Crossing Point Current of Electron and Proton Irradiated Power P-i-N Diodes

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The crossing point current of forward I-V curves (I_{Xing}) at 25 and 125°C was measured and simulated for 4.5kV/320A silicon power P-i-N diode irradiated by electron, proton and combined electron-proton irradiation. The proton and electron irradiation are shown eto decrease the magnitude of I_{Xing} which is beneficial for paralleling of diodes under surge conditions. With increasing irradiation dose this effect saturates. High doses of combined electron-proton treatment can even lead to an increased magnitude of I_{Xing} above that of the unirradiated device. To achieve agreement of electro-thermal simulation with experiment, temperature dependence of the capture cross sections σ_n and σ_p of the deep level dominant in condition of heavy injection had to be taken into account. With the aid of simulation, the dependencies I_{Xing} vs. dose are explained.

1. INTRODUCTION

High current power modules comprise parallel connected diodes in which a homogeneous distribution of current is an important issue, especially in surge conditions. In this respect, a positive temperature coefficient of the diode forward voltage drop TCV_F improves the homogeneity of the current distribution. However, at low currents, the power P-i-N diode always possesses negative TCV_F which switches to positive TCV_F at certain current level. The corresponding current level is usually referred to as the crossing point current I_{Xing}. This point basically appears because there is built-in potential decrease with growing temperature which dominates the forward I-V curve at lower currents. At higher currents, when V_F is dominated by the voltage drop across the low-doped base region, the effect of decreasing mobility with growing temperature takes over and the crossing point appears.

Since a lower magnitude of the crossing point current I_{Xing} facilitates the above mentioned paralleling of devices [1], the design considerations should take into account the impact of process parameters on magnitude of I_{Xing}. In this respect, the decreasing injection efficiency of anode emitter [1, 2] and decreasing size of devices [3] were found helpful. Lifetime issues were also partly accounted for. Reduced SRH lifetime in general was found to decrease the magnitude of I_{Xing} [2]. On the contrary, lifetime killing by means of platinum doping [1] was reported to increase the current I_{Xing}. To our knowledge, there are no reports on influence of irradiation controlled lifetime on the magnitude of I_{Xing}.

In most of applications, power diode is repetitively loaded by high currents and voltages, thus working close to the Safe Operating Area limit. For such exposure, application of lifetime killing techniques is absolutely necessary to reduce the turn-off losses and improve other relevant dynamic parameters and characteristics. For this reason, every bipolar high-power diode is subject to some lifetime treatment. One of the widely used lifetime killing technique is the electron irradiation, because of easy control, no demands on thermal budget and off-line nature. The state-of-the-art approach is the proton irradiation, because it keeps all the pluses of the electron irradiation and, on the top of it, it brings a precise spatially localised control of lifetime. Nowadays, both the proton [4] and combined electron-proton irradiation techniques [5] are of primary importance. Influence of these techniques on the magnitude of I_{Xing} is presented on the basis of both the measurement and simulation of I-V curves at 25 and 125°C.

II. THEORY

Killing of the lifetime means controlled introduction of various deep energy levels into semiconductor band-gap to enhance the excess carrier recombination. Irradiation by means of electron, protons or alpha particles creates up to ten deep energetic levels in the silicon band-gap. Electronic behaviour of the i-*th* deep level depends on energetic position within the band-gap E_{Ti}, concentration of levels N_{Ti}, and capture cross-sections for electrons σ_{ni} and holes $\sigma_{pi.}$ The last two parameters are related to the parameters of the Shockley-Read-Hall model as

$$\tau_{n0i} = 1/(\sigma_{ni} \bullet v_{thn} \bullet N_{Ti}) = 1/(C_{ni} \bullet N_{Ti}) \quad (1)$$

$$\tau_{p0i} = 1/(\sigma_{pi} \bullet v_{thp} \bullet N_{Ti}) = 1/(C_{pi} \bullet N_{Ti}) \quad (2)$$

