Generation and Recombination Carrier Lifetimes in 4H SiC Epitaxial Wafers

G. Chung[1], M. J. Loboda[1], M. J. Marinella[2], D. K. Schroder[2], P. B. Klein[3],
T. Isaacs-Smith[4] and J. W. Williams[4]
[1] Dow Corning Compound Semiconductor Solutions, LLC, Midland, MI 48611, USA
[2] Department of Electrical Engineering and Center for Solid State Electronics Research, Arizona State University, AZ 85287, USA
[3] Naval Research Laboratory, Washington DC 20375, USA
[4] Physics Department, Auburn University, AL 36849, USA
Corresponding author: gil.chung@dowcorning.com

1. Abstract

Compared to silicon, there have been relatively few comparative studies of recombination and carrier lifetimes in SiC. For the first time, both generation and recombination carrier lifetimes are reported from the same areas in 20 µm thick 4H SiC n-/n+ epi-wafer structures. The ratio of the generation to recombination lifetime is much different in SiC compared to Si. Activation energy calculated from SiC generation lifetimes shows that traps with energy levels near mid-gap dominate the generation lifetime. Comparison of both generation and recombination lifetimes and dislocation counts measured in the device area show no correlation in either case.

2. Introduction

Carrier lifetime is an established method for characterizing semiconductor materials. Both carrier recombination and generation lifetimes provide important and complementary information to understand electrical defects in the material and the AC operation of semiconductor devices. Carrier lifetime testing and mapping is well established in silicon technology for grading material quality [1]. To achieve high-temperature high-power and fast switching bipolar SiC devices, information on the complete recombination and generation process is important to fully assess the material performance. In this paper both generation and recombination lifetimes, measured by pulsed MOS-capacitor (MOS-C) and photoluminescence (PL) spectroscopy, respectively, are measured at identical device locations for direct comparison and correlation between lifetime values and material defects.

3. Experimental

MOS capacitors were fabricated on an n-type 4H-SiC epitaxial wafer (t_{epi}=20 µm, N_d =1x10^{16} cm^{-3}) grown based on chlorosilane/propane chemistry at Dow Corning with a 45 nm thermal oxide. Generation lifetimes were measured with the pulsed MOS-C technique. This technique involves biasing a MOS-C into deep depletion and monitoring the capacitance change during the generation of the inversion layer. The data can then be used to calculate an effective generation lifetime for the material. An RIE MESA etch was performed to register accurate MOS capacitor locations, and the gate metals and oxide layers were etched off for recombination lifetime measurements by PL. Recombination lifetimes were measured from the decay of the exciton/band edge PL peak at 391 nm with injection levels of about 10^{16} cm^{-3}. Finally, a KOH etch was performed at 500 °C for a few minutes to count underlying defects in active device areas.

4. Data and Discussion

The theory and experimental work related to generation and recombination lifetimes in silicon is well documented by Schroder [2,3]. From the Shockley-Read-Hall theory of carrier generation and recombination through traps, the generation lifetime τ_g can be written as

$$\tau_g \approx \tau_r e^{|E_T - E_i|/kT} \tag{1}$$

where τ_r is the recombination lifetime and E_T and E_i are defect and intrinsic energy levels, respectively. This simple relation is valid as long as the capture cross sections do not differ too greatly and shows the ratio of the generation to recombination lifetimes to be determined by the energy difference of the trap from the intrinsic energy level.

