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The Role of Carrier Lifetime in Forward Bias Degradation of 4H-SiC PiN Diodes

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Abstract. The role of excess carrier lifetime reduction in the mechanism for on-state voltage (V_f) degradation of high voltage 4H-SiC PiN diodes is investigated. A method is developed to electrically monitor the emitter, base, and end region excess carrier lifetimes at periodic intervals during the forward bias stress condition. The lifetime measurement method involves using the turn-off reverse-recovery waveforms for conditions of high *dI/dt* and low *dV/dt*. The peak reverse-recovery current for high *dI/dt* is related to the excess carrier charge stored before the diode is switched off and is an indication of the total recombination rate. The low *dV/dt* condition minimizes the carrier sweep out and diffusion currents resulting in a current tail with a decay rate that is determined by the base and end-region lifetimes. This lifetime measurement method is used to monitor diodes with degradation times ranging from one minute to over several hundred hours. The measurements indicate that V_f degradation is accompanied by a reduction in end region lifetime and/or reduction in device conduction area.

Introduction

Recently, Silicon-Carbide (SiC) power diodes have begun to emerge with breakthrough static and dynamic performance compared to existing Silicon (Si) power diodes [1-3]. For medium voltage applications (< 3 kV), majority carrier devices such as Schottky diodes and MOSFETs have the best performance, whereas conductivity modulated bipolar type devices generally provide better performance for higher voltage applications. Although rapid progress has been made towards commercialization of majority carrier SiC Schottky power diodes, a potential challenge to the commercialization of high-voltage conductivity modulated SiC power devices is the degradation of the on-state voltage (V_f) with forward bias stress. It is generally recognized that propagation of SiC crystal stacking faults is the origin of V_f degradation [4] although the mechanism by which the electrical properties of the material and device are changed has not been well established. The purpose of this paper is to facilitate the study of the V_f degradation mechanism by providing a method of electrically monitoring the excess carrier lifetimes in various regions of the device at periodic intervals during the forward bias stress.

Forward Bias Degradation Mechanism

Figure 1 shows the on-state characteristics of a high voltage SiC PiN diode after various levels of forward bias stress. The magnitude of increase in V_f is dependent on the length of time and the amount of forward current flowing through the diode [5]. The V_f degradation time for the devices studied in this work ranged from few milliseconds to many hours [6]. Our measurements indicate that the amount of degradation is generally not influenced by switching or by reverse bias blocking

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and is only a function of the total amount of time a device is operated at a given current. The amount of degradation is generally observed to be proportional to the current-time product and increases with increased temperature during stress, although the degradation rate can also exhibit some sporadic behavior due to initiation and termination of individual stacking fault propagations.

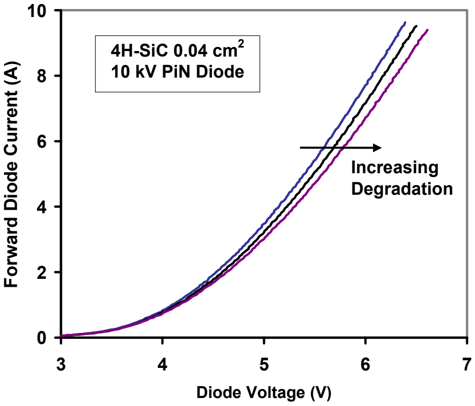

Fig. 1. PiN diode forward bias degradation.

Optical observation of PiN diodes undergoing V_f degradation have demonstrated the simultaneous formation of mobile and propagating crystal stacking faults [4,6,7,8]. It is now established that these mobile stacking faults nucleate from existing substrate crystal defects and process induced defects in hexagonal (eg. 4H and 6H) SiC. It has also been established that the energy from electron-hole pair recombination provides the activation energy necessary for the propagation of the stacking faults. This is substantiated by the activation energy of 0.27 eV calculated from emission spectrum measurements [4]. It is also generally believed that the edges of the stacking faults act as recombination centers that reduce the carrier lifetime in the material and lead to the observed on-state voltage degradation [7]. It is the purpose of this paper to further investigate the lifetime reduction hypothesis by monitoring the lifetime in various regions of the device during the degradation.

Lifetime Measurement Method

In this section, a method of electrically monitoring the emitter, base, and end-region lifetimes (τ_A, τ_B, and τ_K, respectively) is introduced. Figure 2 is a diagram of a PiN diode indicating the location of each lifetime region. The lifetime measurement method involves using the turn-off reverse-recovery waveforms for conditions of high *dI/dt* and low *dV/dt* where the high *dI/dt* is obtained using a vacuum tube driver and *dV/dt* is controlled using a capacitor across the driver [3]. Figure 3 shows the reverse-recovery current and voltage waveforms indicating the features of the waveforms used to measure the lifetimes. The current waveform consists of an initial reverse-recovery peak followed by a slowly decaying tail. The peak reverse-recovery current I_{RRM} for high *dI/dt* is related to the excess carrier charge and is an indication of the total recombination rate from the emitter, base, and end regions.

