PROC. 24th INTERNATIONAL CONFERENCE ON MICROELECTRONICS (MIEL 2004), VOL 1, NIŠ, SERBIA AND MONTENEGRO, 16-19 MAY, 2004

Application of Carrier Lifetime Control by Irradiation to 1.2kV NPT IGBTs

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***Abstract*— Device simulation, based on an extended recombination model and previously determined recombination center parameters, serves as design tool for carrier-lifetime controlled, state-of-the-art 1.2kV NPT IGBTs. Homogenous and local recombination center profiles are considered. The sensitivity of important device characteristics to the type of the recombination center profile is investigated in simulation and experiment. A possible application, the improvement of reverse leakage properties of reverse blocking capable NPT IGBTs, is discussed.**

I. INTRODUCTION

The use of irradiation techniques for carrier lifetime control is nowadays a commonly accepted strategy for optimizing power device characteristics. The improvement and optimization of radiated devices is usually done by time- and cost-consuming experiments. Nevertheless, the use of a device simulation tool with an appropriate extended recombination model allows a significant reduction of the necessary experimental efforts. Based on center parameters determined in earlier work [5], [7], [8], the effects of different lifetime profiles on the forward and reverse-recovery characteristics of common planar 1.2kV NPT IGBTs are studied in this work using 2D device simulation. The validity of the results is demonstrated by comparison with measurements taken on manufactured samples. The use of electron irradiation for the reduction of the reverse leakage current of reverse blocking capable IGBTs, due to the influence on the current gain of the parasitic BJT, is studied.

II. RECOMBINATION MODEL

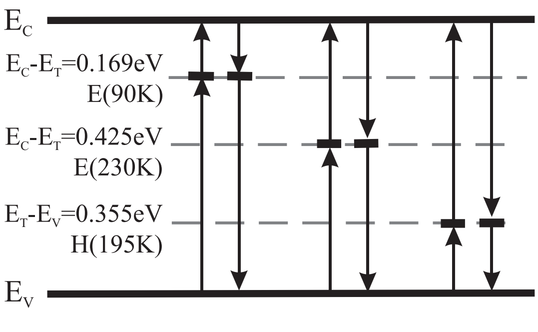

Fig. 1. The Recombination Model

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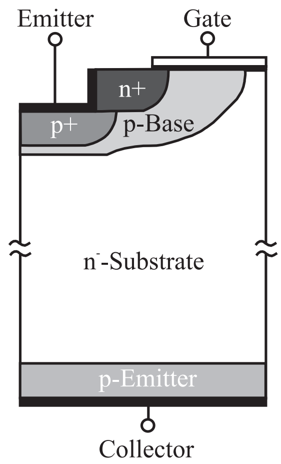

Fig. 2. Basic NPT IGBT Structure

Irradiation generates centers with different energy levels in the band gap of Silicon semiconductors. Each level may act as an effective recombination center where the total recombination rate results from the emission and capture processes of each single level as illustrated in figure 1. The implementation of this extended model, which includes the complete trap dynamics, is fundamental for an appropriate simulation of such devices [2], [10]. Here, the 2D device simulator TeSCA has been used [1]. This simulation system solves the three fundamental semiconductor equations (the Poisson equation as well as the electron and hole current continuity equation). For the consideration of deep traps, additional terms are implemented which consider the charged recombination centers as well as their thermal capture and emission processes. Based on this extended recombination model, the behavior of radiated devices is predicted with qualitatively and quantitatively good results even in case of highly dynamical processes [5], [6], [7]. As shown in figure 1, the radiation-induced centers E(90K), E(230K) and H(195K) have been found and are taken into account for simulations. Electron irradiation results in a homogenous distribution of the recombination centers. In difference, irradiation with protons or helium ions generates a local recombination center profile which follows well the primary damage region. These distributions are approximated by gaussian profiles for the use in device simulation [5].

III. STATE-OF-THE-ART NPT IGBT

A. Device Structure

For the irradiation experiments, it was possible to use manufactured sample wafers of a former development project

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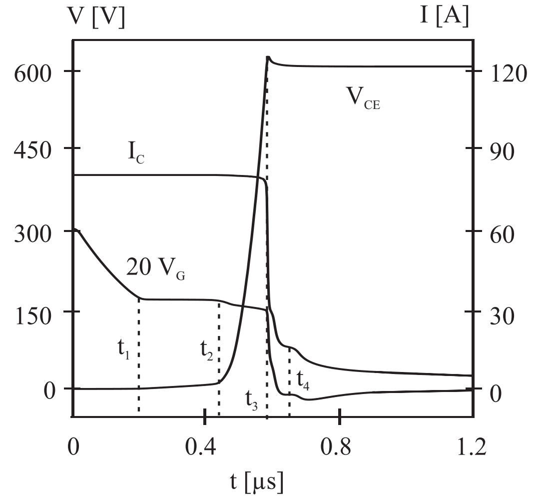

