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Different Contribution of Interface States and Substrate Impurities to Coulomb Scattering in Si MOS Inversion Layer

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Inversion layer mobility has been precisely measured by estimating correct surface carrier density (N_s) under a finite drain bias condition. By using this method, Coulomb scattering has been investigated experimentally, and Coulomb scattering mobility by the substrate impurities ($\mu_{C,sub}$) has been separated from that by the interface states ($\mu_{C,it}$) . Consequently, it has been found that $\mu_{C,sub} \propto N_s$, while $\mu_{C,it} \propto \sqrt{N_s}$. This fact indicates the different contribution of the interface states and the substrate impurities to Coulomb scattering in Si MOS inversion layer.

1 Motivation

High-speed performance under low power-supply voltage is required when CMOS devices are scaled down to the 0.1 μm regime. High mobility at low surface carrier density (N_s) is essential to achieve this performance. It was reported that Coulomb scattering significantly degrades the inversion layer mobility in low N_s region on the substrate with high substrate impurity concentration [1]. However, quantitative behavior of Coulomb scattering mobility has not been fully understood, because the finite drain bias effect brings about serious error in quantitative analysis, especially at low N_s [2]. In this work, Coulomb scattering was investigated experimentally by improving the mobility extraction method, and Coulomb scattering mobility by the substrate impurities was separated from that by the interface states.

2 Experimental

The devices used in this study were conventional n-MOSFETs with single source/drain structures. The substrate impurity concentrations were nearly uniform, ranging from 10^{15} cm^{-3} to 10^{18} cm^{-3}. Gate length was 200 μm and gate width was 100 μm. Oxide thickness was 25 nm.

Inversion layer mobility was measured by the improved split $C-V$ method, which estimates correct N_s under a finite drain bias condition. Figure 1 shows the schematic circuit diagram for the gate-channel capacitance C_{gc} measurement in this work. C_{gc} is obtained by directly adding gate-source (C_{gs}) and gate-drain (C_{gd}) capacitances using the following expression (bias conditions in Fig. 1 are for C_{gs} measurement).

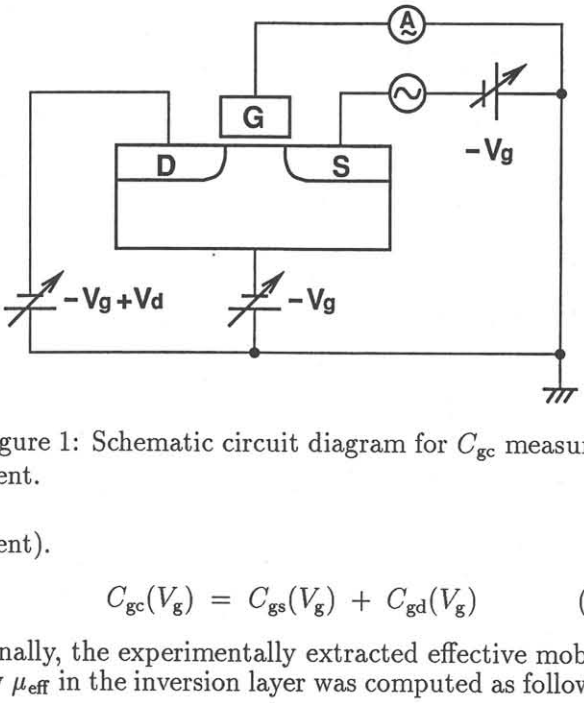

Figure 1: Schematic circuit diagram for C_{gc} measurement.

$$C_{gc}(V_g) = C_{gs}(V_g) + C_{gd}(V_g) \tag{1}$$

Finally, the experimentally extracted effective mobility μ_{eff} in the inversion layer was computed as follows.

$$\mu_{eff} = \frac{L}{W}\frac{1}{qN_s(V_g)}\frac{I_d}{V_d} \tag{2}$$

$$qN_s(V_g) = \int_{-\infty}^{V_g} C_{gc}(V)\,dV \tag{3}$$

This method is different from that proposed by Huang et al. [3] in that an AC ammeter is connected to the gate electrodes in the present work. This makes more precise measurement possible, because drain DC current flows into an AC ammeter in the method employed by Huang et al.

