Radiation Defects and Carrier Lifetime in 4H-SiC Bipolar Devices

Pavel Hazdra[*,1], *Petr Smrkovský*[1] *and Stanislav Popelka*[1]

[1] Department of Microelectronics, Faculty of Electrical Engineering, Czech Technical University in Prague, Technická 2, CZ-166 27 Prague 6, Czech Republic

E-mail: hazdra@fel.cvut.cz

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The effect of radiation damage on the minority carrier lifetime in the 4H-SiC epilayers forming the n-base of the power p-i-n diodes is presented. Irradiation with fast neutrons and MeV protons is used for uniform and local lifetime reduction. Deep level transient spectroscopy in combination with open-circuit voltage decay measurement shows that the carrier lifetime is reduced by increased carrier recombination on Z_1/Z_2, EH_3 and possibly RD_4 levels. The lifetime degrades swiftly and the ON-state carrier modulation capability of high-voltage devices can be easily lost already at very low fluences. The results further show that the proton irradiation provides an excellent tool for local lifetime tailoring. The carrier lifetime can be easily set by proton fluence and localized by proton energy. The proper local lifetime reduction speeds up diode recovery without an undesirable increase of the forward voltage drop. However, attention must be taken to properly locate the damage maximum so as not to increase device leakage.

1. Introduction

The realization of silicon carbide (SiC) bipolar devices has long been limited by a very short carrier lifetime in 4H-SiC epitaxial layers caused by the large number of imperfections introduced during their fabrication. Significant progress was achieved recently, when the origin of the most dangerous lifetime killer, the Z_1/Z_2 level, was identified and methods of its suppression, like carbon implantation or high-temperature thermal oxidation, elaborated. This opened up the possibility of implementing high-voltage SiC bipolar devices.[1]

Bipolar devices for voltages exceeding 10 kV require a long carrier lifetime to modulate the carrier conductivity in thick voltage-blocking layers. They can be therefore very sensitive to radiation, which introduces defects shortening the carrier lifetime.[2] In radiation-hard environment, namely the degradation of device static characteristics like the forward voltage drop (p-i-n diodes, thyristors) or current gain (bipolar transistors) can be therefore expected. On the other hand, the controlled introduction of recombination levels by means of irradiation is an excellent tool for mutual optimization of static and dynamic characteristics. It allows improving the dynamic parameters: the turn-off time, reverse recovery charge or recovery loss. Appropriate irradiation can be therefore used to adjust the ratio between the static and dynamic losses according to the application needs given by an end-user.

Prediction of the effect of radiation on device characteristics necessitates a detailed knowledge about introduced defects, their introduction rates, annealing characteristics, and impact on the carrier lifetime and other electrical characteristics. In this paper, we present such a study and focus on the effect of neutron and proton irradiation applied on high-voltage 4H-SiC p-i-n diodes.

2. Theory

The excess carrier recombination characterized by the minority carrier lifetime τ is an important phenomenon that significantly affects both the static and dynamic parameters of bipolar components. In the case of power p-i-n diodes, high values of the carrier lifetime at high injection levels τ_{HL} are necessary to allow the ON-state carrier modulation, i.e. the flooding of the low-doped n-base by the carriers injected from the p^+ and n^+ emitters (see the ON-state carrier profile in the *n*-base of the unirradiated diode shown in **Figure 1**).

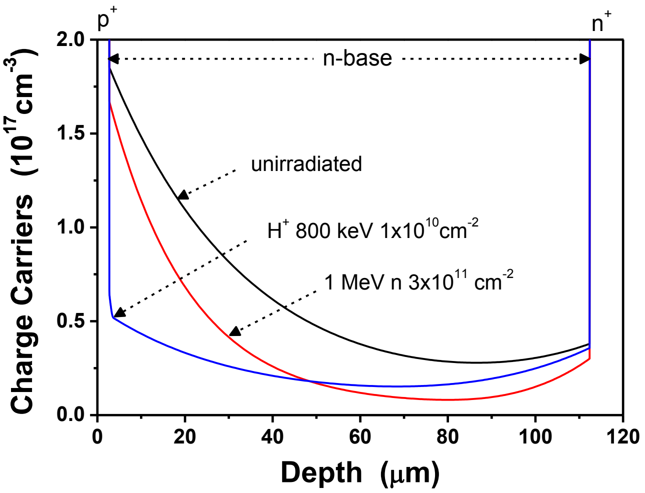

Figure 1. The simulated ON-state carrier profiles in the *n*-base of the unirradiated 10 kV 4H-SiC diode (high value of carrier lifetime), and diodes with uniform (neutron irradiated) and local (proton irradiated) lifetime reduction. Carriers are injected from the anode junction (left) and the cathode emitter (right).

