FREE-WHEELING DIODES WITH IMPROVED REVERSE RECOVERY BY COMBINED ELECTRON AND PROTON IRRADIATION

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Abstract. Reverse recovery of a P-i-N power diode at high dI/dt is subject to two detrimental effects, i.e. avalanche injection and snap-off. Both the effects can be reduced by a proper application of lifetime engineering. For this purpose, combined proton and electron irradiation was found to be the method of choice. For exact design of irradiation parameters, the device simulation, taking into account the electronic structure of the relevant radiation defects, was used. The beneficial effect of the combined irradiation is presented for a 4.5kV/300A free-wheeling diode.

Keywords. P-i-N diode, reverse recovery, lifetime, proton irradiation, electron irradiation, device simulation.

INTRODUCTION

Recent developments in IGBTs and GCTs brought devices with excellent switching and power handling capabilities. However, in the field of power diodes the development was not adequate. Nowadays, there is an increasing demand on free-wheeling diodes to provide snubberless operation. In general, however, diodes are not as fast, rugged and soft as necessary.

The diode reverse recovery at high voltages and dI/dt is subject to two detrimental effects: i.e. dynamic avalanche and snappy behaviour. These effects are illustrated in Fig.1 for the diode used throughout this paper. The effects can lead to destruction either of the device itself or neighbouring circuitry. Fortunately, there are a few approaches for to improving these characteristics.

The aim of this paper is to present the capabilities of lifetime control for improving diode

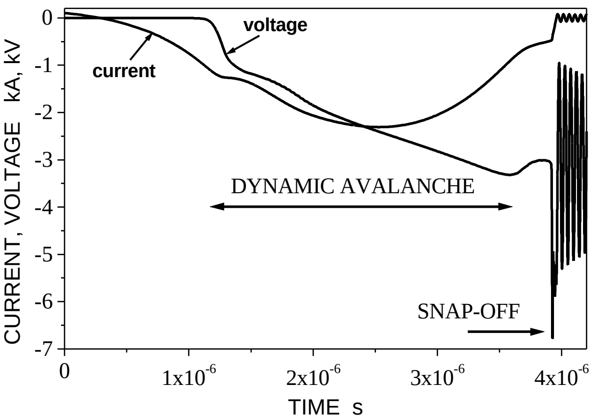

Fig.1: Reverse recovery of the free-wheeling diode at high voltage and high dI/dt (simulation)

reverse recovery characteristics. Influence of proton, electron and combined proton-electron irradiation on reverse recovery is presented with aid of electro-thermal one-dimensional device simulation which is proved correct by means of experiment. Ion irradiation in combination with electron irradiation is shown to be capable of improving both the above mentioned effects thus considerably extending the dynamic Safe Operating Area. The beneficial effect of irradiation is presented on a 4.5kV/300A free-wheeling diode (produced by ABB Semiconductors) operating in conjunction with GTO thyristor.

ELECTRON AND PROTON IRRADIATION PRINCIPLE

High energy irradiation of power devices is widely used for modifying lifetime profiles in order to optimize switching speeds. This is enabled by the fact that the irradiation introduces point defects that act as recombination centers. Higher concentration of these defects increases carrier recombination and brings a lower lifetime. Fig.2 shows differences between the defect profiles resulting from electron, proton and combined electron-proton irradiation. The anode and cathode are placed at x=0 and x=1, respectively. The region $x > 0.2$ is not shown in Fig.2, because the defect concentration is either constant or zero there. For clarity, refer to the profiles to Fig.3, where the whole device with the doping profile is shown.

Electron irradiation produces uniform defect profiles as is shown in Fig.2. The irradiation energy is usually in the range 2 – 10 MeV and the only degree of freedom is the irradiation dose.