Here the temperature dependent parameters are the thermal

$$v_{thn} = \sqrt{\frac{3kT}{m_n}} \text{ and } v_{thp} = \sqrt{\frac{3kT}{m_p}} \quad (3)$$

velocities of electrons and holes resp. and the capture cross-sections for electrons and holes $\sigma_{ni} \sim f(T)$ and $\sigma_{pi} \sim f(T)$, resp. For non-radiative capture at deep levels, where the lowest states are separated from band edge by more than a few phonon energies, the energy of captured electron is most likely to be released by the emission of phonons according to the multiphonon emission model [6]. In this model, the capture cross section is thermally activated and grows with temperature according to the formula [6, 7]

$$s_{ni} = s_{ni0} \cdot e^{-\frac{E_{ni0}}{kT}}, \quad s_{pi} = s_{pi0} \cdot e^{-\frac{E_{pi0}}{kT}} \quad (4)$$

where σ_{ni0} (σ_{pi0}) is the constant proportional to the frequency coefficient of the multiphonon transition probability and E_{ni0} (E_{pi0}) is the barrier height that the electron has to overcome in order to be captured.

The effect of *n* individual deep levels is superimposed in the equation for the SRH recombination rate

$$R = \sum_{j=1}^{n} \frac{p \cdot n - n_i^2}{t_{n0j}\,(p + p_{1j}) + t_{p0j}\,(n + n_{1j})} \qquad (5),$$

where

$$n_{1j} = N_C \cdot e^{\frac{E_{Tj} - E_C}{kT}} \qquad (7)$$

$$p_{1j} = N_V \cdot e^{\frac{E_V - E_{Tj}}{kT}} \qquad (6)$$

where n_i is intrinsic carrier concentration, and N_C and N_V are the effective density of states in the conduction and valence bands, respectively. Parameters of the levels introduced by irradiation treatments and considered in the device simulation presented in this paper are summarized in Tab.1.

III. EXPERIMENTAL

Fast recovery P^+PNN^+ diodes (V_{RRM}=4.5kV, I_{FAV}=320A) from production of ABB Semiconductors AG were used in this study. The starting material is the 240Ωcm n-type float zone silicon. Diodes were irradiated by protons, electrons and combination of both. The energy of proton irradiation, which was performed with doses of 2, 4, and 8×10^{11}cm^{-2}, was chosen to place the defect peak in the anode junction area, which is the most interesting from the application viewpoint [12]. To account for the influence of position of the defect peak in the n-base, the devices were also subjected to the double energy proton irradiation. In this case the first defect peak was that of the single energy proton irradiation above, while the second one was placed close to the middle of the n-base. Regarding the electron irradiation, doses up to 2.6×10^{13} cm^{-2} covered the interval of practical importance. The I-V curves of unirradiated and irradiated diodes were measured at both 25 and 125^{o}C.

For simulation, the device simulator ATLAS from Silvaco was configured to solve the coupled Poisson, continuity, heat-flow and circuit equations [13]. Regarding to models of mobility, impact ionization, Auger recombination and band-gap narrowing, the standard models and parameter settings were used. The mobility model accounted for the phonon, doping, and carrier-carrier scattering.

A special attention was paid for modeling of deep levels. For this purpose, the multi-level SRH model with parameters of individual levels was calibrated for the diode under consideration. The background lifetime of the unirradiated device was adjusted through homogenous spatial distribution of the mid-gap deep level E_C-0.54eV the exact position of which is not important for the case of forward I-V curves. Deep levels generated by the proton irradiation in the n-type float zone silicon were represented by that of the Tab.1 [8]. From these levels, the single-negatively charged state of the divacancy named E4 dominates the low-injection lifetime, while the high-injection lifetime is dominated by the vacancy-oxygen complex named E1. Consequently, the calibration was focused mainly on parameters E_{Ti}, σ_{ni}, σ_{pi}, and N_{Ti} of the two dominant deep levels E1 and E4 [10]. To obtain the non-uniform spatial distribution $N_{Ti}(x)$ resulting from the proton irradiation, fairly well known procedure, which is based on usage the Monte Carlo simulation code TRIM and subsequent re-calculation of spatial distribution of primary defects to that of the secondary ones [11], was used. In this respect, the accuracy of concentration ratio between the levels E1 and E4, which depends on material type (n- or p-type), doping level, etc., is of major importance.