The carrier modulation is then achieved when the ambipolar diffusion length of carriers L_a is greater than or equal to the diode *n*-base width w_B. The diffusion length is proportional to τ_{HL} according to

$$L_a = \sqrt{\mu_a u_T \tau_{HL}} \qquad (1)$$

where μ_a is the ambipolar carrier mobility and u_T is the thermal voltage

$$u_T = \frac{kT}{e} \qquad (2)$$

given by the temperature T, Boltzmann constant k, and the electronic charge e. The carrier lifetime at the high-level injection τ_{HL} is, according to the Shockley-Read-Hall model of carrier recombination[3], inversely proportional to the concentration of introduced recombination levels N_T multiplied by the coefficient α, which is related to parameters of the recombination level

$$\tau_{HL} = \frac{1}{\alpha N_T} = \frac{v_{Tp}\sigma_p + v_{Tn}\sigma_n}{v_{Tp}v_{Tn}\sigma_p\sigma_n}\frac{1}{N_T} \qquad (3)$$

where σ_n and σ_p are the capture cross sections of the level for electrons and holes, resp.; v_{Tn} and v_{Tp} are the electron and hole thermal velocities. Therefore, if we choose the borderline case to meet the conditions of the ON–state carrier modulation $L_a = w_B$, we get following the relation between the required τ_{HL} and w_B

$$\tau_{HL} = \frac{w_B^2}{\mu_a u_T} \qquad (4)$$

The n-base also serves as the blocking layer in the diode OFF-state. Its thickness and doping must be designed to allow suitable widening of the space charge region (SCR) with increasing reverse voltage. For the non-punch-through (NPT) p-i-n diode design, where the maximum SCR width (at breakdown) is set equal to the n-base width w_B, we get following relations between the breakdown voltage V_{BR}, the n-base doping N_D, and w_B

$$V_{BR} = A\,N_D^{-3/4} \quad (5), \qquad w_B = B\,N_D^{-7/8} \quad (6)$$

where A = 3.0x10^{15} and B = 1.82x10^{11} for SiC and N_D is expressed in cm^{-3}. [3] The design parameters V_{BR}, w_B, and τ_{HL} are related to each other by Equation 4-6 (see **Figure 2**). As one can see, we need $w_B > 100$ µm, $N_D < 2\text{x}10^{15}$ cm^{-3}, and $\tau_{HL} > 10$ µs for devices with the breakdown voltages higher than 10 kV. These values delimit our area of interest.

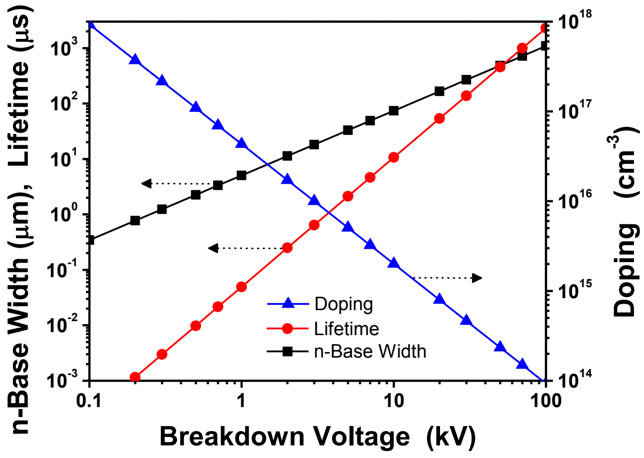

Figure 2. The relationship between the breakdown voltage and the *n*-base width, the minimal carrier lifetime, and the maximal doping level of the 4H-SiC P-i-N diode drift region (NPT design).

Assuming a linear introduction of recombination levels with the particle fluence Φ, i.e. a constant defect introduction rate $dN_T/d\Phi$, the decrease in carrier lifetime can be expressed by the lifetime degradation coefficient K_T [4] derived from the Equation 3

$$1/\tau = 1/\tau_0 + K_T\,\Phi = 1/\tau_0 + \alpha\,\frac{dN_T}{d\Phi}\Phi \qquad (7)$$

where τ_0 is the original lifetime of the unirradiated device.

Uniform introduction of recombination levels by irradiation with electrons, neutrons or GeV protons decreases the accumulated charge in the diode (see the effect of the neutron irradiation in Figure 1) and undesirably increases its forward voltage drop. On the other hand, it has a positive effect on its dynamic characteristics – the diode turns-OFF quickly since the n-base is less flooded by carriers and the accumulated charge quickly recombines.

Carrier lifetime can be also decreased locally, e.g. by irradiation with swift ions. In this case, the damage exhibits a sharp maximum close to the ion's projected range, where the lifetime is decreased significantly. If the damage is properly located, for example near the anode emitter (see the ON-state carrier profile in the *n*-base of the proton irradiated diode shown in Figure 1), it can substantially speed-up diode turn-off without undesirable increase of its forward voltage drop. Lifetime reduction depends on the number and distribution of introduced recombination levels and their electronic properties (energetic positions, capture cross sections, etc.). Its effect is then given by parameters of the device such as the width of the *n*-base or its doping.

