

Coulomb-scattering-limited mobility at cryogenic temperatures due to interface charges induced by Fowler-Nordheim injection in Si n-MOSFETs

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[Background] Cryogenic MOSFETs have potential application in quantum computer systems, while the lack of an accurate physical model is a critical issue in cryo-CMOS circuits [1]. Channel mobility is one of the most important parameters among a variety of MOSFET parameters. Here, Coulomb scattering is known to be the main factor that determines mobility in Si MOSFETs at low temperatures and low carrier surface density (N_s). However, since various types of Coulomb scattering centers contribute differently to mobility, it is important to separately evaluate the influence of each type of scattering centers. In this study, we focus on the influence of MOS interface charges, which is intentionally generated by Fowler-Nordheim (F-N) stress. The Coulomb-scattering-limited mobility due to interface charges is characterized by subtracting the mobility before and after F-N stress based on the Matthiessen's rule. The experimental mobility obtained at 4 K is compared with theoretical Coulomb-scattering-limited mobility under the quantum limit condition.

[Experiments and Simulation] Fig. 1 illustrates the principle of F-N injection of electrons from inversion layers and the generation of interface states [2]. Higher F-N injection fluence can increase the areal density of scattering centers located at MOS interfaces, leading to stronger Coulomb scattering. In the experiment, we used a bulk n-MOSFET with substrate doping concentration of $2 \times 10^{16} \text{ cm}^{-3}$, L/W of $200 \text{ }\mu\text{m}/100 \text{ }\mu\text{m}$, oxide thickness of 25 nm and n⁺ poly-Si gate. F-N stress was performed at 4 K with gate current density of $5 \times 10^{-5} \text{ A}\cdot\text{cm}^{-2}$. Effective mobility was evaluated using quasi-static C-V [3]. Coulomb-scattering-limited mobility only due to generated interface charges is determined as a function of N_s by using the Matthiessen's rule, according to (1) [2, 4].

$$\Delta\mu_{\text{Coulomb}}(N_s)^{-1} = \mu_{\text{After-Stress}}(N_s)^{-1} - \mu_{\text{Before-Stress}}(N_s)^{-1} \quad (1)$$

The theoretical Coulomb-scattering-limited electron mobility due to interface charges was calculated by using the Stern-Howard model [4]. Here, we assume the quantum limit condition that all electrons are in the lowest subband, because the Fermi distribution is extremely steep at cryogenic temperatures [5].

[Results] Fig. 2 shows the threshold voltage shift (ΔV_{th}) after each injection fluence of electrons (N_{inj}) at 4 K and the interface charges estimated from ΔV_{th} . It is observed that hole trapping is dominant first, and electron trapping overcomes hole trapping with increasing N_{inj} , which has been experimentally confirmed at 300 K [6]. Fig. 3 and 4 shows the effective mobility and the Coulomb-scattering-limited mobility, extracted by (1), respectively, at different N_{inj} at 4 K. The Coulomb-scattering-limited mobility decreases with an increase in N_{inj} , indicating that the number of scattering centers increases with N_{inj} . Fig. 5 shows the mobility at $N_s = 10^{12} \text{ cm}^{-2}$ as a function of N_{inj} . The mobility decreases in proportion to $\sim N_{\text{inj}}^{-0.7}$. The black dash line in Fig. 4 shows the simulation results with the interface scattering center density of $1.5 \times 10^{10} \text{ cm}^{-2}$. A good agreement with the experimental result is obtained. The Coulomb-scattering-limited mobility at 4 K is roughly proportional to $N_s^{1.5}$. Fig. 6 shows the temperature dependence of Coulomb scattering-limited mobility from 4 K to 300 K. It is observed that the N_s dependence of the mobility changes from $\sim N_s^{1.5}$ to $\sim N_s^{0.5}$ with increasing both temperature and N_s .

[Conclusion] We characterized Coulomb-scattering-limited mobility by using Matthiessen's rule in a bulk Si n-MOSFET with different interface charges, intentionally generated by F-N injection. The Coulomb-scattering-limited mobility due to interface charges at 4 K has been found to be roughly proportional to $N_s^{1.5}$, which is consistent with a theoretical mobility calculation under the quantum limit.

[References] [1] H. Oka, JSAP Rev. (2022) 220305 [2] S. Takagi et al, IEEE TED **41**(1994) 2357 [3] Y. Chen et al, SSDM (2024) 51 [3] S.-C. Sun et al, IEEE TED **27** (1980) 1497 [4] F. Stern et al, Phys. Rev., **163** (1967) 816 [5] F. Stern, Phys. Rev. **44** (1980) 1469 [6] Y.-H. Lin et al, IEEE TED **44** (1997) 1441

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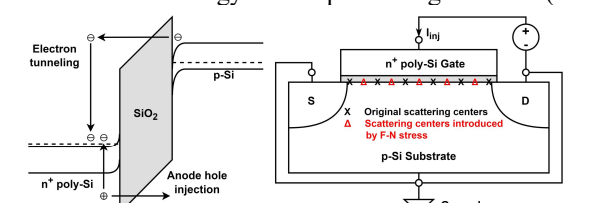


Fig. 1 Principle and setup of F-N injection for a bulk n-MOSFET

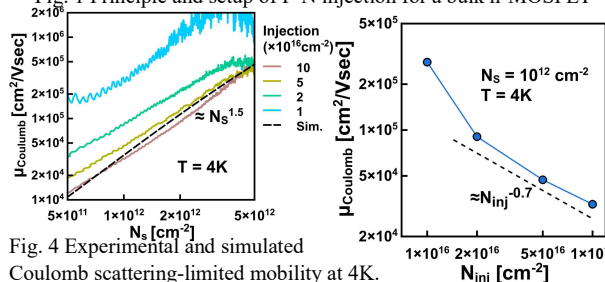


Fig. 4 Experimental and simulated Coulomb scattering-limited mobility at 4K.

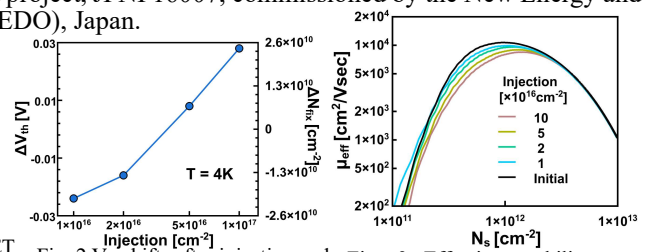


Fig. 2 V_{th} shifts after injection and estimated interface charge change

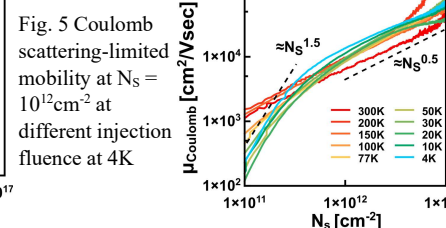


Fig. 5 Coulomb scattering-limited mobility at $N_s = 10^{12} \text{ cm}^{-2}$ at different injection fluence at 4K

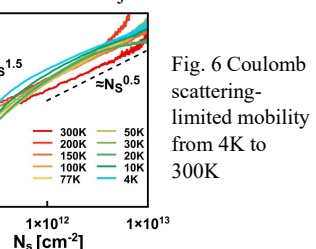


Fig. 6 Coulomb scattering-limited mobility from 4K to 300K