Understanding of Subthreshold Swing of Si n-MOSFETs over a Temperature Range from 300 to 38 K

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【Background】 Attention has recently been paid to the operation of Si MOSFETs at cryogenic temperature, because of the application of Si CMOS to quantum computing system. Thus, understanding of electrical characteristics of MOSFETs at low temperatures is mandatory. Particularly, the behaviors of subthreshold swing (SS) at low temperatures, which have been reported to have peculiar temperature and I_d dependencies [1-3], are one of the key factors in physical understanding of the properties of cryogenic CMOS. In order to explain SS of Si n-MOSFETs at deep-cryogenic temperatures, which does not follow the Boltzmann thermal limit of, $(k_BT/q)\ln 10$, Beckers *et al.* have proposed models of band tail states [2] and localized states with Gaussian distribution near the band edge [3]. However, the validity of those models has been confirmed in SS in a limited temperature range under a given device condition and, thus, the effectiveness has not been proven over a wide range of temperatures and device parameters. In this study, we evaluate SS of Si n-MOSFETs with a substrates boron concentration of 2×10^{17} cm^{-3} as a function of I_d at temperatures from 300 to 38 K. We apply the SS model including band tail states and localized states, proposed by Beckers *et al.* [2, 3], to the SS values taken over a wide range of temperature and I_d and examine the effectiveness.

【Experiments】 N-channel MOSFETs on (100) Si wafers were used for the measurements. The gate stack was composed of n$^+$-poly Si and thermally grown SiO_2. Here, the substrates boron concentration and the thickness of SiO_2 was 2×10^{17} cm^{-3} and 25 nm, respectively. The channel length/width was 50µm/100µm.

【Results】 Fig. 1-3 show the experimental I_D-V_G, SS-I_D and SS-temperature characteristics, respectively. We have experimentally confirmed that, at temperature lower than 100 K, SS tend to saturate with decreasing temperature. In order to quantitatively represent the experimental SS values, we have employed the model of mobile tail states in the vicinity of the conduction band edge and localized interfaces states with a Gaussian distribution, schematically shown in Fig. 4 [3]. Here, the density-of-states (DOS) of the conduction band including band tails are represented by $DOS^{2D}(E)$ for $E>E_c$ and $DOS^{2D}(E)exp((E_C-E)/W_t)$ for $E<E_c$. Also, the energy distribution of interface states is assumed by the Gaussian function with an amplitude N_0 and a standard deviation $W_0/2$. The simulated SS are also plotted as solid curves in Fig. 1-3. Here, W_0 of 60 meV, N_0 of 1.5×10^{11} cm^{-2} and W_t of 4.5 meV are assumed. It is found that the simulated SS can well represent the experimental SS over a wide range of temperature and I_d. This fact indicates that the present mobile and localized state model is effective as a physical model of mobile and localized states at Si MOS interfaces.

【Conclusion】 The SS values of Si n-MOSFETs have been experimentally determined in a temperature range of 300 to 38K and compared with the simulated results. The good agreement suggests the effective of the existing model composed of the mobile tail states and Gaussian-shape localized interface states.

【References】 [1] Beckers et al., IEEE J-EDS, 6 (2018) 1007 [2] Beckers et al., IEEE EDL, 41 (2020) 276 [3] Beckers et al., IEEE TED, 67 (2020) 1357

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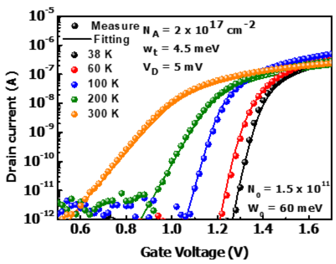

Fig. 1 Comparison of the I_D-V_G characteristics in measured device (points) and fitting data (solid lines)

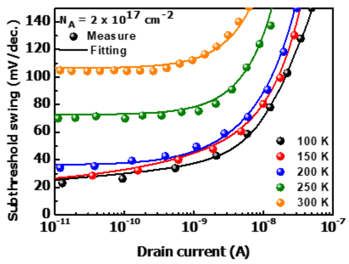

Fig. 2 The SS-I_D characteristics in measured device (points) and fitting data (solid lines)

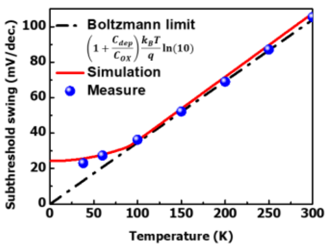

Fig. 3 SS-T plotted data at I_D = 10 pA, black line is Boltzmann limit involved C_{dep}

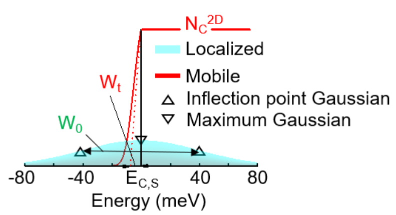

Fig. 4 Zoomed-in on the conduction band at the surface