Fig. 3. Turn-off of NPT IGBT

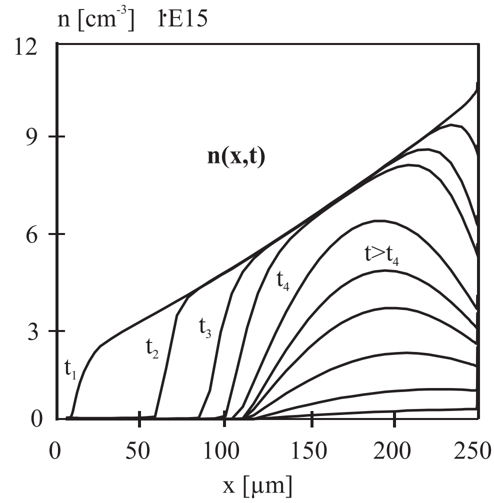

Fig. 4. Carrier Distribution in NPT IGBT during turn-off

[4]. All devices have a common 1.2kV NPT IGBT structure as shown in figure 2. The essential elements of the IGBT cells are a planar gate, a buried p^+-layer and a "vertical" source contact formed through silicon etching. Because of the spacer technology used, the implantation steps for the IGBT cell need no masks. After the fabrication of the top-side IGBT cells, the wafer is thinned by grinding and CMP (chemical-mechanical polishing) in the common way. Finally the p-emitter is implanted from the backside of the device.

All IGBT chips have an active area of app. $0.32cm^2$ and a nominal current of 25A. The wafer thickness is 220μm. Due to a reduced doping of the backside emitter, the forward voltage is slightly larger compared to available devices while the turn-off time is reduced.

B. Carrier Lifetime Profiles

Based on the simulated carrier distribution during the turn-off process of the non-irradiated device, shown in figure 3 and figure 4, different homogenous and local recombination center profiles are considered:

1) No carrier lifetime control (NPT12N)
2) Homogenous lifetime reduction by electron irradiation (NPT12E, figure 5a): Due to the decreased carrier lifetimes, the initial carrier concentration distribution at t_1, equally to the stationary carrier distribution in the devices on-state, is lowered. Consequently, the number of excess carriers is lower which results in a clear increase of the forward voltage and a faster turn-off process. Therefore, turn-off losses are expected to decrease, enabling the use of the device for applications with higher switching frequencies.
3) Shallow recombination center profile by low-energy helium irradiation (NPT12H1, figure 5b): The recombination center peak is placed in the pn-junction region of the backside p-emitter. This reduces the injection efficiency and leads to a lower carrier concentration in the device. Therefore, turn-off losses and turn-off time are reduced while only slightly increasing on-state losses.
4) Deep recombination center profile by high-energy helium irradiation (NPT12H2, figure 5c): As shown in fig. 4, for $t > t_4$ a remaining carrier hill is found with a maximum in a depth of app. 190μm. These carriers are responsible for the tail current which contributes significantly to the turn-off losses of an NPT IGBT. Therefore, the recombination center peak is placed in depth of 190μm to reduce the stored charge. This should result in drastically reduced turn-off losses. Nevertheless, since carrier lifetime is not only reduced in the peak region but also in the region before, on-state losses will increase.

C. Experimental and simulation results

Figures 6 and 7 show the comparison of the IGBTs saturation voltages and of the turn-off losses. As expected, the non-

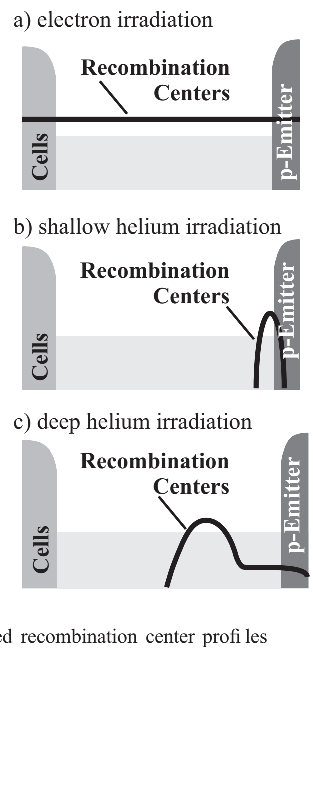

Fig. 5. Investigated recombination center profi les

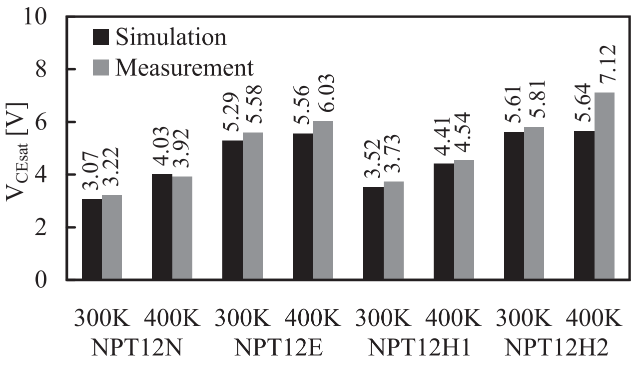

Fig. 6. V_{CEsat} of IGBTs ($V_{GE} = 15V,\ I_C = 25A$)