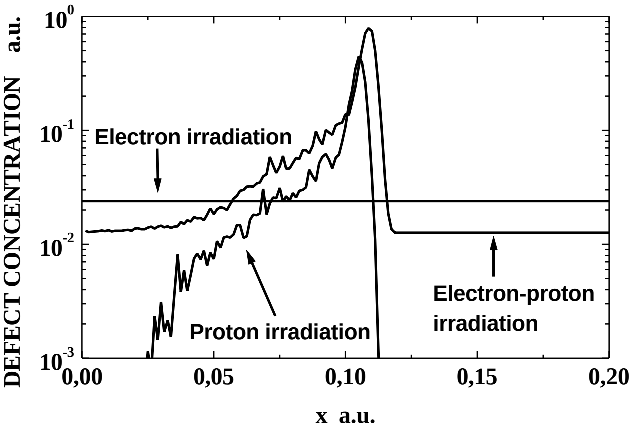

Fig.2: Defect profiles for electron, proton and combined electron-proton irradiation

Proton irradiation produces non-uniform defect profiles allowing local lifetime modification. According to Fig.2, the profile comprises a peak and tail extending to the surface of incident (x = 0). The defect concentration of the tail is at least one order lower than that of the peak. The proton irradiation energy is usually in the range 3 - 7 MeV and determines the position of the defect peak within the device. The height of the peak is determined by the irradiation dose and is usually chosen with regards to the background doping.

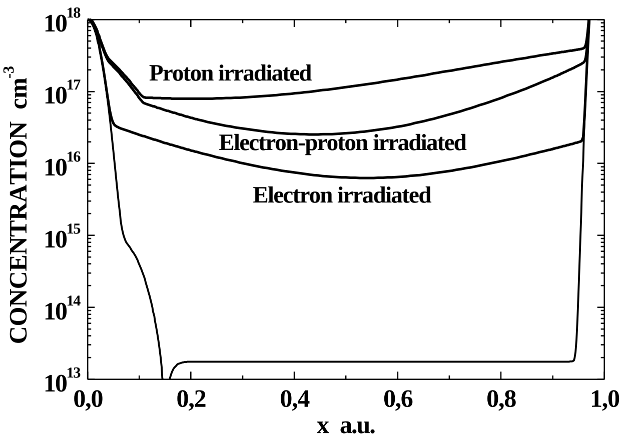

Fig.3: Concentration of sum of electrons and holes vs. depth in the device under test during the ON-state period (I_F = 100A). The doping profile is attached for clarity.

The combined electron and proton irradiation gives the defect profile which is approximately the sum of that of the individual irradiations (see Fig.2). This enables one to change the lifetime within the whole device with varying local concentrations where needed.

Irradiation treatment leading to an optimal defect (lifetime) profile requires knowledge of optimal irradiation parameters (irradiation energy, irradiation dose, etc). For this purpose, device simulation has proven to be very effective [1 - 3]. As an example, Fig.3 shows the simulated ON-state distribution of devices with the defect profiles from Fig.1. The shape of this distribution is very important for the subsequent reverse recovery process, because it predetermines the device dynamics. The reverse recovery process for the three presented profiles is shown below.

EXPERIMENTAL

The device under test is 4.5kV/300A conventional P-i-N diode 38mm in diameter. For the purpose of simulation, the diode is connected in the circuit shown in Fig.4. The circuit enables one to simulate the reverse recovery process of the device under test (DUT) starting from DC ON-state current I1 (typically 100A) with DC reverse voltage V1 (typically 3200V). R2 represents the diode series resistance (typically 0.2mΩ) and L1, the parasitic inductance of leads (typically 200nH). R1 is a time variable resistor representing switching devices which is represented by a Gate Turn-OFF thyristor in the case of the measurements. The reverse recovery is initiated by transient decrease of R1 which is exponential in time with the time constant about 0.4μs.

