
博士論文（要約）

**Characterization and understanding of
subthreshold swing of Si MOSFETs at
cryogenic temperatures**

（極低温での Si MOSFET のサブスレシヨ
ルド・スイングの評価と理解）

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論文の内容の要旨

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Quantum computers, utilizing quantum bits based on quantum effects, have been considered as one of the next-generation semiconductor technologies to overcome the limitations of Moore's law. To enable their commercialization, a quantum-classical interface (QCIF) structure has been proposed, which operates at extremely low temperatures of 4 K by placing a classical controller in a refrigerator. In general, the semiconductor devices used in quantum computers require low power consumption and operate at 4K, and existing Si-based MOS devices meet these requirements. However, CMOS modeling for cryogenic temperatures still requires significant research. The existing compact models can accurately represent the electrical properties of CMOS up to 77 K but exhibit inconsistencies at temperatures below that.

The most significant anomalies observed at cryogenic temperatures are as follows: 1) saturation of subthreshold slope (SS) and 2) inflection. Ideally, SS should decrease linearly with temperature, but in practice, it remains constant at cryogenic temperatures. Additionally, while the subthreshold region should exhibit a constant SS value in the I_{DS} (drain current) dependence, SS increases as I_{DS} increases.

To explain these phenomena, A. Beckers et al. proposed the existence of band tail states with an exponential function form at the edge of the two-dimensional conduction band and localized interface states with a Gaussian distribution function form. This model aimed to represent the cryogenic operation of actual MOS devices but was limited to devices with a specific substrate concentration at 4.2 K. It remains unclear whether this proposed model can accurately represent the electrical properties over a wide temperature range or if it can account for various substrate concentrations. Therefore, this study investigated n-MOSFETs with six substrate concentrations and p-MOSFETs with five substrate concentrations across a wide temperature range from 4 K to

300 K. While many studies have examined the electrical properties of MOS devices at cryogenic temperatures, systematic investigations covering a broad temperature range are still lacking.

Furthermore, most research has focused on n-MOSFETs with a single substrate concentration. Thus, this study systematically characterizes the electrical properties of n- and p-MOSFETs with various substrate concentrations over a wide temperature range for the first time. The proposed model successfully represents the electrical characteristics of n-MOSFETs with different substrate concentrations across a wide temperature range. However, unlike n-MOSFETs, p-MOSFETs tend to exhibit increased SS as the temperature decreases. Unfortunately, the proposed model fails to capture these characteristics of p-MOSFETs. The phenomena of SS saturation at lower temperatures in n-MOSFETs and SS increase at lower temperatures in p-MOSFETs have been previously reported. Additionally, to investigate the physical origin of the band tail parameter used in the proposed model, we proposed impurity-induced band tail states and surface roughness band tails and investigated their behavior through substrate biasing (V_{sub}).

The results showed that the band tail in the proposed model exhibited constant values regardless of V_{sub} , indicating that impurity-induced Lifshitz band tails were the primary effect. Moreover, the localized interface parameters also remained constant regardless of V_{sub} , confirming that the proposed model does not accurately represent the experimental results. To address these issues, we proposed a model that differentiates between deep and mobile states within the existing disordered FET's band tail state.

The proposed long-tail state model includes parameters such as long band tail width (W_t), E_{ref} (dividing the immobile and mobile states), and gradient W_b . We investigated the effect of these proposed parameters on the electrical properties and found that W_t affects the saturation of SS and increases the value of SS. Also, when E_{ref} and W_b increase, SS decreases but the inflection effect increases.

We investigated the effect of these proposed parameters on the electrical properties and found that they accurately represent the electrical characteristics of n-MOSFETs with limited substrate concentrations over a wide temperature range.

In addition, the band tail of the proposed model follows the impurity induced Lifshitz band tail well, which can support the fact that SS- I_{DS} and SS-T characteristics are the same regardless of V_{sub} . However, more research is still needed on immobile state and mobile state.