Crossing Point Current of Power P-i-N Diodes: Impact of Lifetime Treatment

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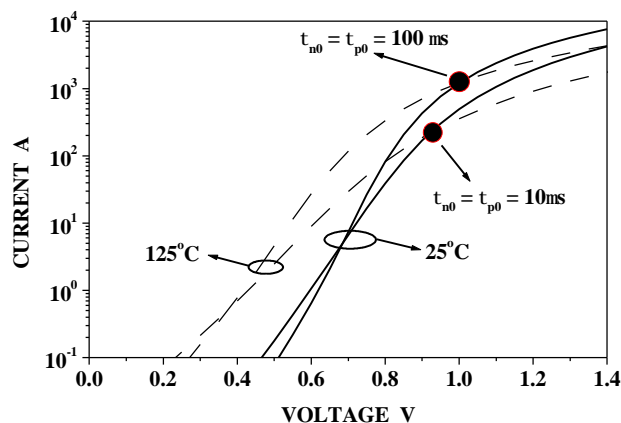
Abstract – **Crossing point current of forward I-V curves at 25 and 125°C was measured and simulated for 4.5kV/320A power P-i-N diodes irradiated by protons. To achieve agreement of electro-thermal simulation with experiment, temperature dependence of the capture coefficients C_n and C_p of the deep levels dominant in condition of heavy injection had to be taken into account. The proton irradiation is shown to decrease the crossing point current which is beneficial for paralleling of diodes under surge conditions.**

I.   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 band-gap narrowing and increase of carrier lifetime with growing temperature which dominates the forward I-V curve at lower currents. At higher currents, 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

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decreasing injection efficiency of anode emitter [1, 2] and decreasing size of devices [3] were found helpful. Lifetime issues were also partly accounted for. On one hand, the lifetime killing based on platinum doping was reported to increase the current I_{Xing} [1]. On the other hand, a decreased current I_{Xing} with reduced SRH lifetime was presented [2]. Although this sounds inconsistent, both the cases are possible. The latter is illustrated in Figs.1 and 2. Fig.1 shows the I-V curves of 4.5kV/320A power P-i-N diode simulated in device simulator ATLAS [4] using the traditional SRH recombination model with the single ideal generation-recombination centre (E_C-0.54eV). For simplicity, the lifetimes t_{n0} and t_{p0}, that represent the background lifetime resulting from high temperature processing, were chosen equal. It is apparent that decreasing lifetimes t_{n0} and t_{p0} decrease the magnitude of I_{Xing} as stated above. Fig.2 shows this fact in a wide range of SRH lifetime magnitudes with temperature coefficient of t_{n0} and t_{p0} as a

parameter.

Fig.1: Simulated I-V curves for various SRH lifetimes

The figure implies the fact that for given lifetimes t_{n0} and t_{p0} at 25°C the negative (positive) temperature coefficient decreases (increases) the magnitude of I_{Xing}. As the temperature coefficient of the background

lifetime is a random result of complex high-temperature processing, there is no way to control it.
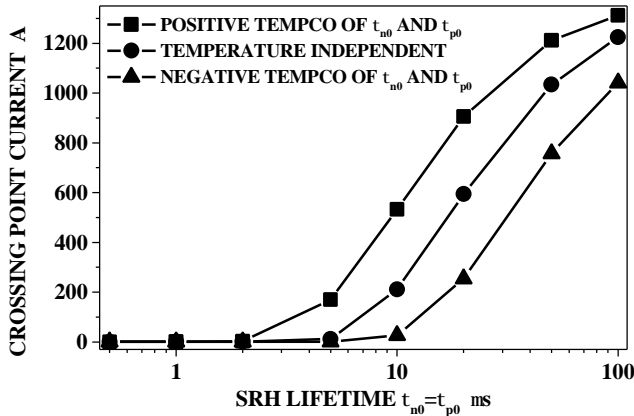

Fig.2: I_{xing} vs. lifetime with temperature coefficient $\pm 3.4 \times 10^{-4}$ /K of t_{n0} and t_{p0} as a parameter

For example, the measured diode in this paper has slightly positive temperature coefficient of the background lifetime represented by the mid-gap level $E_C - 0.54eV$.

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. For this reason, every bipolar high-power diode is subject to some lifetime treatment.

One of the widely used lifetime killing technique is the proton irradiation, because it brings a precise spatially localized control of lifetime with no demands on thermal budget. Influence of this technique on the crossing point current magnitude is presented below.