The low *dV/dt* condition obtained using the added driver capacitance minimizes the carrier sweep out current due to the moving depletion edge boundary and the low voltage condition results in a wide neutral base region minimizing the diffusion currents through the base toward the emitter and end regions. As a result, the current tail is larger and the tail decay rate ($d\ln I/dt$) is determined by recombination in the base and end regions as expressed by the following equations [9,10]:

$$\frac{d\ln I}{dt} = \frac{1}{\tau_B}\left(1+\frac{I}{I_K}\right) \qquad (1) \qquad\qquad I_K\tau_B = qA\frac{D_{pB}}{\sqrt{D_{pK}}}\frac{n_i^2}{n_{iK}^2}N_K\sqrt{\tau_K} \qquad (2)$$

where I is the tail current, I_K is the knee current beyond which end-region recombination becomes dominant, A is the diode active area, D_{pB} and D_{pK} are the base and end-region hole diffusivities, n_i and n_{iK} are the base and end-region intrinsic carrier concentrations, and N_K is the end-region dopant density. The IMPACT model parameter extraction tools [11] are used to perform the measurements, calculate the decay rate derivative, and perform a least squares linear fit to extract τ_B and $\tau_B I_K$.

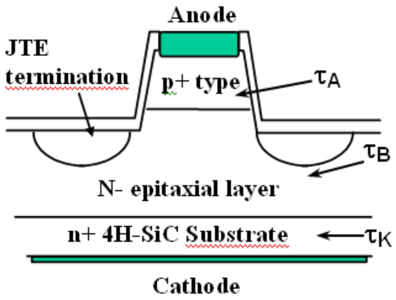

Fig. 2. Diagram of PiN diode indicating the location of each lifetime region.

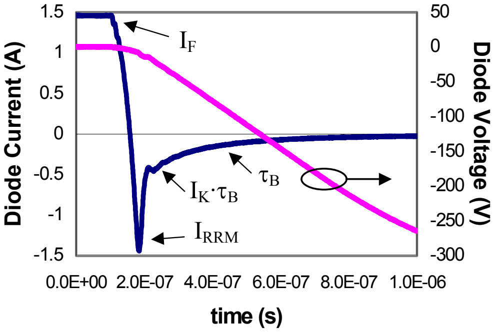

Fig. 3. Low dV/dt reverse-recovery waveforms indicating the features used to monitor lifetime.

Results and Discussion

Diodes with degradation times ranging from one minute to over several hundred hours are studied. Figure 4 is an example of the measurement of V_f, τ_B, $\tau_B I_K$, and I_{RRM}/I_F for a 10 kV, 0.01 cm^2 device stressed at 100 A/cm^2. The extracted value of τ_B is shown for two values of I_F, and I_{RRM}/I_F is shown for three values of I_F. The data indicates that $\tau_B I_K$ and I_{RRM}/I_F decrease, V_f increases and τ_B is relatively constant as the device is stressed.

The relatively constant τ_B implies that the high-level injection lifetime in the base is not reduced although the overall decay time is reduced (i.e., $\tau_B I_K$ and the second term in eq (2) dominate for the current range of interest). From Fig. 4a and eq (2), one can conclude that τ_K and/or active conduction area A are decreased as the device is stressed (reduced A results in increased recombination because the charge per area is higher making end region recombination more important). The decrease in I_{RRM}/I_F of Fig. 4b indicates that the base charge is reduced due to the reduction of τ_A, τ_K, and/or A. This decrease in base charge reduces the base region conductivity modulation and thus increases the V_f as indicated by the data.

Additional degradation results are given in Fig. 5 for a 0.04 cm^2 device from the same lot as the 0.01 cm^2 device of Fig. 4, and in Fig. 6 for a 0.01 cm^2 new low degradation rate device type [2]. Another 0.01 cm^2 low degradation rate device from the same lot as the device of Fig. 6 (not shown) had a V_f of 6.5V@100A/cm^2 and the V_f, $\tau_B I_K$, and I_{RRM}/I_F did not degrade after 300 Amp-Hours, whereas the device of Fig. 6 degraded and then stabilized.