3. Experimental

The influence of radiation defects on carrier lifetime and related electrical parameters was studied on 4.5 and 10kV p-i-n diode chips fabricated on lightly doped ($\leq 10^{15}$ cm^{-3}) *n*-type 4H-SiC epilayers.[1,5] Fast neutrons from the reference field of the LR-0 reactor were used for uniform lifetime reduction.[6] Diodes were irradiated at room temperature with fluences ranging from 5.6x10^{10} to 5.9x10^{12} cm^{-2} (1 MeV SiC equivalent). The local lifetime reduction was realized by irradiation with 800 keV or 1 MeV protons using the 3 MeV tandetron accelerator.[7] Diodes were irradiated at room temperature from the anode side with fluences ranging from 5x10^{9} to 1x10^{11} cm^{-2}. The proton projected ranges in the device were 8.8 µm (800 keV protons) and 11.9 µm (1 MeV protons), respectively. The damage maximum was then located in the *n*-base approximately 1.4 µm (800 keV protons) or 4.5 µm (1 MeV protons) beyond the anode junction. Electrical characteristics of irradiated diodes were recorded prior to and after irradiation. Introduced deep levels were measured by the capacitance deep level transient spectroscopy (DLTS) using the spectrometers DLS-82E and DLS-83D from SEMILAB Inc., which allowed detection of deep levels up to the n-base depth of 6 µm. All DLTS spectra were recorded during the first temperature scan so as to minimize the annealing of unstable defects, which occurs in SiC already at temperatures higher than 300K. The excess carrier dynamics were measured at temperatures ranging from 25 to 100ºC by the open-circuit voltage decay (OCVD) response.[8]

4. Results and Discussion

4.1. Uniform lifetime reduction

Irradiation with fast neutrons generates radiation defects uniformly in the whole volume of the device. Their introduction is evidenced by different deep levels appearing in the SiC bandgap. This is shown in **Figure 3**, which compares majority carrier DLTS spectra recorded in the *n*-base of the p-i-n diode prior to (dashed) and after (solid) neutron irradiation to a fluence of $1.7\text{x}10^{11}$ cm^{-2} (1 MeV equivalent). In the spectrum of the unirradiated diode, we find two peaks that correspond to defects that are typical for n-type SiC epilayers: the titanium acceptor level at E_C - 0.10 eV (T=84 K) and the Z_1/Z_2 lifetime-limiting level.[9] This level is usually accompanied by the EH_6/EH_7 level the peak of which is located at temperatures higher than 600 K.[10,11] The Z_1/Z_2 and EH_6/EH_7 are related to the double acceptor and the single donor states of carbon vacancy, respectively.[12] In the spectrum recorded after the neutron irradiation, we observe enhancement of the Z_1/Z_2 peak and appearance of additional levels evidenced by peaks labelled P_1/P_2, EH_1, EH_3, EH_4 and RD_4.

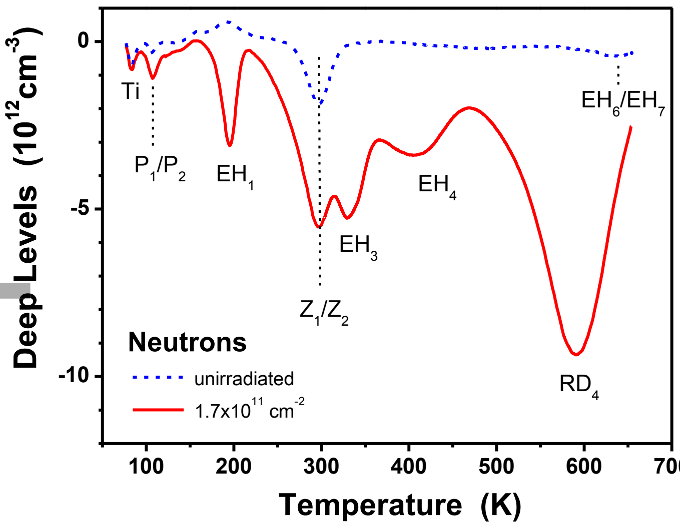

Figure 3. Majority carrier DLTS spectra measured in the n-type 4H-SiC epitaxial layer prior to and after irradiation with fast neutrons to a fluence of $1.7\text{x}10^{11}$ cm^{-2} (1 MeV equivalent), rate window 10.8 s^{-1}.

Energy positions, electron capture cross sections and literature references of these levels are listed in **Table 1**. Levels EH_1 and EH_3, which are related to silicon vacancy[13], are thermally unstable.

They appear in 4H-SiC after irradiation with light particles (electrons, neutrons and protons) [10,11,14] and transform to the S-center by annealing at temperatures higher than 175ºC.[15] The peaks appearing at higher temperatures of the DLTS spectrum are related to more complicated and stable defects. The level EH_4 is related to higher-order defect cluster according to studies performed on 4H-SiC irradiated with electrons with different energies.[11,16] The level RD4, which was detected in 4H-SiC irradiated by helium ions[13] and neutrons[10], is being connected with a defect containing silicon vacancy[17,18].

