Lifetime-limiting defects in n^- 4H-SiC epilayers

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Low-injection minority carrier lifetimes (MCLs) and deep trap spectra have been investigated in n^- 4H-SiC epilayers of varying layer thicknesses, in order to enable the separation of bulk lifetimes from surface recombination effects. From the linear dependence of the inverse bulk MCL on the concentration of $Z1/Z2$ defects and from the behavior of the deep trap spectra in 4H-SiC *p-i-n* diodes under forward bias, we conclude that it is $Z1/Z2$ alone that controls the MCL in this material. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2170144]

Due to its outstanding chemical and thermal stability, superior thermal conductivity and high breakdown field, SiC has become the material of choice for the development of high-power electronic devices capable of performing beyond the theoretical limitations of Si-based technology. While significant progress has been made in both materials growth and device fabrication, the presence of material defects continues to limit the use of SiC devices in many current applications. For example, within the n^- drift region of SiC bipolar devices, low defect concentrations are necessary in order to assure the long minority carrier lifetimes (MCLs) necessary for efficient device operation. Identification of the deep defect(s) that controls the MCL is a key step toward the fabrication of efficient high-power SiC devices.

Several studies of deep traps in undoped epitaxial 4H-SiC layers grown by silane chemical vapor deposition have been reported[1–3] in the literature. Among electron traps, centers with apparent activation energies of 0.15–0.17, 0.65, and 1.5–1.6 eV are commonly observed.[1,2] The first of these traps is believed to be due to Ti,[1] the second pair are the well-known negative-*U* centers $Z1/Z2$,[1,4] which have been ascribed to V_C-V_{Si} divacancies[5] (although this assignment has recently come under question[6]), and the third, often referred to as EH6/EH7 traps,[7] has been associated by some researchers with carbon vacancies.[1] Hole traps have been studied in *n*-type layers by minority carrier transient spectroscopy (MCTS).[1,3] The most commonly reported hole traps are boron acceptors (activation energy of 0.25 eV–0.3 eV) and the so-called (boron-related) *D*-centers with activation energies of 0.6–0.65 eV.[1–3] In some samples an additional electron trap with activation energy of 1.1 eV and hole trap with activation energy of 0.85 eV were detected, but these traps were not observed consistently. Based on correlations between the measured carrier lifetimes and the deep level spectra in corresponding films, the $Z1/Z2$ and EH6/EH7 electron traps[1,2] and boron acceptors[3] have been proposed as possible lifetime killers.

However, a positive identification of the defect that controls the MCL has not been reported. In particular, it is important to understand whether both electron traps ($Z1/Z2$ and EH6/EH7) play equally important roles in recombination and whether the contribution of boron acceptors is indeed significant. In agreement with Zhang *et al.*,[1] the latter seems unlikely due to the fairly fast emission rate of holes at room temperature for these relatively shallow centers and the very low electron capture cross section on the order of 10^{-18} cm^2 reported for boron.[3,8,9] In this work we address these questions by analyzing the deep-trap spectra and the carrier lifetimes in a set of lightly doped *n*-type 4H-SiC films with varying thicknesses: By varying the layer thickness it is possible to separate the contributions of bulk and surface recombination to the measured carrier lifetimes, so that the *bulk* MCL may be determined. Since the inverse MCL is proportional to the concentration of the defect limiting the lifetime, these measurements, in conjunction with deep trap spectra, have enabled us to provide evidence that the $Z1/Z2$ defect alone is the lifetime killer in these n^- CVD-grown epilayers.

The layers were grown by CVD on the Si face of $(000\bar{1})$ 4H-SiC n^+ substrates that were 8° miscut towards the $[11\bar{2}0]$ direction. A 5 μm thick n^+ buffer layer was deposited first, followed by the undoped n^- layer ($N_d - N_a \approx$ low to mid -10^{14} cm^{-3}) between 9 and 104 μm thick. For capacitance-voltage, deep-level transient spectroscopy (DLTS), and MCTS measurements, semitransparent Ni Schottky diodes approximately 500 μm in diameter were prepared by plasma sputtering. DLTS spectra were taken in the standard way,[10] while MCTS measurements employed optically injected pulses from a 365 nm, 100 mW AlGaN/GaN light-emitting diode instead of electrical injection. DLTS spectra were also measured on similarly grown 1.2 mm diameter *p-i-n* diodes with n^- layer thicknesses of 30–100 μm. Carrier lifetimes were measured at room temperature from the decay of the exciton/band edge photoluminescence (PL) peak at 391 nm. No significant substrate emission (with significantly broader spectral features) was observed for any of the layers. Injection levels were kept low ($\leqslant 2 \times 10^{13}$ cm^{-3}) in order to insure that measurements were made within the minority carrier regime. The PL was excited at 355 nm by a frequency-doubled, cavity-dumped Ti:sapphire laser-generating <200 fs pulses at 100–500 kHz with an average power