The two dominant deep levels E1 and E4 generated by electron irradiation in the low-doped n-type and p-type float zone silicon are shown in Tab.1 [7, 9]. These levels are of the same type and impact as that of the protons. However, for the level E1, a different capture cross-section and its temperature dependence had to be used to match the measured I-V curves. The concentration ratio between the levels E1 and E4, which depends mainly on the irradiation energy, was extracted from Fig.1 which was constructed both from the published data [7] and our DLTS measurements [10]. For irradiation energy of our samples, this ratio was two times higher than that of the proton irradiated devices described above

In non-isothermal conditions, as is the case of I-V curves measured at different temperatures, the temperature dependence of σ_n and σ_p of the two dominant levels E1 and E4 plays a primary role. Unfortunately, because of experimental difficulties, these dependencies are not known for the radiation defects in silicon in the temperature interval under study (25 – 125^{o}C) and thus cannot be compared with theoretical model (4). As the crossing point appears at high injection, the temperature dependence of the level E1 plays the dominant role. For this level, the cross-sections for electrons and holes at both 25 and 125^{o}C were fitted from experimental I-V curves, because the extrapolation from the low-temperature DLTS values did not give good results. For the level E4 the extrapolated values from ref. [9] were sufficient.

IV. RESULTS

In Fig.2, the close agreement of the measured and simulated I-V curves of unirradiated diode at 25^{o}C was achieved by fitting the concentration N_T and capture cross-sections σ_n(25^{o}C) and σ_p(25^{o}C) of the mid-gap level and the diode series resistance r_S(25^{o}C). The agreement at 125^{o}C resulted from adjustment of the capture coefficients and temperature dependence of r_S. The latter was calculated using the temperature coefficient of resistance for pure aluminum which is about 3.9×10^{-3} K^{-1}. The parameters σ_n(25^{o}C), σ_p(125^{o}C), r_S(25^{o}C), and r_S(125^{o}C) were further used for simulation of irradiated devices. Although the simulated and measured curves of unirradiated devices are in very good agreement, the simulated magnitude of I_{Xing} (878A) differs from the measured one (725A) about 20%. This is given by the fact that the I-V curves were not fitted to agree only close the crossing point, but within the whole range 0 - 3000A. Since they cross each other at a very small angle, a slight deviation of measured and simulated curves brings a high difference in I_{Xing}.

Fig.3 shows the simulated and measured dependencies of the crossing point current I_{Xing} on the dose of the proton irradiation. For temperature of 25^{o}C and the dose of 2×10^{11}cm^{-2}, the agreement between the measured and simulated I-V curves was achieved by fitting the capture cross-sections σ_n(25^{o}C) and σ_p(25^{o}C) of the level E1 which dominates high injection. For the rest of levels, the extrapolated magnitudes of $\sigma_n(25^oC)$ and $\sigma_p(25^oC)$ were used. For temperature of 125°C and for the dose of $2\times10^{11}cm^{-2}$, the measured and simulated I-V curves were identical only if an increase of electron and hole capture cross sections magnitudes σ_n and σ_p with increasing temperature according to the equation (4) was considered for the level E1 with parameters $\sigma_{n0} = \sigma_{p0} = 5\times10^{-12}cm^2$ and $E_{n0} = E_{p0} = 0.14eV$. For the rest of doses, only the scaling of deep level concentration was applied while the rest of parameters and their temperature dependencies were that of the dose $2\times10^{11}cm^{-2}$.

The crossing point current I_{Xing} was also measured for the case of two successive proton irradiations into the p-type anode and region close to the middle of the n-base of the same device (double peak proton irradiation). Fig.3 shows measured results for two devices with equal positions of the defect peaks, but different anode to the n-base defect peak height ratio by factor of two. The impact of the proton irradiation was found of the same nature, i.e. I_{Xing} decreases with increasing proton irradiation dose. However, a growing defect peak concentration in the n-base increases I_{Xing} for a given integrated irradiation dose.

