Simulation of Proton-Induced Local Lifetime Reduction in 10 kV Diodes

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Abstract—**This paper presents the results of simulation of localized charge carrier lifetime reductions in 10 kV power diodes. These results are compared to experiments with proton irradiation as means for local lifetime reductions. It is shown that also the range straggling inherent in the irradiation process must be taken into account in the simulations.**

I. INTRODUCTION

In production of high-power semiconductors it is nowadays standard practice to reduce the charge carrier lifetime uniformly with the help of electron irradiation. Recently the benefits of localized lifetime reduction by means of proton irradiation have been explored and implemented for various types of thyristors [1]–[3]. The reason why nuclear particles create a nonuniform lifetime is that these particles are stopped in the sample at a depth determined by

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their energy and the lattice damage caused by them appears predominantly at the end of the particle range. The damage distribution is of a Gaussian shape with a skewness towards the surface and broadens for larger penetrating depths due to range straggling. By using combinations of energies and fluences, any lifetime profile can in principle be implemented. In practice, however, the range straggling sets a limit as to how narrow the lifetime reduced regions may be and the skewness of the distribution implies that a "tail" of recombination centers appears all along the ion track.

It is mainly the tradeoff between on-state and turn-off losses that can be improved by the use of proton irradiation as opposed to standard electron irradiation. This is especially true for high power components since they are inherently thicker and the carrier lifetime after processing does not allow for large adjustments with electron irradiation. In this work we explore the applicability of simulation of localized lifetime reduction in order to find an optimum depth of irradiation for 10 kV power diodes. The simulated values of forward voltage drop and reverse charge shows good agreement with experimental values; however, it is necessary to consider the effects of range straggling and the tail of recombination centres along the entire region penetrated by the protons.

II. Experimental

In order to provide an experimental basis against which to test the simulations, a number of diodes of area 6 cm^2, dimensioned to withstand voltages of 10 kV, were produced at ABB Drives' experimental laboratory in Västerås. They were fabricated from 1540 μm thick, n-type silicon (Neutron Transmutation doped) with an initial resistivity of 570 Ωcm. The anode doping concentration profile can be approximated by two Gaussian profiles, one 20 μm deep with a peak value of $4.2 \cdot 10^{21}$ B/cm^3 at the surface, and a second extending 93 μm from the surface and having a peak value of $3.7 \cdot 10^{16}$ Al/cm^3. The cathode emitter is 20 μm deep with a peak value of $3.2 \cdot 10^{19}$ P/cm^3 at the surface. After the diffusion processes the diodes were metallized with a thin conducting layer of aluminium, given a positively bevelled edge and protective edge coating.

The proton irradiations were performed at the tandem accelerator facilities of the The Svedberg laboratory, Uppsala University [4]. Previous experiments show that the region of low carrier lifetime should lie at a depth from the anode surface corresponding to around one third of the device thickness for an optimum improvement of the tradeoff between on-state and switching losses. For this experiment three groups of diodes were irradiated from the anode side to the depths of 350, 450 and 550 μm, respectively, roughly covering the range of the expected optimum depth. The proton energies, determined from TRIM-89 simulations [5], were 6.7, 7.8, and 8.7 MeV, respectively. The fluences were accumulated during three separate irradiations in steps of $3 \cdot 10^9$ cm^{-2}, and forward voltage and reverse recovery charge were recorded after each irradiation. The measurements were performed under room temperature conditions using standard evaluation apparatus. Forward voltage was measured at 1.0 kA and reverse recovery charge was measured at turn-off from 1.0 kA with a 1.0 kA/ms derivative.

III. Simulations

Simulation of the diodes was performed with the one-dimensional program SEMIACE developed at ABB Corporate Research in Västerås. The program evaluates the equilibrium, stationary, and transient solutions to power devices included in a complete circuit. The program used as input the physical characteristics of the experimental diodes including doping profile, element thickness and area, temperature as well as applied current or voltage. In order to reproduce the measured results of the nonirradiated diodes the total carrier lifetime (uniform throughout the diode) was set to 325.0 μs, and the fitted values for the lattice scattering mobilities for electrons and holes was 1448.0 and 437.0 cm^2/s, respectively. The curve which resulted from this fit reproduced well the measured I-V characteristic and total recovery charge of the experimental diodes before irradiation. The values of all parameters except for carrier lifetime were then fixed for the continued calculations of "irradiated" devices. The physical models used in the program can be found in [6], [7]. For simulations of proton irradiation the lifetime was reduced according to the model presented below.

