Electrical Characteristics of Near-Interface Traps in 3C-SiC Metal–Oxide–Semiconductor Capacitors

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Abstract—Deep-depletion capacitance measurements on n-type 3C-SiC MOS capacitors that exhibit both field and temperature dependencies are presented and analyzed in this letter. A two-step electron-detrapping process, in which electrons first tunnel from neutral near-interface traps to interface traps and are subsequently thermally emitted into the silicon carbide conduction band, is identified as the responsible mechanism. A mathematical model is proposed for this two-step detrapping process.

Index Terms—Capacitance transients, MOS capacitors, near-interface traps, 3C-SiC.

I. INTRODUCTION

3C-SiC has an advantage over other SiC polytypes in that it can be integrated with silicon [1], [2]. With the ability to grow high-quality SiO₂ layers by thermal oxidation, together with its wide energy gap, silicon carbide is well suited for the fabrication of MOS integrated circuits for operation in high-temperature environments. However, the high density of defects at the SiO₂/SiC interface degrades the device performance and causes reliability problems [3], [4]. Traditionally, high-frequency capacitance–voltage (HFC–V) and capacitance transient (*C*–*t*) techniques are used in the study of the deep-depletion capacitance relaxation of this interface [5]–[8]. Avila *et al.* observed an increase in the deep-depletion capacitance of 3C-SiC/Si MOS capacitors at room temperature and attributed this to the minority carrier generation mediated by interface traps [5]. In this mode of inversion layer formation, the generation rate is proportional to the intrinsic carrier concentration n_i [9]. For 3C-SiC, n_i is on the order of 10^{-1} cm⁻³ [10], compared to 10^{10} cm⁻³ in silicon. Given that the generation rate in SiC is 11 orders of magnitude smaller than that in silicon, we conclude that this generation process is practically nonexistent in SiC at room temperature. Tang *et al.* proposed that the observed increase in deep-depletion capacitance is due to minority carrier generation by impact ionization [8]. However, impact ionization is weakly temperature dependent [11], which is contrary to our observation that deep-depletion capacitance relaxation is strongly temperature dependent. As such, there is no satisfactory theory to correctly account for the capacitance relaxation.

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Fig. 1. Forward and reverse HFC–V curves of a 3C-SiC MOS capacitor grown in NO (100%) at 1160 °C for two different bias sweeps measured at a frequency of 10 kHz with a sweep rate of 0.1 V/s. The arrows show the directions of the bias sweeps.

In this letter, we combined the results of the measurements from HFC–V and *C*–*t* to arrive at a new model for electron detrapping from near-interface traps at the SiO₂/SiC interface, which accounts for the observed increase in deep-depletion capacitance.

II. EXPERIMENT

3C-SiC MOS capacitors were prepared on nitrogen-doped n-type (10^{15} – 10^{17} cm⁻³) SiC epitaxial films (with a thickness in the range of 4–6 μm) supplied by NOVASiC, Institute of Crystal Growth (Berlin, Germany), and Hoya Advanced Semiconductor Technologies Co. Ltd. Gate oxides were grown in dry O₂ or NO (100%) at 1160 °C. The oxide thickness ranged from 18 to 23 nm, as determined by accumulation capacitance measurements. The gate electrode is aluminum, with an area of 0.0025 cm². The MOS capacitors are characterized by two different methods: 1) HFC–V measurement and 2) *C*–*t* measurement, in which the capacitor is initially biased in accumulation and then pulsed to deep depletion and the capacitance is then measured as a function of time. All measurements were performed under a light-tight and electrically shielded environment.

III. RESULT AND DISCUSSION

Fig. 1 shows a typical HFC–V curve (solid lines) measured at room temperature when swept from 2 to –10 V and vice versa. It can be seen that both the forward and reverse *C*–V plots show deep depletion and are identical. The *C*–V curves display a negative flatband voltage of –4 V

Fig. 2. Capacitance transients for five different oxide fields. The dotted line is the predicted inversion capacitance. The inset shows the two-step electron-detrapping process.

and, otherwise, minimal distortion when compared to the theoretical C - V curve. The negative flatband voltage indicates that the trap density at or near the SiO_2/SiC interface has an effective positive charge of $2.6 \times 10^{12} \text{ cm}^{-2}$. The minimal distortion observed for these two curves indicates that the positive charge is due to traps that do not respond (emit or capture electrons) to the dc sweep in the applied bias range. When the dc negative bias is increased to -16 V , a hysteresis appears between the forward and reverse sweeps of the HFC- V curves, which are shown as dashed lines in Fig. 1. The reverse sweep exhibits a more negative flatband voltage, implying that a more positive charge is introduced, as a result of the higher negative bias. The positive trapped charge decreases as the bias is reduced, implying that the positive charge is being removed as the surface is being swept toward the accumulation. It is also noticed that the forward capacitance starts to increase at -12 V . This is attributed to an increase in the effective positive charge at or near the interface, which has the net effect of reducing the band bending, leading to the reduction in deep-depletion width and, therefore, the increase in capacitance. There is a hysteresis between the forward and reverse curves due to the fact that not all the traps that have emitted electrons between -10 and -16 V can recapture the electrons before an accumulation bias is reached.