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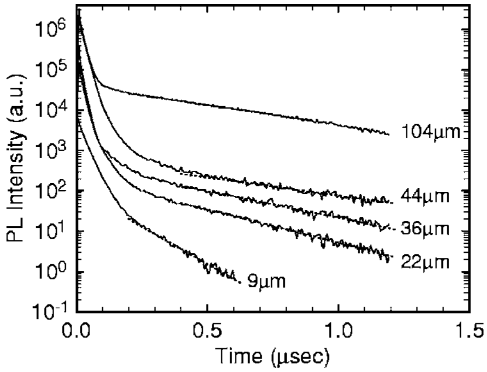

FIG. 1. Low-injection PL decays for n^- epilayers with varying layer thicknesses, as noted in the figure.

≈1 mW. The collected light was focused into a 0.25 m double spectrometer and detected by a photomultiplier using time-correlated photon counting.

The decay of the band edge PL intensity is shown in Fig. 1 for epitaxial layer thicknesses between 9 and 104 μm. It is apparent that the PL decay time decreases for the thinner layers. This behavior is not unexpected, as the effects of surface recombination will dominate in these layers. As we will see subsequently, variations in the defect concentrations with layer thickness also play a significant role.

DLTS spectra typical of the n^- 4H-SiC epilayers are shown in Fig. 2, where the dominant features are the Ti $Z1/Z2$ and EH6/EH7 electron traps and the boron acceptor, D-center and 0.85 eV hole traps. DLTS amplitudes in the figure were converted into concentrations in the usual fashion,[10] with concentrations having meaning *only at the temperature of the peaks*. While the concentrations in the figure do not reflect the so-called "λ-correction,"[11] all defect concentrations determined in this work incorporate this factor. The measured concentrations, as shown in Fig. 3(a), exhibit significant variations with layer thickness. The scatter in the data is undoubtedly due to the fact that each layer thickness represents a separately grown wafer. The apparent decrease of $Z1/Z2$ concentration with thickness may be related to the increase in the time available for diffusion of defects/impurities for the thicker layers, but is not understood in detail at this time. Nonetheless, when this data is compared in the figure to the measured thickness dependence of the inverse PL decay times, it becomes clear that it is only the $Z1/Z2$ defect that shows any significant correlation between the two measurements.

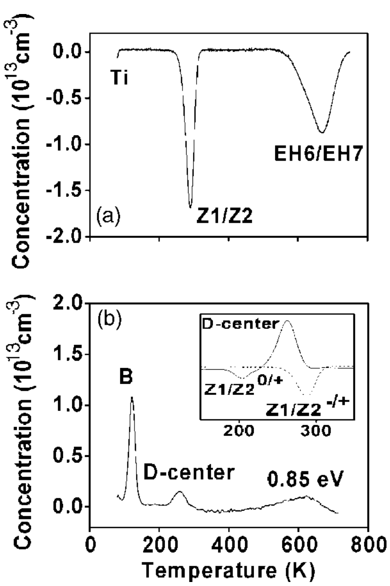

FIG. 2. Typical DLTS spectra of: (a) dominant electron traps and (b) dominant hole traps observed in n^- 4H-SiC epilayers. A $Z1/Z2$ (and D-center) spectrum measured in a p-i-n diode is shown in the inset.