Table 1. Deep levels detected in n-type 4H-SiC after neutron and proton irradiation.

Level	Band gap position [eV]	Capture cross section [cm^2]	Reference
P_1/P_2	E_C-0.18	$1x10^{-16}$	[13,18]
EH_1	E_C-0.39	$6x10^{-15}$	[10,11,13,14]
Z_1/Z_2	E_C-0.69	$6x10^{-14}$	[10,11,13,14]
EH_3	E_C-0.72	$7x10^{-14}$	[10,11,13,14]
EH_4	E_C-1.04	$6x10^{-14}$	[11,18]
RD_4	E_C-1.45	$8x10^{-14}$	[13,17,18]
EH_6/EH_7	E_C-1.64	$4x10^{-13}$	[11,18]

Deep level profiles measured in the diode n-base by DLTS showed that the concentration of introduced levels is homogeneous and grows linearly with increasing neutron fluence. For the dominant lifetime killer, the Z_1/Z_2 level, we obtained the defect introduction rate $dN_T/d\Phi$ eqal 1.6 cm^{-1} (see **Figure 4**).

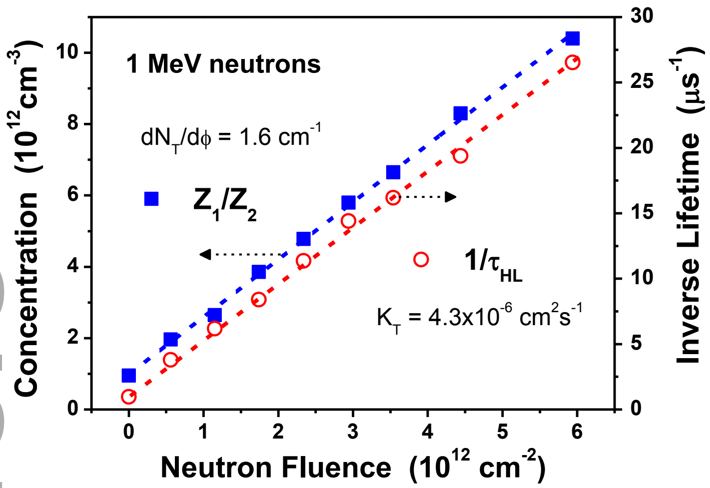

Figure 4. Concentration of the introduced Z_1/Z_2 levels (boxes) and inverse carrier lifetime $1/\tau_{HL}$ versus the neutron fluence (1 MeV equivalent).

Figure 5 shows room temperature OCVD responses of the 4H-SiC p-i-n diode measured after various degrees of neutron irradiation. The OCVD response monitors the time dependent component of the post-injection voltage $V(t)$, which is given by the sum of thermal voltages $V_L(t)$ and $V_R(t)$ across the anode junction and cathode emitter, respectively,

$$V(t) = V_L(t) + V_R(t) = u_T \left[ln \frac{p_L(t)}{n_i} + ln \frac{n_R(t)}{n_i} \right] \quad (8)$$

where n_i is the intrinsic carrier concentration, and p_L and n_R are hole and electron concentrations at the left and right side of the n-base, respectively.[19] The response thus gives information about the time dynamics of the decrease in the concentration of excess carriers (in logarithmic scale). The high-level lifetime τ_{HL} can then be derived from the slope of the voltage decay dV/dt in the linear region (the band corresponding to OCVD voltages between 2.5 to 2.7 V), which follows the initial rapid voltage drop caused by the carrier recombination in the emitters

$$\tau_{HL} = -2\, u_T \left(\frac{dV}{dt} \right)^{-1} \quad (9)$$

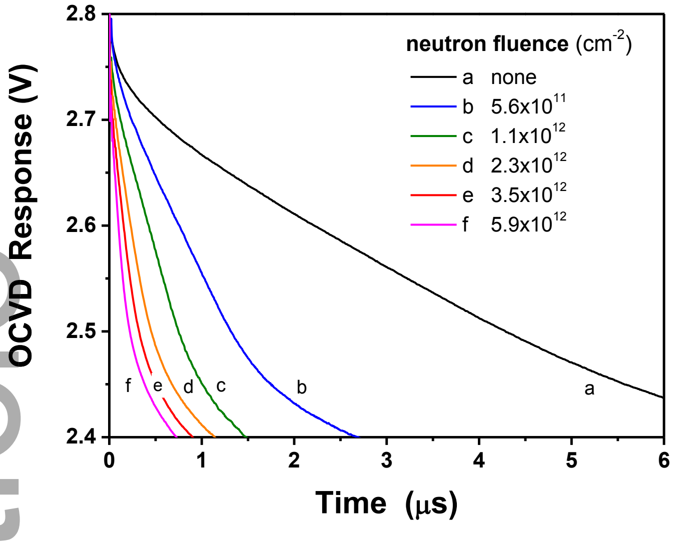

Figure 5. Room temperature OCVD responses of 4H-SiC p-i-n diode irradiated with different neutron fluences (1 MeV equivalent).