Fig. 2 shows the C - t measurements at room temperature for different oxide field values (these are obtained by varying the gate bias) close to where the rise in deep-depletion capacitance started to occur in Fig. 1. If the deep-depletion capacitance relaxation is due to inversion carrier generation, all the curves will reach the same final steady-state inversion capacitance (shown as the dotted line in Fig. 2). It is clear that the final steady-state capacitances are above the predicted inversion capacitance. Furthermore, the capacitance transient is highly dependent on the oxide field. This is distinctly different from the capacitance transient due to the inversion carrier generation. We ascribe this to the electron detrapping from neutral near-interface traps, which leaves behind a positive charge. In order to further investigate the detrapping process, we have developed

a mathematical model to describe the field- and temperature-dependent capacitance transient. The distribution of the near-interface traps per unit area at distance x from the SiC/SiO_2 interface with a single energy level E_t , which was measured from the SiC conduction band, will be labeled $N_T(x, E_t)$. Labeling the corresponding detrapping time constant $\tau(x, E_t)$, the detrapping rate of the near-interface traps can be written as

$$\frac{dN_T(x, E_t, t)}{dt} = -\frac{N_T(x, E_t, t)}{\tau(x, E_t)}. \quad (1)$$

The rate of change of N_T is also related to the rate of change of the total MOS capacitance dC/dt , using the relation [12]

$$\frac{dN_T}{dt} = qN_D C_{\text{ox}} \varepsilon_{\text{SiC}} \frac{1}{C^3} \frac{dC}{dt} \quad (2)$$

where q is the electron charge, N_D is the bulk dopant concentration, ε_{SiC} is the silicon carbide dielectric constant, and C_{ox} is the oxide capacitance per unit area. Equations (1) and (2) can then be integrated and combined to give the following equation:

$$\frac{1}{C^2(t)} = \frac{2N_T(t_0)}{N_D C_{\text{ox}} \varepsilon_{\text{SiC}}} (\exp(-t/\tau) - \exp(-t_0/\tau)) + \frac{1}{C^2(t_0)} \quad (3)$$

where $N_T(t_0)$ is the initial trap density. Using (3), τ can be extracted from the measured $C(t)$ data in Fig. 2. As the extracted τ values shown in Fig. 3 exhibit both field and temperature dependencies, it points toward the two-step electron-detrapping process shown in the inset of Fig. 2 [13]. In this process, the electrons from the neutral near-interface traps tunnel to the interface traps, which are subsequently thermally emitted into the silicon carbide conduction band. This leaves positive charges in the near-interface traps that reduce the semiconductor field and thus cause capacitance relaxation. This is similar to the mechanism behind the transient threshold voltage shifts observed in the electrical stressing of MOSFETs [13]. It should be noted that there is no difference between repeated C - V measurements after setting the MOS capacitor in accumulation. This indicates that the traps that become charged during the voltage sweep through deep depletion very quickly recapture electrons when the bias is set back to accumulation. There is an obvious asymmetry between the slow two-step electron-detrapping process and the very fast electron capture process. The reason for the faster capture process is the huge concentration of electrons in accumulation that are available for capturing by each trap.

Since the tunneling and thermal-emission steps occur in series, an effective first-order time constant for the two-step detrapping process can be written as [13]

$$\tau(x, E_t) = \tau_{\text{tun}}(x, E_t) + \tau_e(E_t). \quad (4)$$

The first term on the right-hand side of (4) represents the carrier tunneling time constant, in which the carrier tunnels from the near-interface traps at E_t to an interface trap at the same energy

Fig. 3. Time constants as a function of oxide field and temperature. The measured temperature ranges from 30 °C to 60 °C. The 3-D plot shows (symbols) the experimentally extracted time constant and (grid) the best fit using (4).

level located at the SiO₂/SiC interface through a trapezoidal potential barrier. This time constant is given by [13]–[15]

$$\tau_{\text{tun}}(x, E_t) = \tau_t \exp\left(\frac{8\pi\sqrt{2m^*}}{3hqE_{\text{ox}}}\left[(E_t)^{3/2} - (E_t - qE_{\text{ox}}x)^{3/2}\right]\right) \quad (5)$$

where τ_t is a fitting constant, h is the Planck's constant, q is the electron charge, m^* is the effective tunneling mass for electrons in the oxide, and E_{ox} is the oxide field. The second term in (4) describes the thermal emission time constant for the carrier at interface traps emitted to the silicon carbide conduction band and is given by [9]

$$\tau_e(E_t) = \tau_o \exp\left(\frac{E_C - E_t}{kT}\right) \quad (6)$$

where τ_o is a preexponential constant, and E_C is the energy at the bottom of the silicon carbide conduction band. By fitting (4)–(6) to the measured time constants shown in Fig. 3, the tunneling distance and the energy level of the near-interface traps are found to be 0.7 nm and 0.40 eV below the conduction band edge, respectively. The extracted near-interface trap tunneling distance is comparable to that extracted from the transient voltage shift relaxation method for the SiO₂/Si interface [13]. It is most likely that there are active near-interface traps at different energy levels and distances from the interface. Therefore, the extracted x and E_t are simply the average values for all these traps.

