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Submicron MOSFET Characteristics with Nanometer Gate Oxide

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Submicron MOSFETs with 54 A gate oxide are fabricated. The effective number of trapped electrons in the gate oxide N_{tr} and the change of the interface-trap density ΔD_{it} caused by the Fowler-Nordheim gate current injection are measured. The number of electrons injected into the gate oxide N_{inj} for 54 A gate oxide MOSFETs is about ten times larger than that for 107 A and 148 A gate oxide MOSFETs for the same N_{tr}. ΔD_{it} saturates with N_{inj} to a constant value independent from the oxide thickness. A generation cross section for interface-trap for 54 A gate oxide MOSFETs is one twentieth less than that for 107 A and 148 A gate oxide MOSFETs.

1. Introduction

Recently, MOSFETs with ultra-thin gate oxide have received considerable attention from the view points of reduction of short channel effect and increase of mutual conductance g_m. In fact, the gate oxide has become thinner as the miniaturization of LSI progresses.

It is, however, impossible to reduce the the gate oxide thickness infinitely, because the gate oxide leakage current due to tunneling effect increases as the oxide becomes thinner. Hoeneisen and Mead [1)] has pointed out, in their pioneering work about the limitation of MOSFET, that the limitation thickness of the gate oxide is about 50 A. However, no report has been published on MOSFETs with about 50 A gate oxide, though there have been reports on MOSFETs with about 100 A gate oxide [2-6)].

The authors fabricated submicron MOSFETs with about 50 A gate oxide and investigated the characteristics of these MOSFETs. In this paper, it is mainly shown that MOSFETs with nanometer gate oxide have superior tolerance to those with thicker gate oxide for Fowler-Nordheim gate current injection.

2. Device structure

The MOSFETs were fabricated using n-channel Si gate technology. The impurity concentration of p-type (100) Si substrate was 3.5×10^{16} cm^{-3}, and the junction depth was 0.25 µm. The gate oxide of 54 A thickness was grown in dry O_2 at 800°C and the gate oxides of 107 A and 148 A thickness were grown at 900°C, which were estimated by ellipsometric technique. Minimum effective channel length was 0.7 µm. H_2/N_2 annealing was carried out at 400°C for 30 minutes.

3. Results

The drain characteristics for a 0.7 µm MOSFET with 54 A gate oxide are shown in Fig. 1. The MOSFET was ion-implanted with 25 keV B^+ for 7.0×10^{12} cm^{-2} dose. This figure shows that the gate breakdown voltage is above 5V and the drain punch-through voltage is about 5V.

In order to investigate conduction mechanism of the 54 A thick gate oxide, gate current I_G was measured under the condition that the gate electrode was positively biased and the source, the drain and the substrate electrodes were grounded. Figure 2 shows Fowler-Nordheim plots of I_G as a function of the gate oxide electric field E_{OX} for a MOSFET with 54 A gate oxide. The MOSFET was not ion-implanted for threshold voltage control. It is found from the figure that the gate current is described by following Fowler-Nordheim tunnel current [7)]

$$I_G \propto E_{ox}^2 \exp(-8\pi\sqrt{2m^*}\phi^{3/2}/3hqE_{ox}), \qquad (1)$$

where h is Plank constant, q electronic charge, m* effective mass of electrons, ϕ potential barrier height of oxide for electrons. From the slope of the straight line in the figure, ϕ is estimated to be 3.25 eV, provided that m^* is 0.42 m_0 [7]. m_0 is mass of free electron. The estimated potential barrier height for the 54 A gate oxide is same as that for thicker oxide [7]. This result for potential barrier height is consistent with the result of photoemission data [8], where more than 43 A thick oxide has the same potential barrier height.

Figures 3 and 4 show typical subthreshold characteristics for MOSFETs, which were not ion-implanted for threshold control, before and after injection of Fowler-Nordheim current into the gate oxides [3], of which thicknesses are 54 A and 148 A, respectively. The characteristics were measured with drain voltage V_D = 0.1V. Fowler-Nordheim current injected was 3.6×10^{-3} A/cm^2 for the MOSFET with 54 A gate oxide and 2.2×10^{-3} A/cm^2 for the MOSFET with 148 A gate oxide for 30 seconds under the condition that the gate electrode was positively biased.