Fig.4 shows the simulated and measured dependencies of the crossing point current I_{Xing} on the dose of electron irradiation. For simulation purposes, the capture cross-sections and their temperature dependencies were fitted in the same way as for the proton irradiated devices, but with quantitatively different results for the level E1. The temperature behavior of lifetime parameters was dominated by capture cross-section of holes for which the values $\sigma_{p0} = 2\times10^{-12}cm^2$ and $E_{p0} = 0.04eV$ were found. The crossing point current was found to decrease with irradiation dose up to the magnitude of $1.7\times10^{13}cm^{-2}$, approximately. Above this dose, the curve I_{Xing} vs. dose turns back.

Fig.5 shows the measured dependencies of the crossing point current I_{Xing} on the dose of electron irradiation for combined electron-proton irradiated devices. Dependencies are shown for three doses of proton irradiation: $2\times10^{11}cm^{-2}$, $4\times10^{11}cm^{-2}$, and $8\times10^{11}cm^{-2}$. Defect peak is placed to the anode region, i.e. irradiation energy is equal to that of circles in Fig.3. The increase of I_{Xing} with growing electron irradiation dose is more pronounced compared to linear combination of Fig.3 and Fig.4. Simulation using the same defect parameters as in Figs.3 and 4 gave qualitatively similar dependencies.

V. DISCUSSION

Analysis of I-V curves implies that the crossing point appears due to the temperature increase of the voltage drop V_{base} across the low-doped n-base region at higher currents. Since this drop is inversely proportional to the product of the effective mobility and lifetime $V_{base} \sim 1/(\mu\cdot\tau)$, it is expected that the reduction of the lifetime with irradiation dose will multiply the effect of temperature dependent mobility and the magnitude of I_{Xing} will decrease. Results obtained from raw simulations assuming temperature independence of carrier lifetime [2] are in agreement with this assumption. Idea of temperature independent lifetime is valid only for the ideal recombination centre with energetic position in the middle of the bandgap where the temperature increase of carrier re-emission from the centre is negligible. However, this is not the case of recombination levels introduced by electron or proton irradiation. The dominant deep level affecting recombination at high current densities, the acceptor level of vacancy-oxygen pair E1, is located close to the conduction band (E_C-0.165 eV) and re-emission of captured electrons back to the conduction band, which substantially increases with temperature, will significantly affect the temperature dependence of carrier lifetime. This is illustrated in Fig. 6 which shows the calculated dependence of electron lifetime on carrier concentration and temperature for recombination centers with identical capture coefficients but different position within the bandgap. This figure implies that with increasing energetic distance from the middle of the bandgap, the positive temperature coefficient (PTC) of the lifetime grows and the region with substantial increase shifts towards the higher injection levels. The figure also indicates that for typical carrier concentrations in the base at high current densities (marked as a Region Of Interest) the carrier lifetime of irradiated devices grows with temperature. This grow, which attenuates and can even eliminate the favorable negative temperature coefficient (NTC) of carrier mobility, increases when carrier concentration in the n-base decreases, e.g. due to increased recombination.

Effect of the electron irradiation on the magnitude of I_{Xing} can be explained by means of Fig. 7 which shows the influence of temperature on the reciprocal product of electron mobility and lifetime modified by the electron irradiation. The mobility temperature dependencies are that of the standard models used in the device simulation. The lifetime temperature dependencies are those resulting from fitting the simulation to experiment. The excess electron concentration in cm^{-3} which corresponds to the selected ROI is used as a parameter. The dependencies show steep increase between 25 and 125°C for carrier concentrations above $1x10^{16}cm^{-2}$. This is the case of low irradiation doses when the average carrier concentration in the base does not decrease below a critical value. If the carrier concentration decreases, due to increased irradiation dose the increment decreases and can even become negative. This is the point of substantial grow of the magnitude of I_{Xing}. This is illustrated in Fig.8 which shows the simulated electron concentration in the n-base at forward current 1kA (above I_{Xing}) and temperature 125°C for the three electron irradiation doses from Fig.4 (solid lines). With irradiation dose increasing from a) to c) the electron concentration decreases below the critical value and the curve I_{Xing} vs. dose turns back. If combined with the proton irradiation (dashed lines, irradiation dose $2\times10^{11}cm^{-2}$), the concentration decrease is higher and the turn-back appears at lower electron irradiation dose (see Fig.5).