IV. CONCLUSION

In summary, we have shown that the electron detrapping from neutral near-interface traps is responsible for the rise in capacitance in the deep-depletion region and the hysteresis effect of the HFC– V curves for 3C-SiC MOS capacitors. We have also established a new model that provides close agreement with the 3C-SiC MOS capacitance behavior experimentally observed. The presented experimental results and model show that inversion carrier generation is not required to account for the rise in capacitance at high deep-depletion bias.

REFERENCES

- [1] S. Nishino, J. A. Powell, and H. A. Will, "Production of large-area single-crystal wafers of cubic SiC for semiconductor devices," *Appl. Phys. Lett.*, vol. 42, no. 5, pp. 460–462, Mar. 1983.
- [2] H. Nagasawa and K. Yagi, "3C-SiC single-crystal films grown on 6-inch Si substrates," *Phys. Stat. Sol. (B)*, vol. 202, no. 1, pp. 335–358, Jul. 1997.
- [3] V. V. Afanas'ev, F. Ciobanu, G. Pensl, and A. Stesmans, *Recent Major Advances in SiC*, W. J. Choyke, H. Matsunami, and G. Pensl, Eds. New York: Springer-Verlag, 2003, pp. 343–371.
- [4] P. Jamet, S. Dimitrijevic, and P. Tanner, "Effects of nitridation in gate oxides grown on 4H-SiC," *J. Appl. Phys.*, vol. 90, no. 10, pp. 5058–5063, Nov. 2001.
- [5] R. E. Avila, J. J. Kopanski, and C. D. Fung, "Behavior of inversion layers in 3C silicon carbide," *Appl. Phys. Lett.*, vol. 49, no. 6, pp. 334–336, Aug. 1986.
- [6] S. Zaima, K. Onoda, Y. Koide, and Y. Yasuda, "Effects of oxidation conditions on electrical properties of SiC-SiO₂ interfaces," *J. Appl. Phys.*, vol. 68, no. 12, pp. 6304–6308, Dec. 1990.
- [7] M. Shinohara, M. Yamanaka, S. Misawa, H. Okumura, and S. Yoshida, "C–V characteristics of MOS structures fabricated of Al-doped p-type 3C-SiC epilayers grown on Si by chemical vapor deposition," *Jpn. J. Appl. Phys.*, vol. 30, no. 2, pp. 240–243, Feb. 1991.
- [8] S. M. Tang, W. B. Berry, R. Kwor, M. V. Zeller, and L. G. Matus, "High frequency capacitance-voltage characteristics of thermally grown SiO₂ films on β -SiC," *J. Electrochem. Soc.*, vol. 137, no. 1, pp. 221–225, Jan. 1990.
- [9] W. Shockley and W. T. Read, "Statistics of the recombinations of holes and electrons," *Phys. Rev.*, vol. 87, no. 5, pp. 835–842, Sep. 1952.
- [10] M. E. Levinstein, S. L. Rumyantsev, and M. S. Shur, *Properties of Advanced Semiconductor Materials GaN, AlN, SiC, BN, SiC, SiGe*. New York: Wiley, 2001, pp. 93–148.
- [11] S. M. Sze, *Physics of Semiconductor Devices*. New York: Wiley, 1981, ch. 1.
- [12] D. K. Schroder, *Semiconductor Material and Device Characterization*. New York: Wiley, 2006, ch. 5.
- [13] T. L. Tewksbury, III and H. S. Lee, "Characterization, modeling, and minimization of transient threshold voltage shifts in MOSFETs," *IEEE J. Solid-State Circuits*, vol. 29, no. 3, pp. 239–252, Mar. 1994.
- [14] T. K. Kang, M. J. Chen, C. H. Liu, and S. K. Fan, "Numerical confirmation of inelastic trap-assisted tunneling (ITAT) as SILC mechanism," *IEEE Trans. Electron Devices*, vol. 48, no. 10, pp. 2317–2322, Oct. 2001.
- [15] T. Wang, L. P. Chiang, N. K. Zous, T. E. Chang, and C. Huang, "Characterization of various stress-induced oxide traps in MOSFETs by using a subthreshold transient current technique," *IEEE Trans. Electron Devices*, vol. 45, no. 8, pp. 1196–1791, Aug. 1998.