This value is supposed to be identical with the high-level lifetime derived from the Shockley-Read–Hall (SRH) model of carrier recombination (Equation 1). The OCVD characteristics presented in Figure 5 show that the recombination at high-injection levels accelerates gradually with increasing neutron fluence. The inverse values of subtracted τ_{HL}, which are presented in Figure 4, show a linear dependence on neutron fluence giving K_T=4.3x10^{-6} cm^{2}s^{-1}. The value of the coefficient α = 2.7x10^{-6} cm^{3}s^{-1}, which is calculated from the ratio of K_T and dN_T/dΦ (Equation 7), is slightly larger than the value obtained from the parameters of the Z_1/Z_2 level (Equation 3). This indicates that other levels also play a significant role in the excess carrier recombination. The possible candidates are levels EH_3, whose electronic parameters are very close to the Z_1/Z_2, and RD_4, which exhibits a high introduction rate. The high-level lifetime controlled by the Z_1/Z_2, EH_3, and RD_4 levels shows a very good temperature stability. OCVD measurements showed that the increase in device temperature from 25 to 100°C resulted in only 20% increase of τ_{HL} for both the unirradiated and heavily irradiated diode.

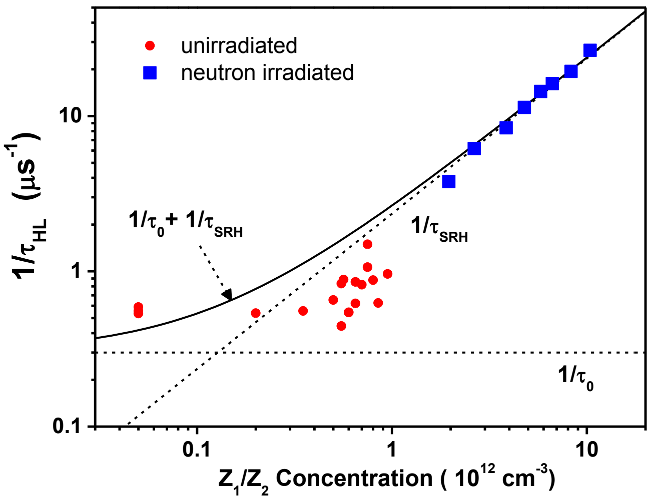

Figure 6. Relationship between the inverse high-level carrier lifetime $1/\tau_{HL}$ and the Z_1/Z_2 level concentration measured in the 4H/SiC p-i-n diodes - unirradiated samples (circles), neutron irradiated samples (boxes).

The relationship between the inverse carrier lifetime $1/\tau_{HL}$ measured by OCVD and the Z_1/Z_2 level concentration obtained from DLTS profiling is shown in **Figure 6**. Data measured on both the irradiated and non-irradiated samples are presented. The experimental data are fitted using the Equation 7 and following fitting parameters τ_0 = 3 μs and α = 2.7x10^{-6} cm^3s^{-1}. Figure 6 shows that the inverse carrier lifetime is proportional to the Z_1/Z_2 level concentration, when the Z_1/Z_2 level concentration is higher than 1x10^{12} cm^{-3}. For lower concentrations, the correlation between the Z_1/Z_2 concentration and lifetime is not clear. In this case, the carrier lifetime is probably controlled by other processes: contaminants (Ti, W), surface recombination, etc. Figures 4 and 6 clearly show, that the carrier lifetime in high-voltage SiC bipolar power devices can be easily controlled in the required range (100 μs to 1 μs) by neutron irradiation with fluences ranging from 10^{10} to 10^{12} cm^{-2} (1 MeV SiC equivalent). A similar effect can be achieved by electron irradiation with energies higher than 1 MeV.[15,20] In this case, the spectrum of introduced level is similar, but defect introduction rates are ten times lower.[15]

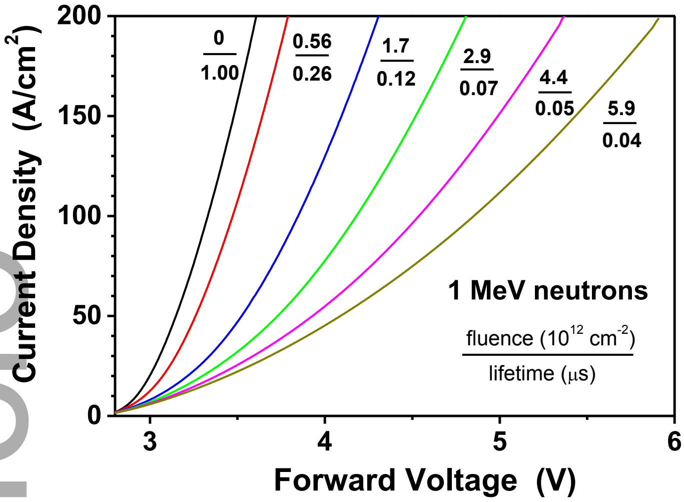

Figure 7. Forward I-V characteristics of 4H-SiC p-i-n diode irradiated with different fluences of 1 MeV equivalent neutrons. The corresponding carrier lifetimes measured by OCVD are shown in the denominator.

