Substrate Impurity Concentration Dependence of Sub-threshold Swing of Si n-channel MOSFETs at Cryogenic Temperature

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【Background】 The sub-threshold swing (SS) of Si nMOSFETs at cryogenic temperature has been reported to have the following characteristics: 1) saturation of SS with decreasing temperature, 2) increased inward bending (inflection) of SS as a function of the drain current (I_D). To explain these two phenomena, Beckers *et al.*[1] have proposed models of band tail states and localized interface states near the band edge with a Gaussian distribution as Fig. 1. The Gaussian distribution has an amplitude N_0 and a standard deviation $W_0/2$, while the band tail has a characteristic tail of W_t. We have succeeded in representing experimental SS of Si nMOSFETs with a substrate impurity concentration of 2.0×10^{16} cm^{-3} in wide ranges of temperature and I_D by assuming these band tail states and localized interface states [2]. However, the influence of the substrate impurity concentration (N_A) on SS has not been studied so far. In this study, we have evaluated SS of nMOSFETs with different substrate impurity concentrations at 300 to 4 K and examined if the present model can quantitatively represent experimental SS.

【Experiments】 (100) nMOSFETs with n^+-poly Si gate and thermal oxidation SiO_2 gate insulator were used for measurements. The substrates impurity (acceptor) concentration, N_A, was varied from 2.0×10^{16} cm^{-3} to 7.7×10^{16} cm^{-3}, 1.1×10^{17} cm^{-3} and 3.0×10^{17} cm^{-3}. The channel length/width was 100 μm/100 μm.

【Results】 Fig. 2 shows the measured I_D-V_G transfer curve in different substrate concentrations at 4 K. Also, Fig. 3 shows the experimental SS-I_D characteristics of MOSFETs with N_A of 3.0×10^{17} cm^{-3}. The SS value decreases with a decrease in temperature, while the decrease in SS saturates at low temperatures. Fig. 4 shows the temperature dependence of SS at I_D of 10^{-8} μA/μm with the four different N_A. Here, the dash-dotted line shows SS under the Boltzmann limit involving the effect of depletion capacitance. It is found that the saturated SS increases with an increase in N_A. In order to quantitatively understand the N_A dependence of SS, we performed the simulation using the same model with tail states and the localized states as in [2]. As seen in Fig. 2 and 3, the simulation can quantitatively represent the experimental I_D-V_G and SS-I_D characteristics under given parameters of W_t, N_o and W_o, which are dependent on N_A. Fig. 5 shows the N_A dependence of each parameter. The present values are in fairly good agreement with the values previously reported [1]. It is found that each parameter increases with an increase in N_A. This fact indicates that the N_A dependence of these interface properties of electronic states must be taken into account to understand SS at low temperature.

【Conclusion】 We experimentally evaluated SS of MOSFETs with difference N_A at 300 to 4 K. It has been found that the increase in N_A leads to higher saturated SS at low temperature. The physical model with the band tail states and localized interface states has well represented the experimental SS under the considerations of the N_A dependence of the tail state and localized state parameters.

【References】 [1] Beckers et al., IEEE Trans. Electron Devices, 67, 1357, 2020. [2] Kang et al., SSDM, A-1-03, 2021.

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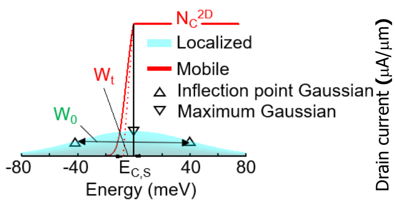

Fig. 1 Employed model of electronic states near the conduction band edge including band tail states and localized interface states

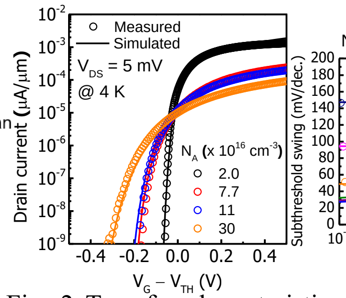

Fig. 2 Transfer characteristics of Si nMOSFETs with different N_A at 4 K.

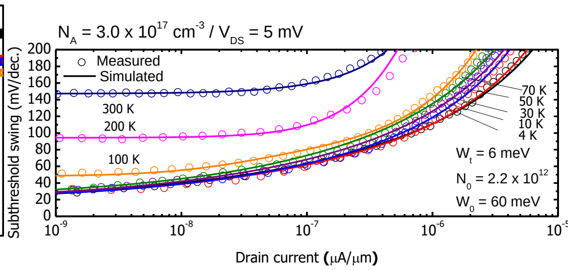

Fig. 3 SS-I_D characteristics of nMOSFETs with N_A of 3.0×10^{17} cm^{-3} at 300 to 4 K.

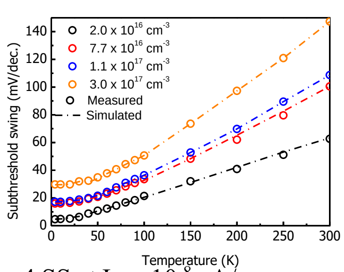

Fig. 4 SS at I_D = 10^{-8} μA/ μm versus T plot.

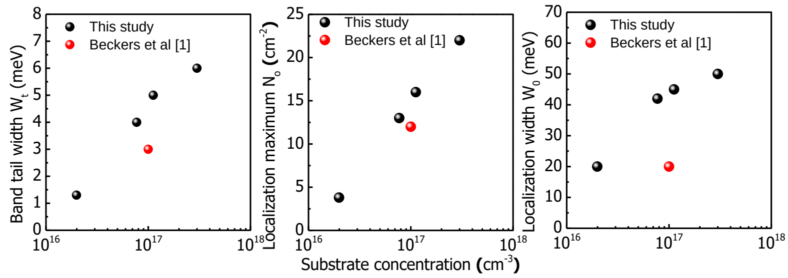

Fig. 5 Substate concentration dependence of (a) W_t in band-tail state, (b) N_0 and (c) W_0 in localized interface states.