Fig. 1 shows a box plot of effective recombination and generation lifetimes from the three sample pieces (270 MOS capacitors) of about 1 cm^2 of 4H SiC epitaxial wafer. Effective recombination and generation lifetimes are measured at room temperature and 400 ^{o}C, respectively. Since the generation rate is n_i / τ_g, the inversion layer takes a very long time at room temperature to form in the 4H-SiC MOS. All generation lifetimes in this plot are measured at 400 °C in order to reduce the measurement time to several minutes. For this sample the average effective generation and recombination lifetimes are 706 and 631 ns, respectively. Effective generation lifetime shows much wider standard deviation than effective recombination lifetime. In the pulsed MOS-C measurements, oxide leakage currents result in an increase in the calculated generation lifetime as compared to the true generation lifetime due to loss of inversion charges through the oxide. The "probe-lift" technique [4] has been developed to measure oxide leakage currents down to a few hundred fA and data applied to correct generation lifetime. In measurements where the leakage current is known, the corrected lifetime can be obtained by defining an inversion current as

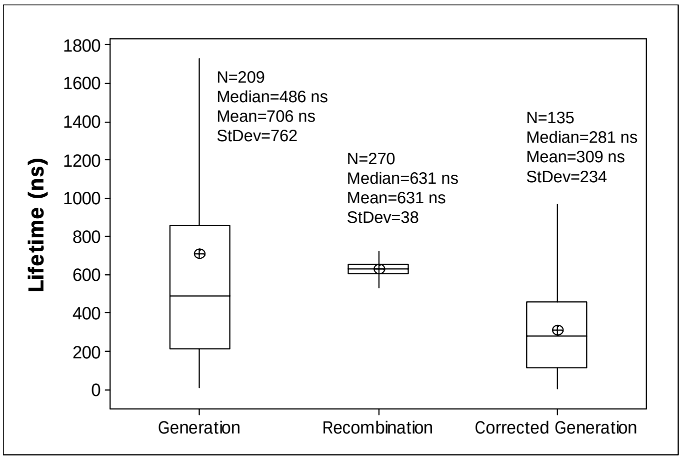

Fig. 1. Boxplot of generation, recombination and corrected generation lifetimes (ns) of 4H-SiC MOS capacitors. N is the total sample number.

$$I_{inv} = \frac{dQ_{inv}}{dt} \approx \frac{\Delta Q_{inv}}{\Delta t} \tag{2}$$

where ΔQ_{inv} is the net inversion charge gained during the recovery from deep depletion to inversion; the time to gain this charge is Δt. Then, we define the ratio of leakage to inversion current as

$$r = I_{leak} / I_{inv} \tag{3}$$

We assume that the inversion current is given by

$$I_{inv} = I_{generation} - I_{leak}\,, \quad I_{generation} = I_{inv}(1+r) \tag{4}$$

Since the generation lifetimes are proportional to the inverse of their respective currents, we obtain the corrected generation lifetime

$$\tau_{g-corrected} = \tau_{measured}(1+r)^{-1} \tag{5}$$

The average corrected generation lifetime is much shorter than the uncorrected one indicating that gate oxide leakage current affects the effective generation lifetime. With use of this technique, the error in generation lifetime calculation due to leakage currents has been greatly reduced. The ratio of corrected generation to recombination lifetime of n-type 4H-SiC is about 0.5 and very different from what is expected from silicon which typically shows 50~100 higher generation lifetime than recombination lifetime. To understand this discrepancy the trap energy $E_T - E_i$ in (1) needs to be determined. A simple way to extract the trap energy, using the pulsed MOS-C is to record the generation lifetime as a function of temperature. We consider the general temperature dependent form of the lifetime with assumptions that the temperature dependence of thermal velocity and capture cross sections is negligible:

$$\tau_g = \tau_{g0} e^{\Delta E / kT} \tag{6}$$

From (6), we define $\Delta E = E_T - E_i$ and the trap energy is given by $E_T = E_i \pm \Delta E$. ΔE from the Arrhenius plot is the difference of the trap energy and the intrinsic energy level. Fig 2 shows Arrhenius plots of the effective generation lifetime of 4H-SiC and demonstrates that the effective generation lifetime is nearly constant with temperature and ΔE is very low. This implies that the trap levels are near the center of the band and $\tau_g / \tau_r \approx 1$. Wang et al. reported the activation energy of the recovery time is, in some cases, near E_i in a SiC n-p-n capacitor [5]. It is also recently reported that the defect level at mid gap dominates recombination in 4H-SiC BJT [6].