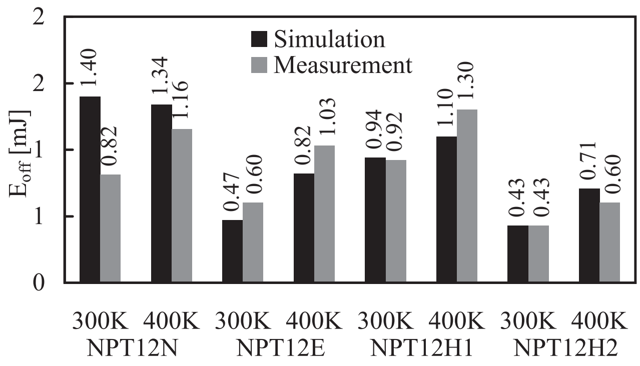

Fig. 7. E_{off} of IGBTs ($V_{DC} = 600V,\ I_C = 15A,\ R_G = 33\Omega$)

radiated device has the lowest V_{CEsat}, followed by the device applied to shallow helium irradiation. The electron-radiated and the deep helium-radiated samples show similar on-state losses except in case of 400K - here, the structure with a deep recombination center profile shows a dramatical increase of the on-state voltage. In case of the turn-off losses, the device NPT12H2 shows a reduction of almost 50% compared with the non-radiated device. The electron-radiated device shows clearly reduced turn-off losses only at room temperature while the reduction is less remarkable at working temperature. Sample NPT12H1 does not fulfill the expectations - the turn-off losses increase in comparison with NPT12N at higher temperature which is in difference with the simulation results. Probably, since the basic structure already owns an emitter with reduced efficiency, the irradiation effect is superimposed by the wafer fluctuations due to the process technology still being in development.

Beside that, the accordance of simulation and experiment is sufficient. Device simulation is capable to support the development and optimization process.

IV. Reverse blocking NPT IGBT

A. Structure of Reverse Blocking IGBT (RB IGBT)

It has been shown in this work, that carrier lifetime control is suitable for the optimization of NPT IGBTs, nevertheless similar results can be realized by a cost-saving variation of the backside doping profile as well. But, carrier lifetime control should be essential for the improvement of NPT IGBTs with reverse blocking capability [3], [9]. Basically, the NPT IGBT is capable to block a negative collector-emitter voltage, but an additional p-layer stop is necessary to prevent a break through of the device as shown in figure 8. The high doping of the surface p^+-region is needed to prevent the latch-up of the parasitic thyristor, but also increases the injection efficiency of the collector of the internal BJT and thereby its current gain. This directly results in an increase of the reverse leakage current which can be a significant problem [9].

B. Leakage Current Improvement by Carrier Lifetime Control

Introduction of carrier lifetime control by electron irradiation in the RB IGBT leads to a decrease of the diffusion length of the carriers and therefore to a reduction of the common emitter current gain. This could be used for a reduction of the reverse leakage current. Nevertheless, the irradiation with high-energy electrons generates different recombination centers within the bandgap. A center with a energetic position close to the middle of the bandgap acts not only as an effective recombination center, but it also causes a high generation current. To prevent an increase of the total leakage current due to an increased generation current, irradiation and annealing parameters have to be chosen carefully. Using an electron irradiation energy of 1MeV and an annealing temperature larger than 330°C, the center which contributes to an increased generation should already anneal out [5].

Figure 9 shows simulation results for the leakage and the reverse leakage current of the NPT IGBT structures NPT12N and NPT12E. Since only the IGBT structure itself is regarded in the device simulation and since the NPT structure is reverse blocking capable, the results support the given considerations. In case of the electron-radiated structure, the reverse leakage current is clearly reduced in comparison with the non-radiated structure.