The effect of the neutron irradiation and the corresponding reduction of carrier lifetime on forward characteristics of 4H-SiC power p-i-n diode is shown in **Figure 7**. Gradual degradation of characteristics can be observed, which is manifested by an increase in the forward voltage drop and series resistance. It is worth noting that the SiC p-i-n diode is very sensitive to neutron irradiation due to the very high lifetime degradation coefficient K_T. For example, the 10 kV diode loses its carrier modulation capability when the neutron fluence reaches a value of $2x10^{11}$ cm^{-2}. On the other hand, the loss of carrier modulation capability due lifetime reduction does not necessarily mean a sharp increase of the forward voltage drop as in the case of the silicon power diode. Due to the high dielectric strength of SiC, the n-base of the SiC p-i-n diode is sufficiently doped to show a sufficiently low resistance even in the unipolar regime.

4.2. Local lifetime reductio

Proton irradiation is an excellent tool for local lifetime reduction in SiC since light protons provide long ranges at acceptable acceleration voltages and, in contrast with silicon, produce only pure radiation defects.[21] An overview of deep levels produced by 800 keV protons in 4H-SiC provides **Figure 8**, which compares majority carrier DLTS spectra measured prior to

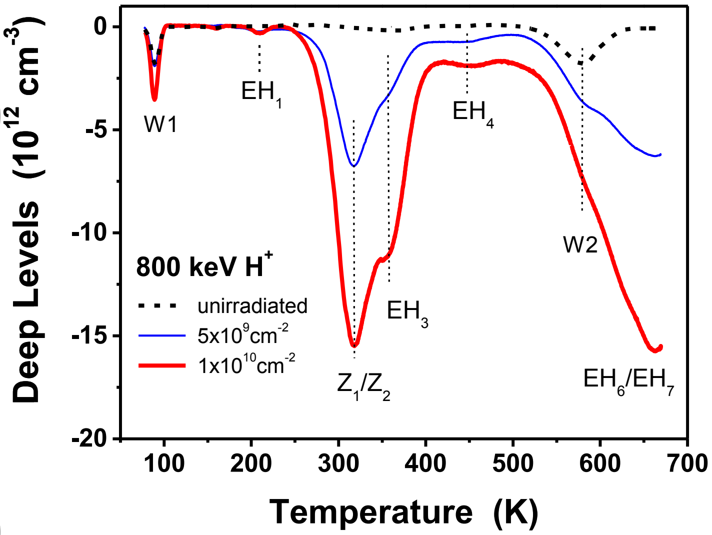

Figure 8. Majority carrier DLTS spectra measured in the n-type 4H-SiC epitaxial layer prior to (dashed) and after irradiation with 800 keV protons to fluences 5x10^{9} cm^{-2} (solid thin) and 1x10^{10} cm^{-2}(solid thick) respectively, rate window 56 s^{-1}.

and after proton irradiation to fluences of 5x10^{9} cm^{-2} and 1x10^{10} cm^{-2}, respectively. The spectra were measured under conditions allowing the detection of the entire profile of the introduced damage. The spectrum recorded before irradiation contains two peaks labelled W1 (E_C- 0.17eV) and W2 (E_C-1.41eV), which are related to tungsten and originate from diode fabrication.[22] Spectra measured after irradiation show that protons create similar recombination levels in SiC as neutrons. The dominant are levels related to carbon vacancy: Z_1/Z_2 and EH_6/EH_7. The generation of EH_1 and EH_4 levels is suppressed. At low doses of irradiation, the number of introduced recombination levels grows linearly with increasing fluence (see Figure 8).

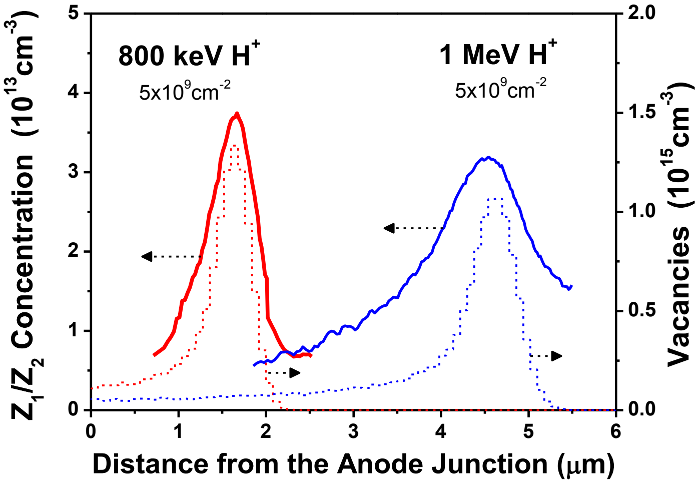

Figure 9. Concentration profiles of the dominant recombination level Z_1/Z_2 (solid) measured in the n-base of the 4H-SiC p-i-n diodes irradiated with 800 keV and 1 MeV protons to a fluence of $5\text{x}10^9$ cm^{-2}. The simulated profile of primary defects (vacancies) is also shown (dashed).

