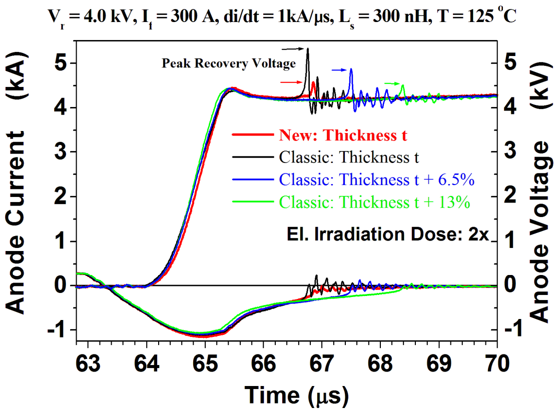


Fig.7: Reverse recovery for the electron irradiation dose 2x. The thickness of the classical device is the varied parameter.

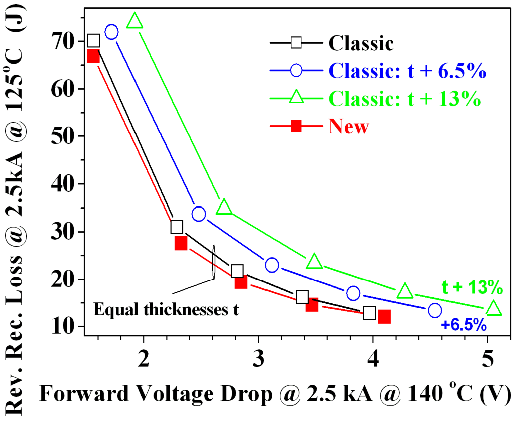


Fig.8: Technology curves E_{rec} vs V_f. of the classical and new diodes. The thickness of the classical device is the varied parameter.

Reliable operation of diodes requires a safe operation to close to zero currents. Considering the conditions of practice, like the signal to noise ratio, it is possible to measure the diodes down to the range between 0.1 and 0.5 A/cm^2. Since the softness at reverse recovery is temperature dependant, the whole range of operational temperatures must be taken into account. A self-contained overview is achieved, when the voltage overshoot called also peak recovery voltage (see the arrows in Fig.7) is evaluated to a zero forward current. Figs.9a) and b) compare the current dependence of the peak recovery voltage at room and maximal operation temperature T_{jmax} = 140 °C for the dose of electron irradiation “2x”. The softness of the classical diode decreases slightly with growing temperature. On the contrary, the softness of the new diode decreases strongly with decreasing temperature. It is the cathode shorts of the new diode in combination with the electron irradiation what makes the diode more snappy at low temperatures. This is demonstrated in Fig.10, where the new diodes with and without the electron irradiation are compared. It implies an excellent and nearly temperature independent softness of the shorted diode, if no electron irradiation is applied. The growing dose of the electron irradiation disrupts the ideal behaviour.

While the worst case for the classical diode appears at a high temperature, which is not necessarily at T = 140 °C, that of the new diode occurs at a room or a lower temperature. Combining together, the classical diode has to be at least 6.5% thicker to achieve the same softness as the new device in the whole range of operating temperatures.

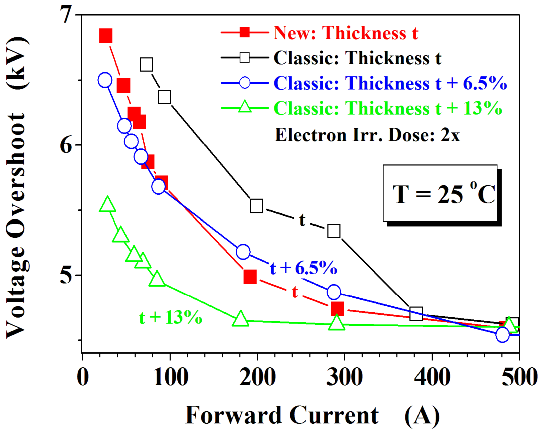


Fig.9a): Voltage overshoot at reverse recovery vs. forward current for the electron irradiation dose 2x. The thickness of the classical device is the varied parameter. V_{DC} = 4.1 kV, di/dt = 1.2 kA/ms, T = 25 °C.

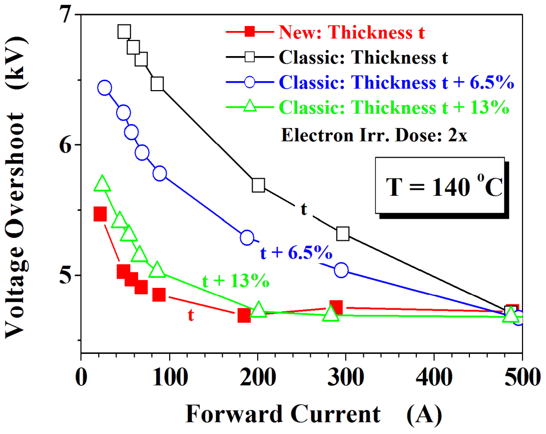


Fig.9b): Voltage overshoot at reverse recovery vs. forward current for the electron irradiation dose 2x. The thickness of the classical device is the varied parameter. V_{DC} = 4.1 kV, di/dt = 1.2 kA/ms, T = 140 °C.

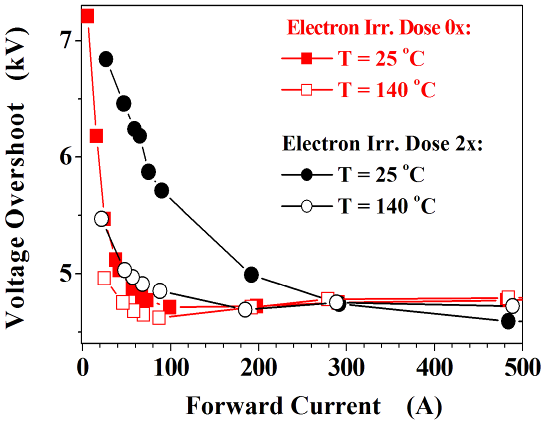


Fig.10: Voltage overshoot at reverse recovery vs. forward current for the electron irradiation doses “0x” and “2x” of the new diode at T = 25 °C and T = 140 °C. V_{DC} = 4.1 kV, di/dt = 1.2 kA/ms.

4. Conclusions

A fully functional large area fast recovery diode with cathode shorts for improved softness of the reverse recovery has been demonstrated. We have shown that, if the original concept of cathode shorts is properly optimized, the technology curve can be significantly improved ($\geq$ 20%) by using thinner silicon than the classical diode.

A positive aspect of the concept of shorts is that it can improve the technology curve even without decreasing the thickness of the starting wafer. An adverse aspect is that the benefit of the shorting structure is disrupted by the increasing dose of the electron irradiation. This feature has then been compensated by a further increased efficiency of the shorts according to the concrete situation.

The importance of the work consists in the fact that the new diode of the 6.5 kV voltage class has the increased power handling capability, which can satisfy the demands of the future applications of the IGCT applications with the 4 kV DC link voltage up to the $T_{jmax} = 140\ ^{o}C$.

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