Recombination lifetimes were also measured at various temperatures (Fig. 3). Although the expected monotonic increase in the PL lifetime with increasing temperature was not observed in this sample, the projected recombination lifetime at 400 °C is about 350 nsec and very comparable to measured generation lifetime at 400 ^{o}C. The unusual temperature dependence of the recombination lifetime is not well understood at this time. Chlorosilane based epi-wafers showed $Z_{1/2}$ concentration less than $5x10^{11}$ cm^{-3} from DLTS [7] and this low value suggests that $Z_{1/2}$ is not the dominant recombination trap in chlorosilane based SiC epilayers, in contrast to results which show that $Z_{1/2}$ is the recombination lifetime limiting trap in silane based SiC epiwafers [8].

Both generation and recombination lifetimes are affected by surface states which are generally characterized by surface velocities. Surface generation velocity (S_g) which is lateral to the gate area depends on interface trap density (D_{it}) of the SiC/SiO$_2$ interface. S_g of 4H-SiC/SiO2 interface would be in the order of 10^3 cm/s based on an interface trap density of 10^{11} $cm^{-2}eV^{-1}$ and has no significant impact on effective generation lifetime. Recombination lifetime is affected by the surface recombination velocity (S_r). Bulk recombination lifetime for SiC materials used in this study might be about two times higher than effective recombination lifetime in the 4H-SiC based on the previous reported S_r and ambipolar diffusion coefficient (D) [8,9]. Therefore, the magnitude of the ratio of generation to recombination lifetime of 4H-SiC in this study is not the result of surface effect and is primarily influenced by bulk recombination and generation.

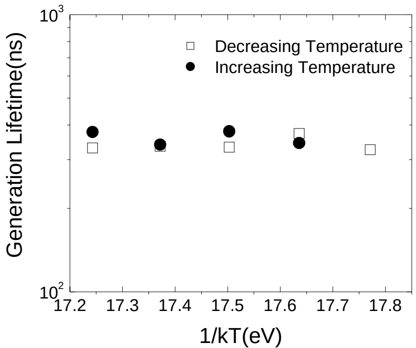

Fig. 2. Arrhenius plot of the effective generation lifetime.

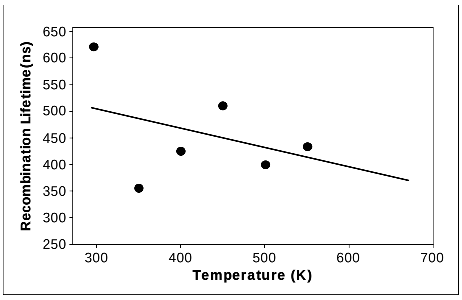

Fig. 3. Recombination lifetime at various temperatures

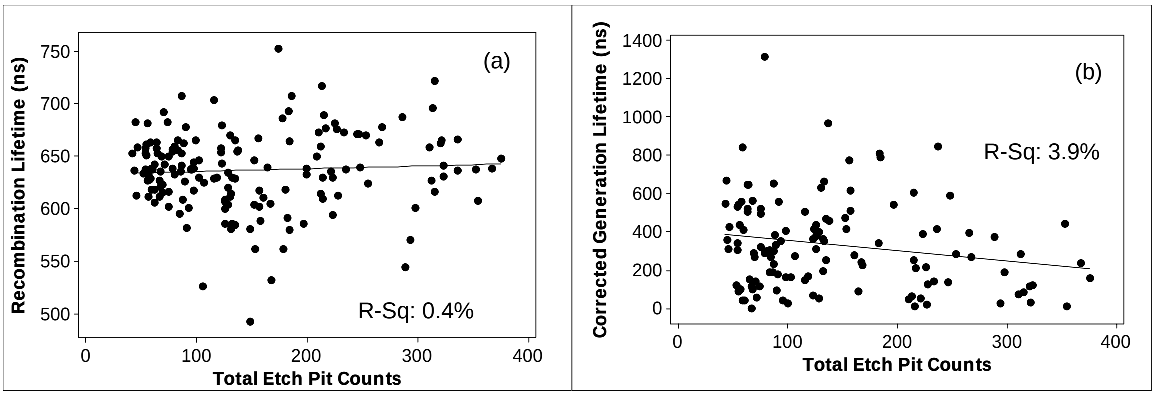

Fig. 4. Recombination and corrected generation lifetimes with total etch pit counts in the tested devices of area $1.22x10^{-3}$ cm^2.