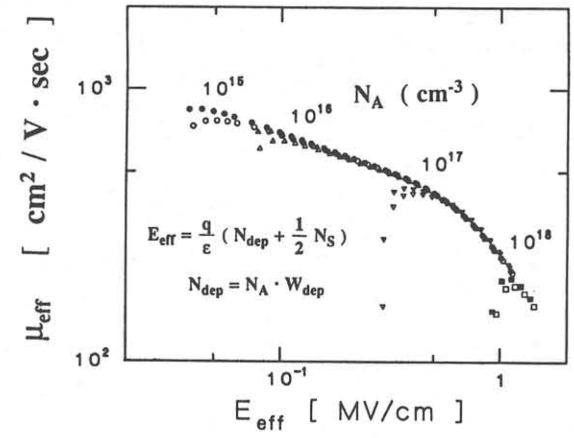

Figure 2: Dependence of μ_{eff} on E_{eff}. Solid symbols stand for μ_{eff} measured by the improved method, while open symbols for μ_{eff} measured by the conventional method.

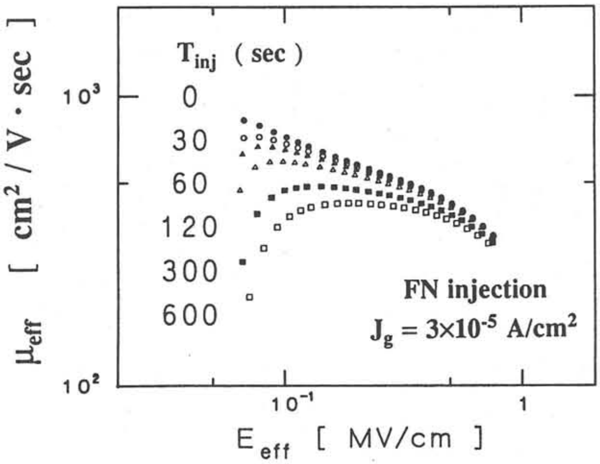

Figure 3: Dependence of μ_{eff} on E_{eff} as a function of FN injection time T_{inj}.

As a result, μ_{eff} has been exactly obtained in low N_s region as well as in moderate or high N_s region, as shown in Fig. 2, where μ_{eff} measured by the conventional split $C-V$ method [4] is also shown. Note that μ_{eff} is underestimated in low effective normal field (E_{eff}) region, where Coulomb scattering is dominant, in any substrate acceptor concentration (N_{A}) when the conventional method is employed.

3 Results and Discussion

Coulomb scattering mobility μ_{Coulomb} includes two components: one is $\mu_{\text{C,sub}}$ which is associated with Coulomb scattering by the substrate impurities, and the other is $\mu_{\text{C,it}}$ which is associated with that by the Coulomb scattering centers at the Si/SiO$_2$ interface. Coulomb scattering by the oxide charge is neglected here because of low carrier scattering probability.

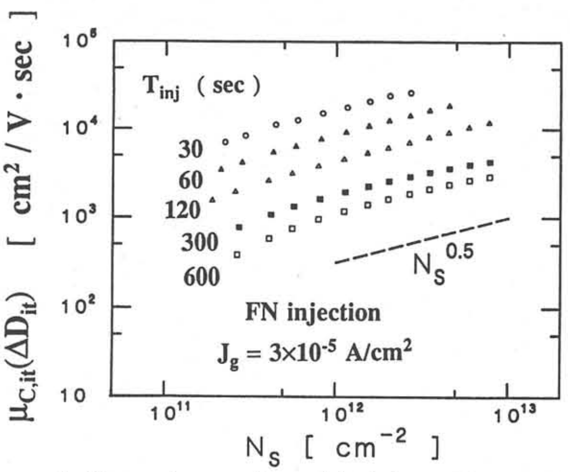

Figure 4: Dependence of $\mu_{\text{C,it}}(\Delta D_{\text{it}})$ on N_s as a function of T_{inj}. Note that $\mu_{\text{C,it}}(\Delta D_{\text{it}}) \propto \sqrt{N_s}$, independent of T_{inj} or ΔD_{it}.