By comparing the characteristics before and after injection of Fowler-Nordheim gate current, it is found that the MOSFET with 54 A gate oxide shows little change in characteristics. On the other hand, the MOSFET with 148 A gate oxide shows the large threshold voltage shift and the remarkable change of subthreshold swing. The effective number of electrons trapped per unit area, N_{tr}, and the change of the interface-trap density, ΔD_{it}, during the injection can be estimated by the following relations;

$$N_{tr} = \Delta V_{th} C_{ox}/q, \qquad (2)$$

$$\Delta D_{it} = \left[\Delta S C_{ox}\left\{1-2C_D^{\,2}/(a^2 C_{ox}^{\,2})\right\}\right]/kT\ln 10 \;^{9)}, \qquad (3)$$

where $a=\sqrt{2}(C_{FB}/C_{ox})$ and C_{ox} is gate oxide capacitance, C_D depletion-layer capacitance, C_{FB} flat band capacitance, k Boltzmann constant, T absolute temperature, ΔV_{th} the change of threshold voltage, ΔS the change of subthreshold swing caused by the injection. Threshold voltage is defined as a gate voltage giving 0.1 μA drain current normalized by channel length and channel width [10]. In the cases of Figs. 3 and 4, N_{tr} and ΔD_{it} are estimated to be $7.5 \times 10^{10}/cm^2$, $2.2 \times 10^{11}/eVcm^2$ for the MOSFET with 54 A gate oxide and $4.9 \times 10^{11}/cm^2$, $1.6 \times 10^{12}/eVcm^2$ for the MOSFET with 148 A gate oxide, respectively. N_{tr} and ΔD_{it} for the MOSFET with 54 A gate oxide are about one order of magnitude less than those for the MOSFET with 148 A gate oxide, though the injection current density for the 54 A gate oxide MOSFET is greater than that for the 148 A gate oxide MOSFET.

Figure 5 shows N_{tr} as a function of the number of electrons N_{inj} injected into gate oxides by Fowler-Nordheim tunnel current. t_{ox} and V_G indicated in the figure are thickness of gate oxides and gate voltages during Fowler-Nordheim gate current injection. After Fowler-Nordheim gate current injection for a certain time, N_{tr} was measured from the shift of threshold voltage using Eq. (2). N_{inj} was estimated by current density and injection time. The figure shows that N_{tr} monotonically increases with N_{inj} for each MOSFET, and that N_{tr} for MOSFETs with 107 A gate oxide agrees with that with 148 A gate oxide within measurement errors. It is also shown in the figure that N_{inj} for MOSFETs with 54 A gate oxide is about one order of magnitude larger than that for MOSFETs with thicker gate oxide for the same N_{tr} in the range of $10^{11}/cm^2$ and $2 \times 10^{12}/cm^2$.

ΔD_{it} is shown in Fig. 6 as a function of N_{inj}. It is found from this figure that ΔD_{it} increases with N_{inj} and saturates to a constant value independent from the gate oxide thickness. It is also shown in the figure that ΔD_{it} for MOSFETs with 107 A agrees with that for 148 A gate oxide within measurement errors as well as N_{tr}. ΔD_{it} for MOSFETs with 107 A and 148 A gate oxide in this work almost agrees with that for MOSFETs and MOS capacitors with approximately 100 A gate oxide in Ref. 3).

In order to analyze the experimental results, a simple differential equation was introduced, as follows

$$dD_{it}/dt = (D_{it,sat} - D_{it})\sigma J/q, \qquad (4)$$

where $D_{it,sat}$ is the saturation value for D_{it}, J the injected Fowler-Nordheim current density and σ is cross section for generation of interface-trap.

Solving Eq. (4), ΔD_{it} is obtained as follows.

$$\Delta D_{it} = D_{it}(t) - D_{it}(t=0)$$
$$= \left\{D_{it,sat} - D_{it}(t=0)\right\}\left\{1-\exp(-\sigma Jt/q)\right\}. \quad (5)$$

By making use of the relation $N_{inj} = Jt/q$ and $D_{it,sat} \gg D_{it}(t = 0)$, the following equation is obtained.

$$D_{it} = D_{it,sat}\left\{1 - \exp(-\sigma N_{inj})\right\}. \quad (6)$$

Calculated results with Eq. (6) are shown in Fig. 6 as solid lines for the cases where $\sigma = 2.7 \times 10^{-18} cm^2$, $1.4 \times 10^{-19} cm^2$ and $5.3 \times 10^{-20} cm^2$ under the condition that $D_{it,sat} = 3 \times 10^{12}/eVcm^2$. By comparing the experimental results and calculated results, it is found that σ for the MOSFETs with 54 A gate oxide is in the range of 1.4×10^{-19} cm^2 and 5.3×10^{-20} cm^2, and that σ for the MOSFETs with 107 A and 148 A gate oxide is about 2.7×10^{-18} cm^2. σ for the MOSFETs with 54 A gate oxide is one twentieth less than that for MOSFETs with thicker gate oxide.