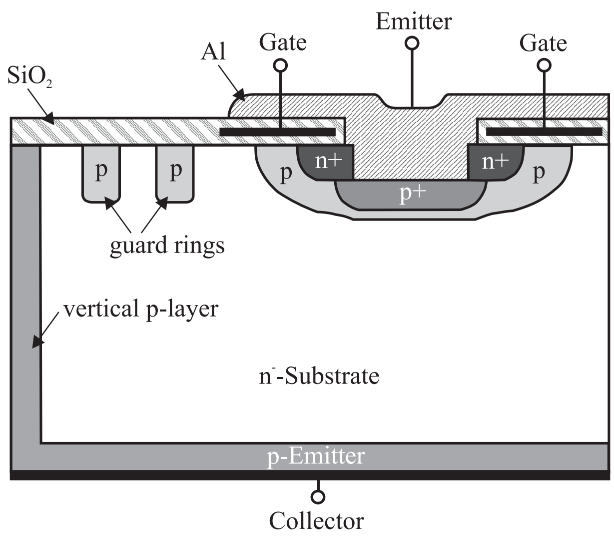

Fig. 8. Basic Structure of Reverse Blocking IGBT

TABLE I

COMPARISON OF CHARACTERISTIC PARAMETERS OF 1.2KV RB IGBT BEFORE AND AFTER ELECTRON IRRADIATION

	T=300K		T=400K	
	standard	radiated	standard	radiated
$I_{RF}(V_{DC} = 1200V)$	24.5nA	34nA	46μA	49μA
$I_{RR}(V_{DC} = -1200V, V_{GE} = 0V)$	-585nA	-180nA	-390μA	-860μA
$V_{CEsat}(V_{GE} = 15V, I_C = 40A)$	2.7V	4.4V	3.3V	5.0V
$E_{off}(V_{DC} = 500V, I_{GE} = 40A, R_G = 22\Omega)$	2.1mJ	0.64mJ	2.49mJ	1.18mJ

C. First experimental results

In a first experiment, manufacturing samples of RB IGBT from IXYS were irradiated with electrons ($E = 1MeV$, $d = 2 \times 10^{14} cm^{-2}$) and subsequently annealed. Table I gives a comparison of first results. A reduction of the reverse leakage current I_{RR} is gained at room temperature, but this effect vanishes at higher temperature. Most probably, not all of the centers which cause a increased generation are annealed out. The saturation voltage of the IGBT is increased, while the turn-off losses are clearly reduced. To meet the saturation voltage of the non-radiated device, the number of recombination centers must be decreased. In a next step, annealing conditions will be improved and the electron irradiation dose reduced in order to fulfill the expectations toward a lower reverse leakage current over the full operating temperature range and toward only slightly increased forward losses.

V. CONCLUSION

In this work, the influence of different recombination center profiles (homogenous, a shallow profile placed at the pn-junction of the backside emitter and a deep profile placed in the region with maximal stored charge at turn-off) on the stationary and turn-off losses is investigated. As expected, a significant reduction of the turn-off losses is feasible by using either a homogenous reduction of carrier lifetime or by a local reduction deep in the n-base region of the IGBT. In case of a reduced emitter efficiency of the backside emitter as result of local carrier lifetime reduction, no improvement was achieved. In all cases, the reduction of turn-off losses was connected with an increase of the forward voltage drop. Nevertheless, the use of these irradiation techniques might be interesting for the realization of fast switching devices or in case of devices with a reduced width of the n$^-$-substrate due to improvements in the manufacturing process. Furthermore, irradiation offers a possibility for an easy adjustment of device parameters in dependence of the targeted application case (especially switching frequency).

Another promising application is found in the improvement of the reverse leakage current in IGBTs with bidirectional blocking capability. It is discussed, that the use of electron irradiation can reduce the reverse leakage current without a noteworthy increase of the forward voltage drop. In a first experiment, the gained improvements were not as expected but results give a first evidence for the chances offered by irradiation technique. For the realisation of a low reverse leakage current without an distinct increase of the conduction losses, the irradiation parameters have to be chosen very carefully.

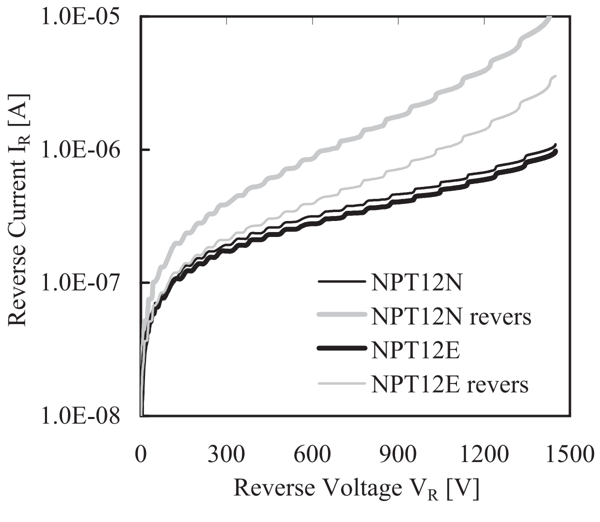

Fig. 9. Simulation of blocking characteristics

ACKNOWLEDGEMENTS

The authors wishes to thank Dr. Lindemann and the IXYS Semiconductor GmbH for providing manufacturing samples of reverse-blocking capable NPT IGBTs for the investigations presented in this paper.

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