3.1 Interface States

N_s dependence of $\mu_{\text{C,it}}$ was estimated from the mobility degradation by Fowler-Nordheim (FN) electron injection, as shown in Fig. 3. Electrons were injected into SiO$_2$ from the inversion layer in nMOSFETs. The injection current density J_{inj} was 3×10^{-5} A/cm^2.

N_s dependence of $\mu_{\text{C,it}}(\Delta D_{\text{it}})$, which is a Coulomb scattering mobility associated with the generated interface state density ΔD_{it} by FN injection, was estimated by the difference of mobilities before and after FN injection, which was deduced by using Matthiessen's rule.

$$\frac{1}{\mu_{\text{C,it}}(\Delta D_{\text{it}})} = \frac{1}{\mu_{\text{C,it}}(D_{\text{it}}+\Delta D_{\text{it}})} - \frac{1}{\mu_{\text{C,it}}(D_{\text{it}})} \qquad (4)$$

Here, D_{it} is an interface state density before FN injection. The experimental results are shown in Fig. 4. It was found that the same N_s dependences of $\mu_{\text{C,it}}(\Delta D_{\text{it}})$ were obtained in any ΔD_{it}. This result leads to the fact that $\mu_{\text{C,it}}$ is generally proportional to N_s^{α}, where $\alpha \sim 1/2$.

ΔD_{it} dependence of $\mu_{\text{C,it}}(\Delta D_{\text{it}})$ is shown in Fig. 5. ΔD_{it} was measured by the charge pumping method. It is noted that $\mu_{\text{C,it}}(\Delta D_{\text{it}}) \propto \Delta D_{\text{it}}^{-1}$. From this relationship and Eq. (4), the following relationship is substantially deduced.

$$\mu_{\text{C,it}}(D_{\text{it}}) \propto \frac{\sqrt{N_s}}{D_{\text{it}}} \qquad (5)$$

3.2 Substrate Impurities

N_s dependence of $\mu_{\text{C,sub}}$ was estimated from the N_{A} dependence of the mobility curve, which is typically shown in Fig. 2. The experimental results are shown in Fig. 6, where $\mu_{\text{C,sub}}$ was deduced by using Matthiessen's rule.

$$\frac{1}{\mu_{\text{C,sub}}} = \frac{1}{\mu_{\text{measured}}} - \frac{1}{\mu_{\text{universal}}} \qquad (6)$$

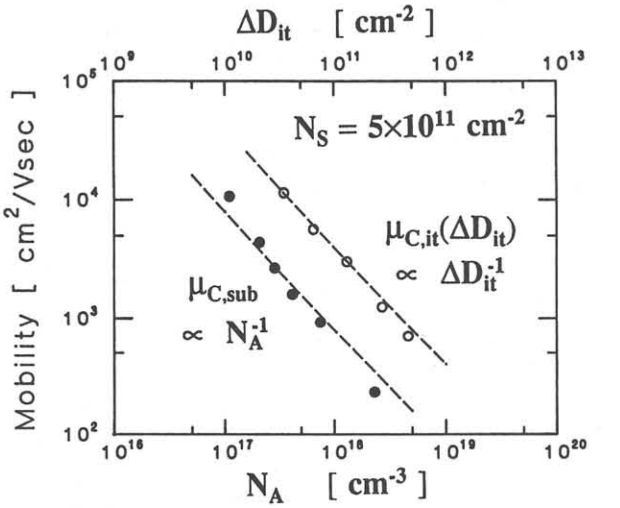

Figure 5: N_A dependences of $\mu_{C,sub}$ and ΔD_{it} dependence of $\mu_{C,it}(\Delta D_{it})$. Note that Coulomb scattering mobility is inversely proportional to the total number of Coulomb scattering centers in each case.