To understand the influence of material defects on carrier lifetimes, the samples were etched in KOH and the defects were categorized by etch pit shapes and counted under microscope. Fig. 4 shows regression plots of the recombination and corrected generation lifetimes with the number of etch pits in each device. About 98% of the total etch pits are threading edge dislocations (TED) in the tested devices. Note that devices containing micropipes were included. There is no correlation between the lifetimes and number of etch pits. S_r might be a dominant lifetime limiting factor in the case of recombination lifetime. In contrast to recombination, the generation lifetime can be drastically changed with the field enhanced carrier generation. The field enhanced emission depends on impurities, defects including point and material defects and their interaction [10]. Some of the MOS capacitors of 4H-SiC show a negative activation energy of the generation lifetime to suggest field enhanced emission. If the generation lifetime in 4H-SiC depends on field enhanced emission then the generation lifetime can vary widely over a narrow range of dislocation densities. Local stacking faults like 3C inclusions can be also responsible for the negative activation energy. In contrast to correlating lifetimes with dislocation densities, Fig. 5 shows correlations of oxide leakage currents at 400 ^{o}C and corrected generation lifetime (a) and oxide leakage currents and total etch pit counts (b). Measured generation lifetimes show significant variation, even at very low oxide leakage currents. Oxide leakage currents, showing no correlation with total etch pit counts, can be influenced as much by oxide quality itself, rather than just underlying defects.

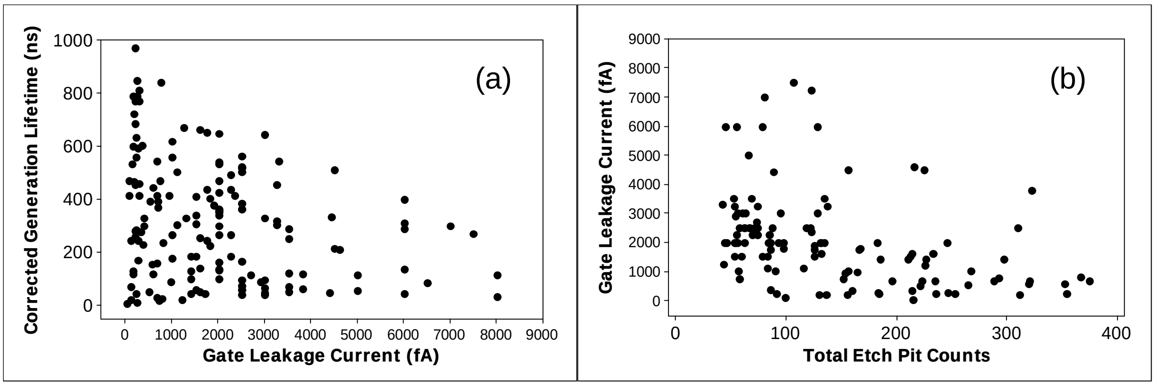

Fig. 5 Corrected generation lifetimes with gate leakage currents (a) and gate leakage currents with total etch pit counts.

5. Conclusions

Both generation and recombination lifetimes of 4H SiC epitaxial materials are measured. The magnitude of the ratio of generation to recombination lifetime of 4H-SiC is quite different from silicon. Generation and recombination lifetimes and activation energy of generation lifetime data support the conclusion that traps near the center of the band gap dominate the generation lifetime. Generation and recombination lifetimes do not show correlation with dislocation densities in the active device area. Field-enhanced generation emission can account for large generation lifetime variations observed at constant dislocation density.

6. Acknowledgement

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7. References

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