Since the electron, proton and helium irradiation introduce similar defect structure (the E1/E4 concentration ratio is in the range between 4 to 20 what guarantees the dominant influence of E1) , the effect of irradiation on the magnitude of I_{Xing} will be in principle identical. At low doses, when the reduction of the lifetime does not substantially decrease the excess carrier concentration in the n-base, the magnitude of I_{Xing} decreases. This effect saturates when lifetime reduction decreases carrier concentration to the level where the effect of PTC of lifetime starts to eliminate the NTC of carrier mobility. At high doses, when the PTC of the lifetime becomes dominant due to substantial reduction of the carrier concentrations in the n-base, I_{Xing} starts to grow. This effect is strong for electron irradiation where the lifetime is equally reduced in the whole volume of the device (Fig.3). In the case of proton irradiation with defect peak in the anode, which modifies the n-base carrier distribution only partly (see Fig.8), the saturation effect from Fig.4 was not found for irradiation doses of practical importance. However, when combined with electron irradiation (Fig.5), the saturation effect is strengthened. This is in agreement with the double-energy proton irradiation, where the second peak located deeply in the base more effectively participates in charge reduction, shows lower I_{Xing} than that of the single-energy protons with identical dose.

VI. CONCLUSIONS

The crossing point current of proton irradiated 4.5kV/320A diodes was found to decrease with irradiation dose for the defect peak placed to the p-type anode. For double peak proton irradiation this current decreases as well. For electron irradiation, a monotonous decrease of the crossing point current with irradiation dose was found only up to a certain level. Above this level, the crossing point current decrease is limited. For combined electron-proton irradiation this effect is even more pronounced so that for high electron and proton doses the crossing point current can get over that of unirradiated device. To achieve the lowest crossing point current with optimal magnitudes of relevant static and dynamic diode parameters the double peak proton irradiation is the method of choice.

Agreement of simulated and measured static I-V curves at 25 and 125^{o}C was achieved provided that the positive temperature coefficient of the capture coefficients of the deep level dominant at high injection was assumed in agreement with the multiphonon emission model. This calibration approach can be extended to any kind of dc or transient electro-thermal simulation of proton and electron irradiated power devices thus providing accurate simulation tool for a wide range of operation temperatures. Explanation of the crossing point current dependence on the irradiation dose in this paper is a clear evidence.

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FIGURE CAPTIONS:

Fig.1: Ratio between concentration of deep levels E1 and E4 versus electron irradiation energy.

Fig.2: Measured and simulated I-V curves of unirradiated diode at 25 and 125^{o}C

Fig.3: I_{Xing} vs. the dose of proton irradiation with the defect peak placed to the anode p-region (cubes and circles) and double peak proton irradiation with anode to n-base peak height ratio two times higher for one device (star) compared to the second one (triangle).

Fig.4: : I_{Xing} vs. the dose of electron irradiation

Fig.5: I_{Xing} vs. the dose of electron irradiation measured on devices subjected to combined electron and proton irradiation with the proton irradiation doses 2×10^{11}cm^{-2}, 4×10^{11}cm^{-2}, and 8×10^{11}cm^{-2} identical to those of Fig.3.

Fig.6: The influence of the band gap position of recombination center on excess carrier lifetime.

Fig.7: The temperature dependence of inverse product of mobility and lifetime of electron irradiated device plotted for different levels of excess carrier concentration.

Fig.8: Electron concentration in the n-base at forward current $I_F = 1$kA and temperature 125^{o}C for electron irradiation dose of 8.5×10^{12} (a), 1.7×10^{13} (b), and 2.6×10^{13} cm^{-2} (c) (solid lines). For the electron irradiation combined with the single-energy proton irradiation from Fig.5 (dose 2×10^{11} cm^{-2}) see the dashed lines.

TABLE CAPTIONS:

Tab.1: Deep levels in the float zone n-type silicon considered in the device simulation (T=25^{o}C)