The broadening with greater range of the highly damaged region at the end of the proton range, and the level of the tail in relation to the damage peak maximum have been experimentally investigated using Deep Level Transient Spectroscopy [8], [9]. The carrier lifetime reduction model used for these simulations is an idealized model based on these experimental results. In the model, charge carrier lifetime is reduced from a constant "background" level (corresponding to the diode before irradiation) in proportion to the increased recombination expected from the greater number of defects. The carrier lifetime reduction at the depth with the maximum amount of lattice damage (the proton range) is accomplished by adding an inverted Gaussian, centred at a given irradiation depth, to the "background" lifetime. The Gaussian is also broadened as the irradiation depth increases to account for range straggling, which is expressed in terms of the full width of the Gaussian curve at one half of the maximum carrier lifetime reduction: FWHM = (depth + 50)/20 [μm]. This results, for example, in a FWHM of 20 μm at a depth of 350 μm. A relatively small constant reduction in carrier lifetime, equal to 1/7 of the maximum reduction, has been used to account for the tail region.

IV. Results and Discussion

The calculation results of diodes with localized carrier lifetime reductions are shown in Fig. 1. Each curve consists of a set of points where the x-coordinate is the calculated forward voltage drop (V_t) at a current of 1.0 kA and the y-coordinate is the corresponding calculated recovery charge, Q, as found by integrating the reverse current during turn-off. All the curves have the common point at the upper left which corresponds to an unirradiated diode. As the localized lifetime decreases, corresponding to an increased fluence, the value for Q is reduced and the value of V_t is increased. For comparison the figure also shows the effects of simulated electron irradiation, i.e., a uniform lifetime reduction throughout the diode. Closer examination reveals that the depth which gives the greatest reduction in Q with the smallest increase in V_t is located between 150 and 550 μm. By plotting the value of V_t for a fixed Q as a function of depth it is easier to visualize the location of the minimum. This has been done in Fig. 2 for an arbitrary Q value of 1400 μC. The figure also shows the value of V_t for the simulated electron irradiation which is plotted as a line since the lifetime reduction is not localized to any given depth. Finally, the figure shows the corresponding data from the experiments. From Fig. 2 it can be seen that simulation yields an optimum depth for proton irradiation of 350 μm while the experiment indicates that a depth of 450 μm is optimal, although there are only three points. (Each of the experimental points is a mean of four components and has a standard deviation of about 80 mV.) The slight difference in these depths can be attributed to variations in measurement or to inadequacies

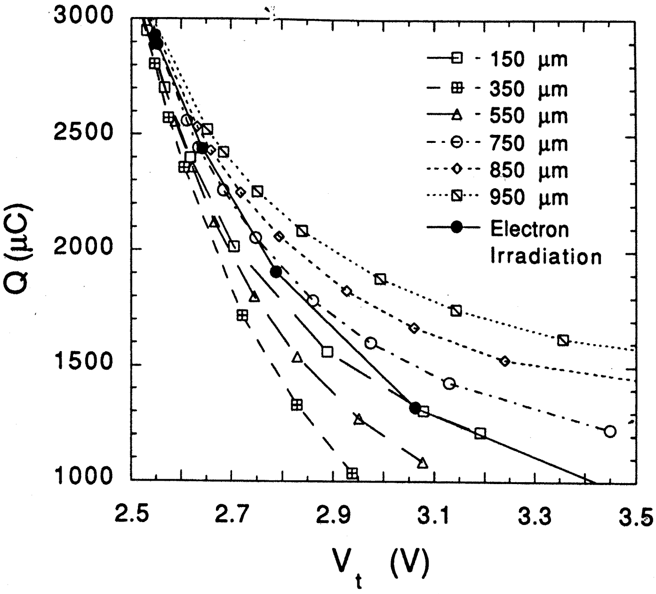

Fig. 1. Simulated Q–V_t curves for localized carrier lifetime reductions centered at given depths. Simulated curve for nonlocalized lifetime reduction shown as electron irradiation. Optimum tradeoff is for curve centered at 350 μm.