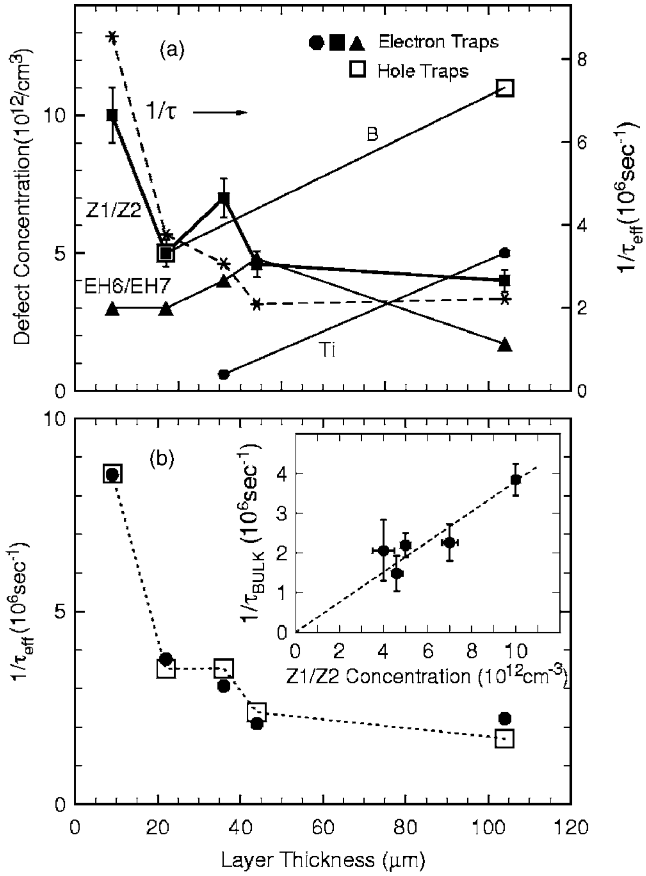

FIG. 3. (a) Dependence of measured defect concentrations and $1/\tau_{\rm eff}$ on layer thickness. (b) Fit of the dependence of $1/\tau_{\rm eff}$ on layer thickness (open squares and dashed line) using Eq. (2), compared to the measured values (solid circles). Inset: Dependence of the extracted inverse bulk MCL on $Z1/Z2$ concentration.

The PL decay time represents an effective lifetime $\tau_{\rm eff}$ with contributions at low injection from both the bulk MCL and surface recombination. Since it is the bulk recombination time that is related directly to the defect concentration:

$$\tau_{\rm bulk}^{-1} = \sigma_p v_{\rm th} N_T, \qquad (1)$$

it is necessary to extract $\tau_{\rm bulk}$ from the measured lifetimes. Here, σ_p is the hole capture cross section, $v_{\rm th}$ the hole thermal velocity, and N_T is the trap $(Z1/Z2)$ concentration. The relationship between the effective and bulk lifetimes is usually expressed as[12]

$$\frac{1}{\tau_{\rm eff}} = \frac{1}{\tau_{\rm bulk}} + \left(\frac{d^2}{\pi^2 D} + \frac{d}{2S}\right)^{-1}, \qquad (2)$$

where the last term represents the contribution from surface recombination; d is the layer thickness, D is the diffusion coefficient for holes in 4H-SiC (see Ref. 13) and S is the surface recombination velocity (SRV). This expression assumes the same SRV for both the sample surface and the n^-/n^+ interface,[12] so that S in Eq. (2) actually reflects an average SRV for the layer. Using Eq. (1) for the bulk lifetime and the measured values of the $Z1/Z2$ concentrations for N_T, the measured dependence of $1/\tau_{\text{eff}}$ on d [Fig. 3(a)] may be fitted using Eq. (2), where σ_p and S are the only fitting parameters. The resulting fit is shown in Fig. 3(b), where the measured points are the filled circles and the fit is represented by the open squares/dotted line. The fitted curve is not smooth because the measured concentrations, which exhibited some scatter, were used in Eqs. (1) and (2) rather than treating N_T as a freely varying parameter. The data is fitted well by Eq. (2), with fitting parameters $S=2500$ cm^2/s and $\sigma_p=3.5\times10^{-14}$ cm^2. This SRV is comparable to values published in the literature,[14] and the large hole capture cross section agrees well with DLTS results for *p*-*i*-*n* structures presented below.

Using this value for σ_p, the inverse *bulk* lifetimes extracted using Eq. (1) are plotted against the $Z1/Z2$ concentration in the inset in Fig. 3(b). The dashed line is a least-squares linear fit of the data, with a slope corresponding to $\sigma_p=3.4\times10^{-14}$ cm^2: essentially the same as that determined from the fit in Fig. 3(b). Within our experimental error, there is a linear dependence of the inverse bulk lifetime on $Z1/Z2$ concentration, which represents strong evidence that this defect dominates the recombination of the minority carriers.