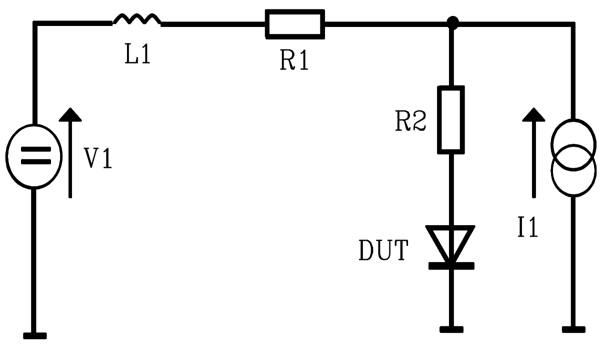

Fig.4: Circuit for simulation of free-wheeling diode operation

The simulation results were carried out by means of the device simulator ATLAS which was arranged to solve coupled Poisson, continuity (for electrons and holes), heat-flow and circuit equations, i.e. 5 equations in total [1, 3]. The ambient temperature was chosen to be 110°C in agreement with the conditions of measurement. Models of various physical effects were the default settings. Parameters of models covering the influence of irradiation were calibrated to precisely account for the resulting changes of carrier lifetime. The details of setting the model parameters may be found elsewhere [2 - 4].

The simulation enabled us to optimize the irradiation parameters, i.e. mainly the irradiation energy and dose. Subsequently, the diodes were irradiated and measured. The results obtained are compared below.

EXPERIMENTAL RESULTS

Firstly, the influence of individual proton and electron irradiations on the reverse recovery process was studied to disclose benefits and drawbacks of both the approaches. Secondly, the irradiation approaches were combined in a way leading to utilization of the benefits. Comparison of measured and simulated results is given below.

Electron irradiation

Fig.5 shows both measured and simulated reverse recovery waveforms of an electron irradiated diode for the defect profile of Fig.2 and the ON-state excess carrier distribution of Fig.3. The waveforms are in good qualitative agreement thus enabling optimization of irradiation procedure as well as detailed study of underlying physical phenomena by means of device simulation. It is clear that the device exhibits a low stored charge (compared to an unirradiated device not surviving such a high voltage and therefore not presented herein) and acceptably low avalanche generation in the fall period. However, an excessively snappy behaviour at t≈2µs is evident.

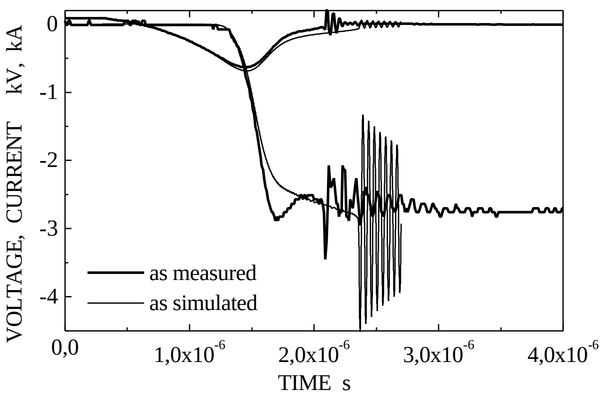

Fig.5: Simulated and measured reverse recovery waveforms of the electron irradiated diode

The snap-off (t > 2µs) is the result of the anode and cathode space charge regions meeting when the quasi-neutral electron-hole plasma region is fully trapped by the electric field and the abrupt fall of the carrier concentration follows. Consequently, the anode current snaps to zero and the anode voltage overshoots as a result of energy transfer from the inductance in series with the diode. The overshoot causes a total carrier removal and changes the device into a capacitor which in series with the parasitic leads inductance L1 forms a series oscillation circuit. A typical example of resulting harmonic oscillations is shown in the simulated waveforms of the Figs.5 – 7. In a real circuit, the harmonic oscillations are not present at all, because of total damping by parasitic losses that are not present in the simplified simulation circuit from Fig.4. The snap-off resulting from the measurement (see Fig.5) appears when the anode overvoltage, induced when the two space charge regions meet, approaches a value leading to the impact generation. The generated carriers reduce the rate-of-current rise dI/dt and thus limit the overshoot. Subsequently, the anode voltage decreases below a value leading to the impact generation and dI/dt increases again. This repeats many times and therefore leads to the non-harmonic oscillations. They can be observed in both measurement and simulation.

The snappy behaviour is attributed to all electron irradiated devices and becomes more dominant with increasing irradiation dose. This implies that the electron irradiation is not a good technique for obtaining soft recovery diodes at high supply voltages and high dI/dt. The reason is that electron irradiation reduces carrier lifetime uniformly within the whole device as is clear from Fig.3.