Here, $\mu_{universal}$ is the universal mobility curve, which is described by the phonon and surface roughness scatterings. Note that $\mu_{C,sub}$ is proportional to N_s^{β}, where $\beta \sim 1$. This behavior is obviously different from that of $\mu_{C,it}$. In fact, the interface state density increased slightly in MOSFETs with $N_A \gtrsim 10^{18}$ cm^{-3}. However, it was verified that this increase have little influence on the N_s dependence of $\mu_{C,sub}$.

Different N_s dependence between $\mu_{C,sub}$ and $\mu_{C,it}$ has been confirmed by the numerical calculation, using the scattering theory developed by Stern and Howard [5]. It has also been found by the calculation that each N_s dependence is determined by the screening effect and that the effect of lowering the scattering probability by the increase in electron energy with increasing N_s is very small.

An intuitive physical image of the weak N_s dependence of $\mu_{C,it}$ is as follows. At higher N_s, electrons are scattered more frequently by the interface states, because the electron distribution shifts towards the surface. This effect suppresses the mobility enhancement caused by the screening effect. This means the weak N_s dependence of $\mu_{C,it}$.

N_A dependence of $\mu_{C,sub}$ is also shown in Fig. 5.

$$\mu_{C,sub} \propto \frac{N_s}{N_A} \qquad (7)$$

is clearly shown. Eq. (5) and Eq. (7) verify the validity of describing Coulomb scattering mobility in terms of Born approximation.

4 Conclusion

Inversion layer mobility has been accurately measured by estimating correct surface carrier density under a finite drain bias condition. Consequently, it has been found that

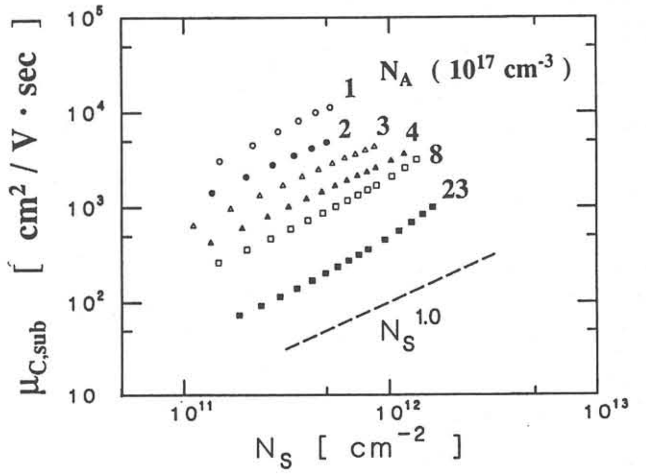

Figure 6: Dependence of $\mu_{C,sub}$ on N_s. It is noted that $\mu_{C,sub} \propto N_s$, which behavior is obviously different from that shown in Fig. 4.

$$\frac{1}{\mu_{Coulomb}} = \frac{1}{\mu_{C,sub}} + \frac{1}{\mu_{C,it}}$$

$$\mu_{C,sub} \propto \frac{N_s}{N_A}$$

$$\mu_{C,it} \propto \frac{\sqrt{N_s}}{D_{it}}.$$

This fact indicates the different contribution of the interface states and the substrate impurities to Coulomb scattering in Si MOS inversion layer. It is concluded that the separation of $\mu_{Coulomb}$ into $\mu_{C,sub}$ and $\mu_{C,it}$ is especially important when quantitatively describing the inversion layer mobility at low surface carrier density, which is essentially related to high-speed performance under low power-supply voltage in 0.1 μm regime CMOS devices.

Acknowledgment

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References

[1] S. Takagi et al. : IEDM Tech. Dig., p. 398, 1988.

[2] K. Nishinohara et al. : VPAD Tech. Dig., p. 176, 1993.

[3] C. L. Huang et al. : IEEE Trans., ED-40, p. 1134, 1993.

[4] C. G. Sodini et al. : Solid-State Electron., 25, p. 833, 1982.

[5] F. Stern and W. E. Howard : Phys. Rev., 163, p. 816, 1967.