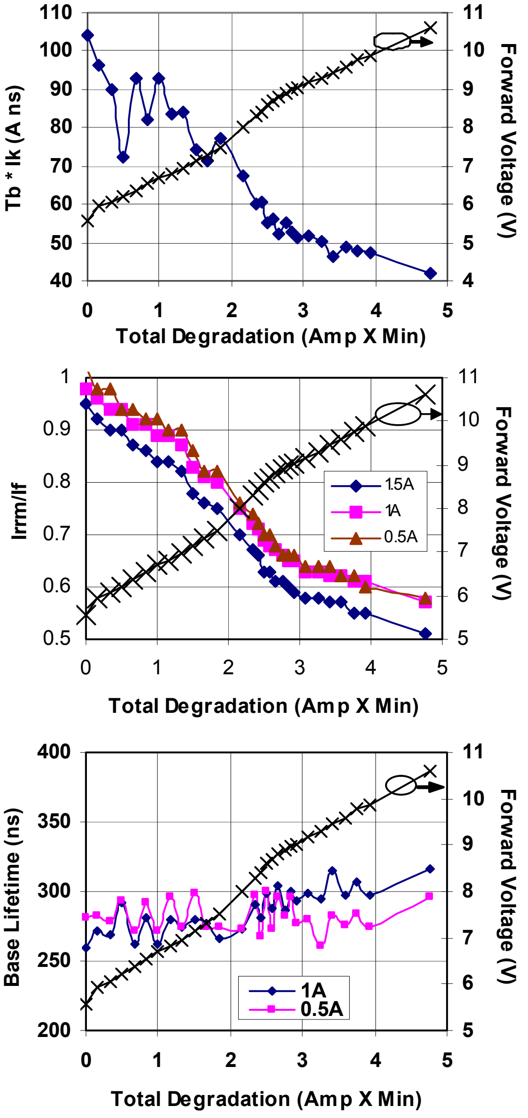

Fig. 4. Degradation measurements for a 10kV, 0.01 cm^2 device stressed at 100 A/cm^2 indicating V_f @ 1A on each graph and a) $\tau_B I_K$ extracted at I_F = 1 A, b) I_{RRM}/I_F for three values of I_F, and c) τ_B extracted at two values of I_F.

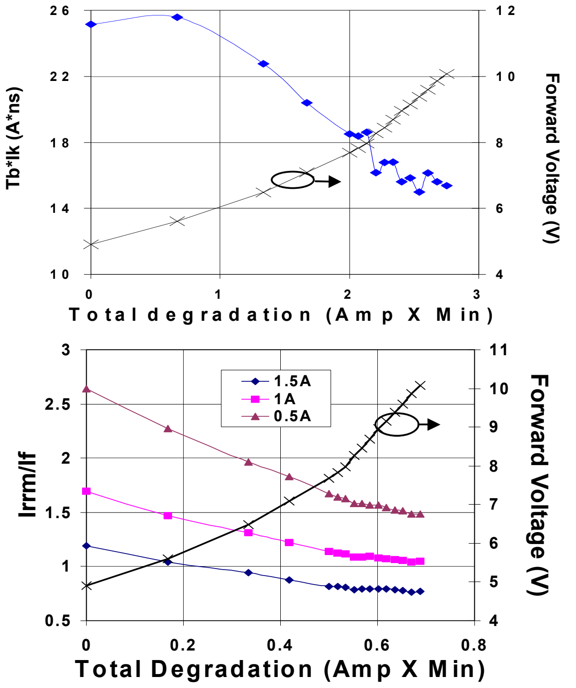

Fig. 5. Degradation measurements for a 10kV, 0.04 cm^2 device from the same lot as the device in Fig.3 stressed at 100 A/cm^2 indicating V_f @ 1A on each graph and a) $\tau_B I_K$ extracted at I_F = 1 A, and b) I_{RRM} /I_F for three values of I_F.

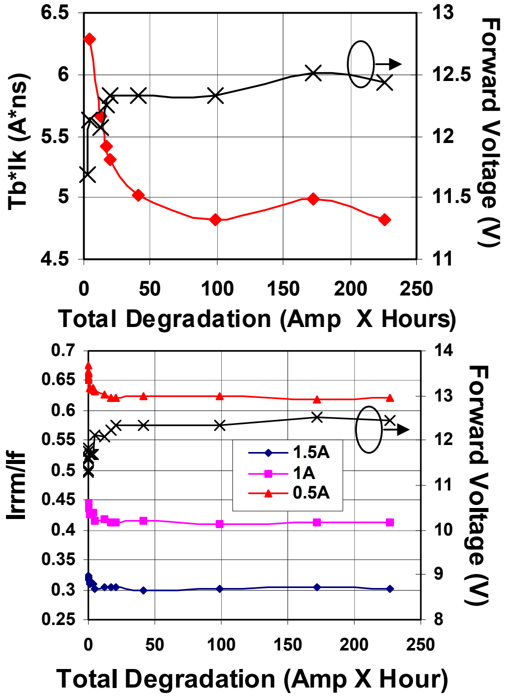

Fig. 6. Degradation measurements for a 10kV, 0.01 cm^2 device stressed at 300 A/cm^2 indicating V_f @ 1A on each graph and a) $\tau_B I_K$ extracted at I_F = 1 A, and b) I_{RRM} /I_F for three values of I_F.

The separation of the I_{RRM} /I_F curves in Figs. 5 and 6 indicate that these devices are dominated more by τ_K and τ_A than the device of Fig. 4.

Conclusions

A new lifetime measurement method is introduced and used to monitor diodes with degradation times ranging from one minute to over several hundred hours. Individual extraction of the emitter, base, and end-region lifetimes suggests that the effective end-region lifetime and/or conduction area are reduced. The reduction in lifetimes and/or conduction area results in a reduced charge to modulate the base conductivity resulting in the increased forward voltage drop.

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