II. THEORY

Killing of the lifetime means controlled introduction of various deep energy levels. 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 σ_{pi}. The last two parameters are related to the lifetime as

$$\tau_{n0i} = 1/(\sigma_{ni0} \cdot v_{thn} \cdot N_{Ti}) = 1/(C_{ni} \cdot N_{Ti}) \quad (1),$$

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

where $C_{ni} \sim f(T)$ and $C_{pi} \sim f(T)$ are the capture coefficients for electrons and holes, resp., $v_{thn} \sim \sqrt{T}$ and $v_{thp} \sim \sqrt{T}$ are the thermal velocities of electrons and holes. The effect of n individual deep levels is superimposed in the equation for the SRH recombination rate

$$R = \sum_{i=1}^{n} \frac{p \cdot n - n_i^2}{t_{n0i} (p + p_{1i}) + t_{p0i} (n + n_{1i})} \quad (3),$$

$$p_{1i} = N_C \cdot exp(E_V-E_{Ti})/kT, \quad n_{1i} = N_V \cdot exp(E_{Ti}-E_C)/kT,$$

where N_C and N_V are the effective density of states in the conduction and valence bands, respectively.

The proton irradiation is known to generate about ten deep levels (divacancies, vacancy-oxygen pairs, hydrogen-related defects, etc.) in the low-doped n-type float zone silicon [5]. From these levels, the single-negatively charged state of the divacancy located at $E_C-0.42eV$, named E4, dominates the low-injection lifetime. On the other hand, the high-injection lifetime is dominated by the vacancy-oxygen complex located at $E_C-0.164eV$, named E1. Consequently, for accurate device simulation, the parameters E_{Ti}, C_{ni}, C_{pi}, and N_{Ti} of at least the two dominant deep levels E1 and E4 must be known[6]. To obtain the non-uniform spatial distribution $N_{Ti}(x)$ resulting from irradiation, the 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 [7], can be 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.

In non-isothermal conditions, as is the case of I-V curves measured at different temperatures, the temperature dependence of C_n and C_p of the two dominant levels E1 and E4 plays an important role. Unfortunately, because of experimental difficulties, these dependencies are not known in the temperature interval under study. At present, the only way to obtain them is an extrapolation from the low-temperature values [5] which is used in this paper.

III. EXPERIMENTAL

The fast recovery diode 5SDF03D4501 (V_{RRM}=4.5kV, I_{FAV}=320A) from production of ABB Semiconductors AG was used in this study. The diode was irradiated by protons to the doses 2, 4, and 8×10^{11}cm^{-2}. The irradiation energy was chosen to place the defect peak in the anode junction area, which is the most interesting from the application viewpoint [8]. The I-V curves of unirradiated and irradiated diodes were measured at both 25 and 125°C.

For simulation, the device simulator ATLAS from Silvaco was configured to solve the coupled Poisson, continuity, heat-flow and circuit equations [4]. 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. To account for the deep levels, the multi-level SRH model with parameters of individual levels calibrated for the diode under consideration was applied. The background lifetime of the unirradiated device was adjusted through the mid-gap deep level E_C-0.54eV with homogenous spatial distribution. The proton irradiation was governed by seven deep levels with emphasis on the levels E1 and E4.

IV. RESULTS

In Fig.3, the close agreement of the measured and simulated I-V curves at 25°C was achieved by fitting the concentration N_T and capture coefficients C_n(25°C) and C_p(25°C) of the mid-gap level and the diode series resistance r_S(25°C). The agreement at 125°C resulted from adjustment of the capture coefficients and thermal 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 C_n(25°C), C_p(125°C), r_S(25°C), and r_S(125°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}.
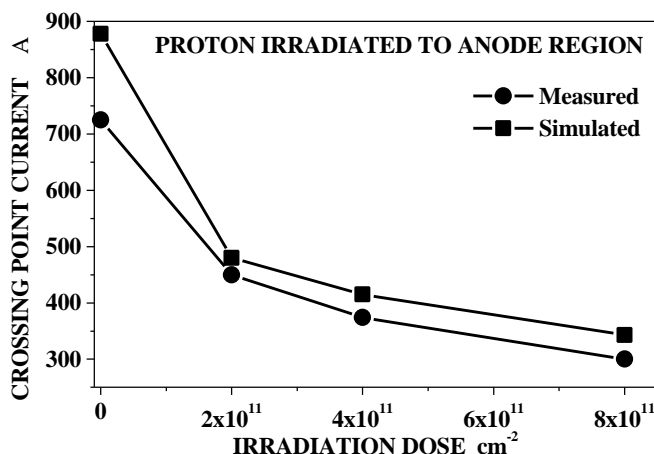
Fig.4 shows the simulated and measured dependencies of the crossing point current I_{Xing} on the dose of proton irradiation. For temperature of 25°C Fig.3: Measured and simulated I-V curves of unirradiated
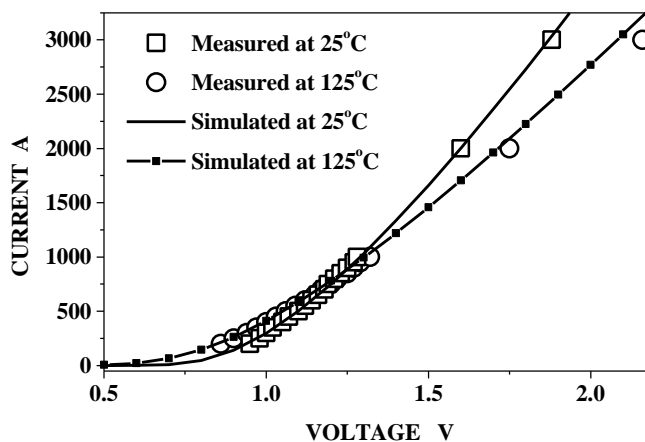
diode at 25 and 125°C