Concentration profiles of the dominant recombination level Z_1/Z_2, which were registered by DLTS after with 800 keV and 1 MeV protons, are shown in **Figure 9** and compared with the axial distribution of the primary damage (silicon and carbon vacancies) simulated by the code SRIM2008.[23] Figure 9 clearly shows that the profile of introduced recombination levels follow well the distribution of primary damage (the Bragg curve) without significant broadening. That's because the diffusivity of defects in SiC is negligible. The defect peak thus stays very narrow and can be easily shifted by the change of accelerating voltage or by the use of energy degraders. The introduction rate of Z_1/Z_2 levels is very high and achieves up to $7\text{x}10^3$ cm^{-1} at the damage maximum (800 keV protons). If we consider a similar structure of recombination levels as in the case of neutron irradiation, it is possible to estimate the lifetime degradation coefficient K_T for protons using the coefficient α, which was determined above. The estimated value $K_T = 0.019$ cm^2s^{-1} is extremely high and means that proton fluences about 10^{11} cm^{-2} are sufficient to suppress the carrier lifetime to nanoseconds.

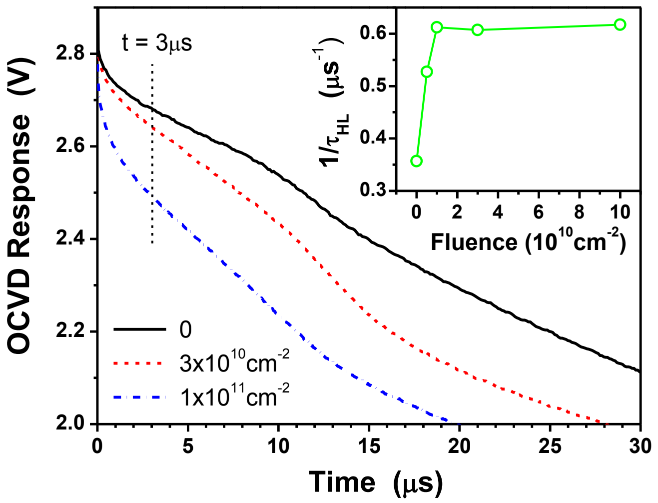

Figure 10. Room temperature OCVD responses of 4H-SiC p-i-n diode irradiated with different fluences of 800 keV protons. The influence of the proton fluence on the inverse carrier lifetime ($1/\tau_{HL}$) is shown in the inset.

Figure 10 presents OCVD responses of p-i-n diodes, where the carrier lifetime was killed locally in the anode area. Responses show different dynamics compared those, where the uniform lifetime reduction was applied (Figure 5). As one can see, the local lifetime reduction at the anode speeds-up mainly the initial part of the recovery (t<1μs), and, at higher irradiation fluences, substantially decreases the excess charge accumulated in the *n*-base (compare with Figure 1). Since the majority of the *n*-base is not affected by irradiation, the rest of the response (t > 2μs) proceeds with the same time constant, although the irradiation fluence continues to increase (see the inset in Figure 10). OCVD measurements performed on proton irradiated diodes in the temperature range from 25 to 100°C have shown that the effect of temperature on the OCVD response (carrier lifetime) is negligible.

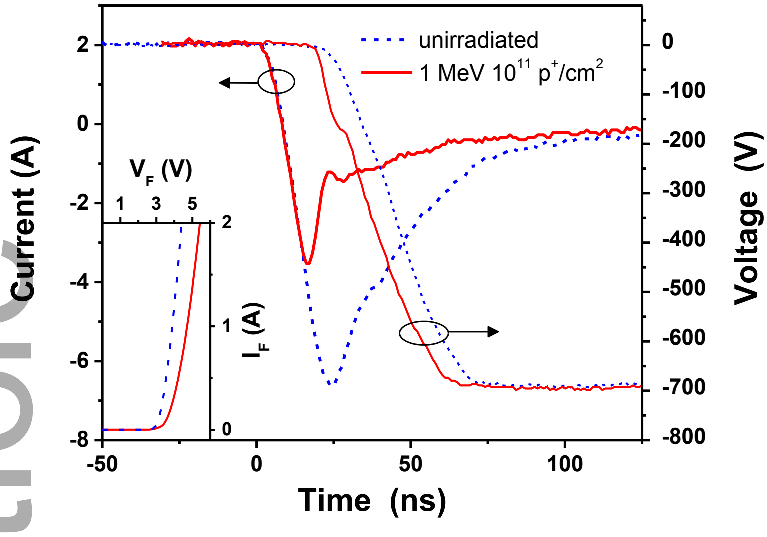

Figure 11 Reverse recovery waveforms measured on the 4H-SiC p-i-n diode prior to (dashed) and after irradiation with 1 MeV protons to a fluence of 10^{11} cm^{-2}. The corresponding forward I-V characteristics are shown in the inset.