Confirmation of the dominant role of $Z1/Z2$ in recombination was provided by DLTS measurements on *p*-*i*-*n* diodes. With no applied forward bias, the same electron traps seen in the single-layer structures [Fig. 2(a)] were observed in the diodes. With the application of forward bias (and the injection of minority holes), hole trap signals due to boron and *D*-centers emerged. For the EH6/EH7 and 1.1 eV electron traps, the peak amplitude was unchanged with injection for forward bias pulses up to +5 V, indicating that these traps have a low capture cross section for holes, and are not likely to be the defects limiting the MCL.

Unlike EH6/EH7, for forward voltages greater than 2.5 V, the amplitude of the $Z1/Z2$ peak near 300 K, corresponding to the $-/+$ transition of the negative-*U* center,[4] vanished completely, while a new electron trap appeared near 220 K with apparent activation energy of 0.4 eV [inset, Fig. 2(b)]. This new feature most likely corresponds to the $0/+$ transition of $Z1/Z2$ with reported activation energy of 0.45 eV.[4] From the magnitude of the decrease of the DLTS amplitude for this transition with a further increase in hole injection, and from the relationship between the ratio σ_p/σ_n and the fraction of filled traps[8,9] $(\cong\frac{1}{2})$, we can conclude that for these two transitions, $\sigma_p \geqslant \sigma_n$. Since σ_n is already large, 2×10^{-14} cm^2 (from this work and consistent with other published data), this indicates that $Z1/Z2$ also has a large capture cross section for holes that is also consistent with the value of σ_p determined earlier. Thus, negatively charged $Z1/Z2$ centers capture holes very effectively, and are converted into the metastable neutral state. Therefore, these DLTS measurements lead to the same conclusion as the lifetime studies: $Z1/Z2$ defects, with a large capture cross section for holes, dominate in limiting the MCL in these n^- epilayers.

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[1]J. Zhang, L. Storasta, J. P. Bergman, N. T. Son, and E. Janzen, J. Appl. Phys. **93**, 4708 (2003).
[2]T. Tawara, H. Tsuchida, S. Izumi, I. Kamata, and K. Izumi, Mater. Sci. Forum **457–460**, 565 (2004).
[3]L. Storasta, J. P. Bergman, C. Hallin, and E. Janzen, Mater. Sci. Forum **389–393**, 549 (2002).
[4]C. G. Hemmingsson, N. T. Son, A. Ellison, J. Zhang, and E. Janzen, Phys. Rev. B **58**, R10119 (1998).
[5]T. Dalibor, G. Pensl, T. Kimoto, H. Matsunami, S. Sridhara, R. P. Devaty, and W. J. Choyke, Diamond Relat. Mater. **6**, 1333 (1997).
[6]N. T. Son, T. Umeda, J. Isoya, A. Gali, M. Bockstedte, B. Magnusson, A. Ellison, N. Morishita, T. Ohshima, H. Itoh, and E. Janzen, Mat. Sci. Forum (in press).
[7]C. Hemmingsson, N. T. Son, O. Kordina, J. P. Bergman, E. Janzen, J. L. Lindstrom, S. Savage, and N. Nordell, J. Appl. Phys. **81**, 6155 (1997).
[8]M. M. Anikin, N. I. Kuznetsov, A. A. Lebedev, A. M. Strelchuk, and A. L. Syrkin, Sov. Phys. Semicond. **24**, 869 (1990).
[9]M. M. Anikin, A. S. Zubrilov, A. A. Lebedev, A. P. Stel'chuk, and A. E. Cherenkov, Sov. Phys. Semicond. **25**, 289 (1991).
[10]D. V. Lang, J. Appl. Phys. **45**, 3023 (1974).
[11]G. M. Martin, A. Mittonneau, D. Pons, A. Mircea, and D. W. Woodard, J. Phys. C **13**, 3855 (1980).
[12]M. Boulou and D. Bois, J. Appl. Phys. **48**, 4713 (1977).
[13]P. Grivickas, J. Linnros, and V. Grivickas, Mater. Sci. Forum **338–342**, 671 (2000).
[14]A. Galeckas, J. Linnros, M. Frischholz, and V. Grivickas, Appl. Phys. Lett. **79**, 3654 (2001).