Proton irradiation

Fig.6 shows both measured and simulated reverse recovery waveforms of a proton irradiated diode that are also in good agreement. The waveforms correspond to the defect profile from Fig.2 and the ON-state excess carrier distribution of Fig.3. The device exhibits low stored charge and soft recovery behaviour. The reason is that proton irradiation was used to reduce carrier lifetime only locally close to the anode [2] as is shown in Fig.3.

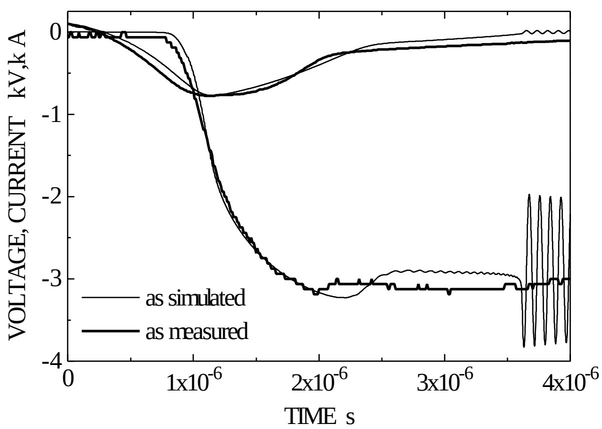

Fig.6: Simulated and measured reverse recovery waveforms of the proton irradiated diode

However, this leads to a relatively high dynamic avalanche generation (t≈1-2µs) caused by a large amount of holes drifting from the cathode side of the (unirradiated) N-base to the anode side.
This behaviour is typical for proton irradiated diodes application and becomes more dominant with increasing reverse supply voltage V1 and dI/dt. It implies that proton irradiation is a good technique for obtaining soft recovery behaviour, but at high supply voltages and dI/dt there is a high probability of device

destruction through the dynamic avalanche leading to destructive avalanche injection.

Combined electron-proton irradiation

Fig.7 shows both measured and simulated reverse recovery waveforms of a combined proton and electron irradiated diode for the defect profile from Fig.2 and the ON-state excess carrier distribution of Fig.3. The device shows reduced reverse recovery charge, negligible dynamic avalanche and soft recovery behaviour. This is because the combined irradiation takes the advantages of the two individual approaches presented above.

The oscillations of the simulated device (starting at t≈2.5µs) result from the LC resonant circuit and in a real circuit they are damped by parasitics that are not present in the simplified simulation circuit. The device represents a significant improvement in recovery parameters.

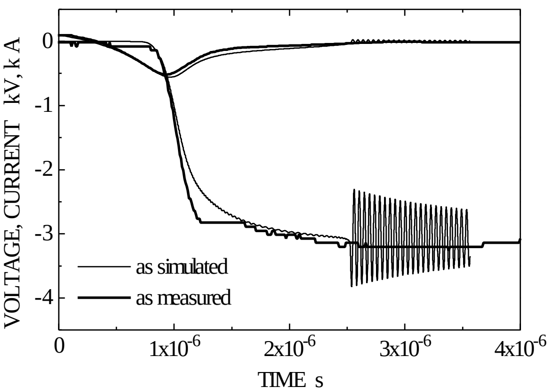

Fig.7: Simulated and measured reverse recovery waveform of the combined proton-electron irradiated diode

CONCLUSIONS

It is shown that combined proton and electron irradiation can substantially improve the reverse recovery characteristics of fast diodes operating at reverse voltages of over 3kV with dI/dts and dV/dts of about 1000A/µs and 7kV/µs, respectively. Suppression of the snap-off and dynamic avalanche by properly applied irradiation technology enables one to extend the dynamic Safe Operating Area.

Comparison of simulated and measured results shows that device simulation with calibrated parameters of relevant defects resulting from irradiation is capable of predicting device behaviour thus enabling fast and precise optimization of irradiation procedures. This is of great importance for the efficient design of optimal irradiation procedures for a variety of industrial applications. At present, both electron and proton irradiation techniques are commercially available thus enabling state-of-the-art defect engineering with the advantage of "OFF-line" features for a variety of applications [5].

Acknowledgements

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