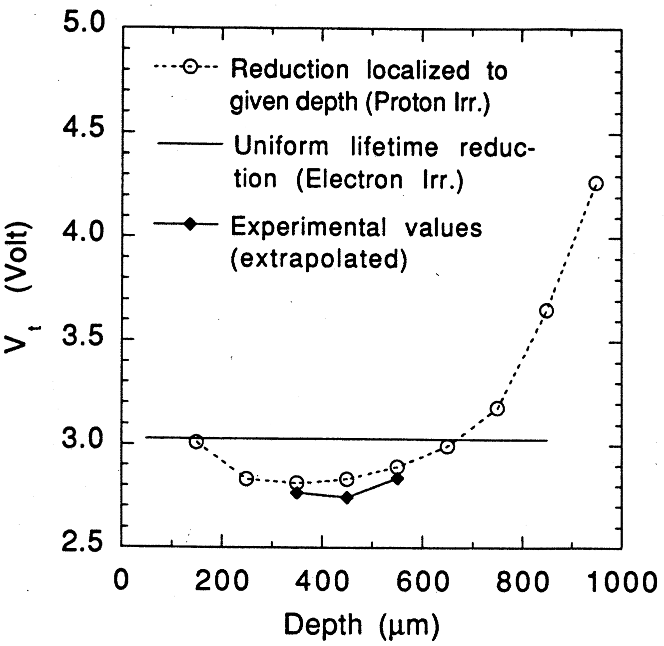

Fig. 2. Simulated and experimental values of V_t corresponding to Q = 1400 μC. The uniform carrier lifetime reduction of electron irradiated diodes is represented with a straight line since it is nonlocalized. Depth is measured from the anode side of the diodes (the side which was irradiated by protons).

of the simplified lifetime model. Nevertheless, the agreement is sufficient to show the benefits of simulating experiments.

Previous experiments with irradiation of thyristors [10] have shown that an even better tradeoff between on state and turn-off losses can be achieved if a combination of proton and electron irradiations, or proton irradiations using two different energies [1], [11], are employed. For these diodes the forward voltage drop would be unacceptable if a deeper proton irradiation was added and the best tradeoff is probably achieved by combining a low fluence proton irradiation 350 μm from the anode, and low fluence electron irradiation. Of course, proton irradiation could also be performed from the cathode side, but the cost in foward voltage drop for these thick devices would be too high.

Temple and Holroyd [12] have also used simulations to optimize the tradeoff between turn-off time and forward voltage drop for devices with local regions of low lifetime. Their conclusion is that the optimum location for a low lifetime region in a p-i-n-diode is at the middle of the low-doped region. However, there are at least two reasons to explain why we find the optimum position closer to the anode. Firstly, the elements in [12] are much faster than the line commuted diodes presented here and optimization in [12] favors switching speed rather than low forward voltage drops. Secondly, they discuss a more hypothetical case without a "tail" of low lifetime between the peak and the implanted surface. If a tail is included, the forward voltage drop increases and their optimum would perhaps also appear closer the irradiated surface.

Although a fairly simple empirical model has been used to simulate the charge carrier lifetime reduction caused by proton irradiation, the computed results are in good agreement with the measured values. A more sophisticated model, taking into account recombination at various levels having certain capture cross sections for electrons and holes according to SRH statistics, may have a larger physical significance but we believe that our results justify the simpler approach. One reason for the good agreement is, of course, that we have not correlated the fluence to the actual lifetime reduction. Instead we have fitted the calculated V_t values to the values measured after the irradiations by varying the amplitude of the Gaussian. However, since the object of the study is to find the optimum position for the lifetime reduced region, it is not necessary to know the exact relation between the proton fluence and lifetime.

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