Subthreshold characteristics of 4H-SiC n- and p-channel MOSFETs at low temperature

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Extremely high density of interface states (D_{it}) exist in SiC MOS systems and the D_{it} values rapidly increase with approaching the conduction band edge (E_C) and the valence band edge (E_V) [1]. However, conventional characterization methods of D_{it} based on *C-V* measurement of MOS capacitors have limits to estimate D_{it} at the energy level very close to the band edges (e.g., $E_C - E_T < 0.2$ eV). In previous studies, D_{it} very close to E_C was evaluated from subthreshold slopes of MOSFETs at low temperature [2, 3]. On the other hand, very few studies have been reported on the D_{it} very close to E_V and no comparison with the conventional characterization methods has been made. In this study, D_{it} very close to both E_C and E_V was evaluated from the low-temperature subthreshold slopes of n- and p-channel MOSFETs annealed in NO or N_2.

The lateral n- and p-channel MOSFETs were fabricated on p- and n-type 4H-SiC (0001) epilayers on p- and n-type substrates, respectively. The doping concentrations of the p- and n-type epilayers were 1×10^{15} cm^{-3} and 8×10^{15} cm^{-3}, respectively. The gate oxide was formed by dry oxidation at 1300 ℃ for 20 min, followed by NO annealing (1250 ℃, 70 min) or N_2 annealing (1400 ℃, 45 min) [4]. The oxide thickness was about 30 nm, and the channel length and width were 8–10 μm and 170 μm, respectively. Gate characteristics of the fabricated MOSFETs were measured at 77, 100, 200 and 300 K.

Fig. 1 shows the subthreshold characteristics of the fabricated n- and p-channel MOSFETs at 77, 200, and 300 K. In order to estimate D_{it} very close to the band edges, the *SS* values at the normalized drain current ($I_{DN} = I_D \times L/W$) of 1×10^{-10} A (n-channel) and 1×10^{-11} A (p-channel) at different temperatures were used. For estimating the energy levels of D_{it}, the theoretical drain current was calculated using the following approximation formula:

$$I_{DN} = e n_{free}(E_f) \mu V_d \quad (1)$$

where e is the elementary charge, $n_{free}(E_f)$ is the density of free carriers, μ is the mobility of free carriers, and V_d is the drain voltage. In the calculation, the mobilities of electrons and holes were assumed to be constant and the two-dimensional density of states was considered for the calculation of n_{free}. Fig. 2 depicts comparison of the D_{it} distributions obtained from the *SS* values in this study and extracted by the C-ψ_s method from *C-V* characteristics of SiC MOS capacitors in our previous study [4]. D_{it} in the energy range very close to the band edges ($E_C - E_T < 0.2$ eV or $E_T - E_V < 0.2$ eV) was obtained. The extracted D_{it} values show good agreement with the results of C-ψ_s method in the assessable energy range of the C-ψ_s method and it follows the trends extrapolated from the C-ψ_s results in the energy range closer to the band edges. The N_2-annealed p-channel MOSFETs exhibited a slightly lower D_{it} than the NO-annealed ones at the energy levels very close to E_V, and the peak value of field-effect mobility (μ_{FE}) of the N_2-annealed p-channel MOSFETs (17 cm^2/Vs) was higher than that in the NO-annealed ones (13 cm^2/Vs) at 300 K [4]. On the other hand, although the NO-annealed n-channel MOSFETs showed a slightly higher D_{it} at the energy levels very close to E_C than the N_2-annealed ones, the peak value of μ_{FE} in the NO-annealed n-channel MOSFETs (40 cm^2/Vs) was higher than that in the N_2-annealad ones (34 cm^2/Vs) at 300 K [4].

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[3] T. Kobayashi *et al, Appl. Phys. Lett.* **108**, 152108 (2016). [4] K. Tachiki and T. Kimoto, *IEEE Trans. Electron Devices* **68**, 638 (2021).

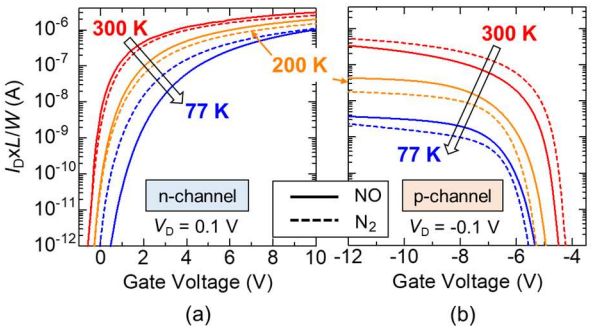

Fig. 1. Subthreshold characteristics of NO- and N_2-annealed (a) n-channel and (b) p-channel SiC (0001) MOSFETs at different temperatures (77, 200 and 300 K).

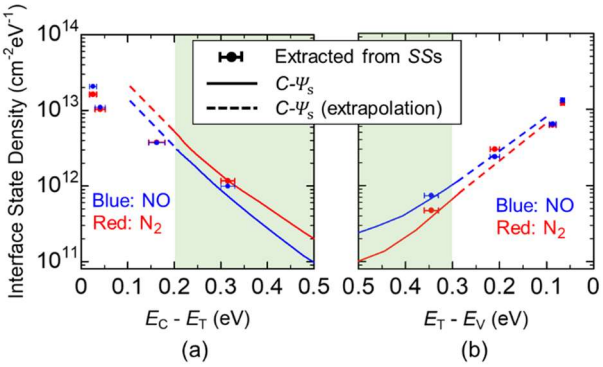

Fig. 2. Comparison of D_{it} distributions extracted by the C-Ψ_s method from MOS capacitors and extracted from *SS*s of SiC MOSFETs at different temperatures near (a) E_C and (b) E_V.