Fig.4: I_{Xing} vs. the dose of proton irradiation with the defect

peak placed to the anode p-region close to the p-n junction

and dose of 2×10^{11}cm^{-2}, the agreement between the measured and simulated I-V curves was achieved by fitting the capture coefficients C_n(25°C) and C_p(25°C) of the level E1 which dominates the high injection. For the rest of levels, the ordinary magnitudes of C_n(25°C) and C_p(25°C) according to our own measurements and literature were used. For temperature of 125°C and for the dose of 2.10^{11}cm^{-2}, the measured and simulated I-V curves were identical only if an appropriate increase of C_n(125°C) and C_p(125°C) of the dominant deep levels E1 and/or E4 with increasing temperature was considered. In qualitative agreement with ref. [5], where the temperature coefficient was measured positive for the

capture coefficients of the two relevant deep levels E1 and E4 at low temperatures, at high temperatures in this work, the same resulted from simulation for any reasonable concentration ratio $N_{TE1}:N_{TE4}$. For the rest of doses, only the scaling of deep levels' concentration was applied while the rest of parameters was kept equal to those received for the dose of 2×10^{11}cm^{-2}.

The crossing point current I_{Xing} was also measured for the case of the diode irradiated into the p-type anode and n-type base. The impact of the proton irradiation was found of the same nature, i.e. I_{Xing} decreases with increasing proton irradiation dose. As the n-base is of different conductivity type and doping level, the dose dependence is different.

IV. DISCUSSION

The crossing point current I_{Xing} decreases with growing proton irradiation dose, i.e. with increasing concentration of deep levels introduced by irradiation. As these concentrations are 10^{14}cm^{-3} as a maximum, they are too low to influence the carrier mobility temperature dependence. On the contrary, the increasing irradiation dose decreases the conductivity modulation of the base and shifts the crossing point to the area of lower currents and higher voltages with consequence of decreasing I_{Xing}.

Influence of deep level energetic distance from the conduction band E_C on resulting lifetime is shown for 25 and 125°C in Fig.5, where situation of the defect peak in the p-anode region is taken into account. Figure implies that with increasing energetic distance from the E_C, impact of a level on the temperature dependence of lifetime decreases. For given lifetime treatment, there is various concentration ratio of individual deep levels. For this is reason, different lifetime killing techniques can increase or decrease the crossing point current according to electrical properties of deep levels which they are introducing.

V. CONCLUSIONS

The crossing point current of proton irradiated devices was found to decrease with irradiation dose for the defect peak placed to the p-type anode and n-base as well. Agreement of simulated and measured static I-V curves at 25 and 125°C was achieved provided that the positive temperature coefficient of the capture coefficients of the dominant deep levels was assumed. This approach can be extended to any kind of dc or transient electro-thermal simulation of

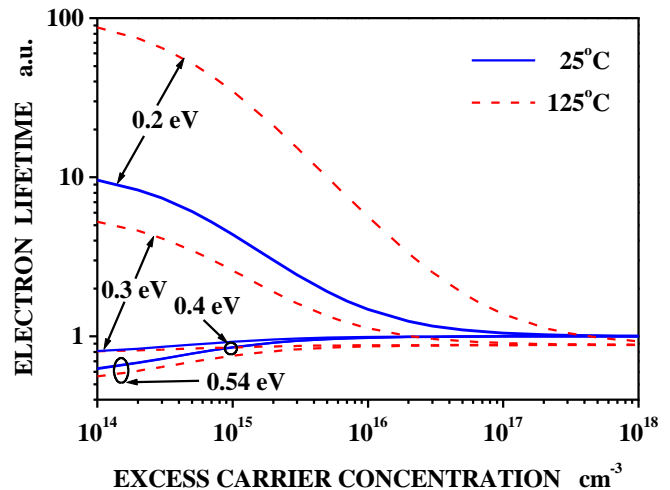proton irradiated power devices thus providing accurate simulation tool for a wide range of operation temperatures.

Fig.5: Influence of energetic position of the deep level on the excess carrier lifetime (σ_{ni}, σ_{pi}, N_{Ti} are constant)

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