The favorable effect of the local lifetime reduction placed close to the anode emitter is shown in **Figure 11**, which presents reverse recovery waveforms measured on the p-i-n diode prior to and after irradiation with 1 MeV protons to a fluence of 10^{11} cm^{-2} (the recovery from I_F=2A to V_R=700V) and the corresponding forward I-V characteristics in the inset. After irradiation, the reverse recovery current maximum decreased twice and the reverse recovery charge dropped to one third while the forward voltage drop V_F at I_F=2A increased only by 25%. Moreover, the long carrier lifetime in the *n*-base, which has not been affected by irradiation, guarantees a sufficiently gradual course of the final phase of recovery, the so-called “softeness” of the diode.

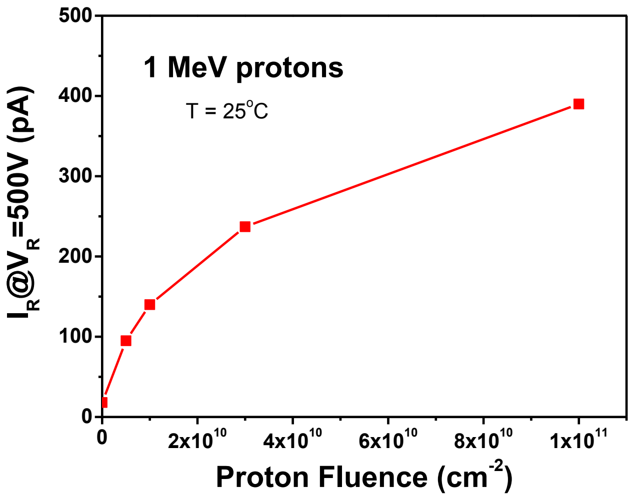

Figure 12. Room temperature reverse current I_R of the 4H-SiC p-i-n diode measured after irradiation with different fluences of 1 MeV protons.

Finally, we should mention that both the uniform and local lifetime killing degrade the generation lifetime, i.e. increase the rate of carrier generation via introduced deep levels. The EH_6/EH_7 (proton irradiation) and RD_4 (neutron irradiation) levels are located close to the middle of the 4H-SiC bandgap and therefore they are the most effective levels for generation of charge carries. In the OFF-state of the diode, when the SCR extends into the diode n-base, the increased generation of carriers in the SCR increases the leakage of irradiated device. The wide bandgap of 4H-SiC guarantees that carrier generation rates in devices irradiated with neutrons or electrons stay low enough and the increase in diode leakage can be usually neglected.[24] Compared to that, the local lifetime killing, which is placed in the optimal position (behind the anode junction), introduces a high number of defects into the region with a high electric field. The generation of charge carriers can then be enhanced due to the Frenkel-Pool effect and a significant increase in reverse current can be observed. This is shown in **Figure 12** presenting the results obtained on 4H-SiC p-i-n diode irradiated with 1 MeV protons. Although the absolute value of the leakage current is very low, the increased generation can be a serious problem at higher operating temperatures and voltages.

5. Conclusions

Radiation defects produced by fast neutrons and protons were used for uniform and local modification of the minority carrier lifetime in the *n*-base of the 4H-SiC high-voltage p-i-n diode. Results show that the carrier lifetime is reduced by increased recombination on the introduced Z_1/Z_2 and EH_3 levels. In the case of neutron irradiation, the effect of the RD_4 level also cannot be ruled out. Radiation damage must be annealed at low temperatures (removal of the EH_3 levels) to ensure a stable effect. In neutron irradiated devices, the lifetime degradation accelerates with increasing fluence and the ON-state carrier modulation capability of high-voltage devices can be easily lost. In the case of low-voltage devices, lower thickness and higher doping level of the n-base can compensate for this negative effects. Proton irradiation provides an excellent tool for local lifetime control in SiC bipolar power devices. The carrier lifetime in the damage peak, whose location is easily controlled by irradiation energy, is drastically shortened already at very low fluences. The local lifetime reduction then speeds-up diode turn-off without undesirable increase of the forward voltage drop. Proton irradiation localized in the *n*-base increases carrier generation and the associated leakage of the modified device. It is therefore necessary to pay particular attention to the correct location of the damage peak.

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Radiation Defects and Carrier Lifetime in 4H-SiC Bipolar Devices

Pavel Hazdra, Petr Smrkovský, Stanislav Popelka

Fast neutrons and MeV protons are used for uniform and local lifetime reduction in 4H-SiC bipolar devices. Carrier lifetime degrades swiftly with irradiation dose, the ON-state carrier modulation in high-voltage devices can be easily lost by the neutron irradiation. Proton irradiation then provides an excellent tool for local lifetime tailoring which can optimize the trade-off between device static and dynamic parameters.