These results for the Fowler-Nordheim current injection into the gate oxide suggest that hot electron injection tolerance for the MOSFET with 54 A gate oxide is higher than that for the MOSFETs with thicker gate oxide.

4. Conclusion

Submicron MOSFETs with 54 A gate oxide have been fabricated. N_{tr} and ΔD_{it} caused by the Fowler-Nordheim current injection into gate oxide were investigated for MOSFETs with gate oxides of 54 A, 107 A and 148 A thickness. N_{tr} and ΔD_{it} were measured from the shift of threshold voltage and the change of subthreshold swing, before and after Fowler-Nordheim current injection, respectively. N_{tr} and ΔD_{it} increase with N_{inj} and ΔD_{it} saturates to a constant value independent from the oxide thickness. N_{inj} for 54 A gate oxide MOSFETs is about one order of magnitude larger than that for the thicker gate oxide MOSFETs for the same N_{tr} in the range of $10^{11}/cm^2$ and $2 \times 10^{12}/cm^2$. A generation cross section for interface-trap, σ, is estimated from ΔD_{it}. σ for the 54 A gate oxide MOSFETs is one twentieth less than that for thicker gate oxide MOSFETs.

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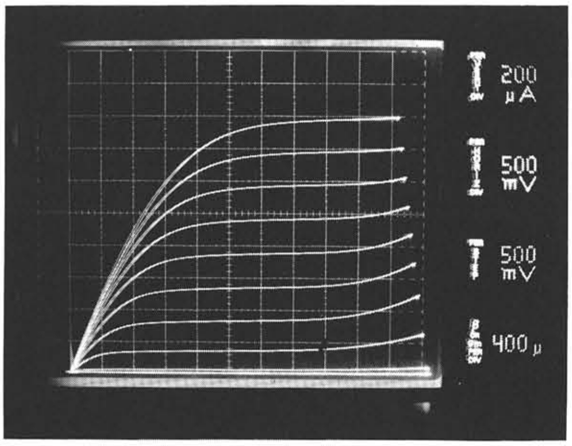

Fig.1 Drain characteristics for a 0.7μm channel length MOSFET with 54 A gate oxide. Maximum gate voltage is 5 V.

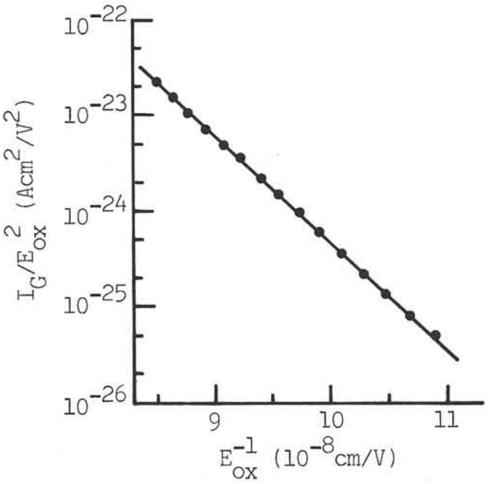

Fig.2 Fowler-Nordheim plots of gate current I_G for a MOSFET with 54 A gate oxide. Effective channel length and width are 2.2μm and 14.3μm.

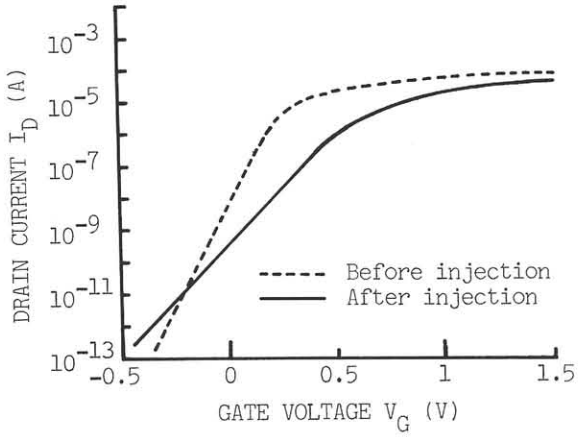

Fig.4 Subthreshold characteristics for a 1.2μm channel length MOSFET with 54 A gate oxide, before and after Fowler-Nordheim gate current injection.

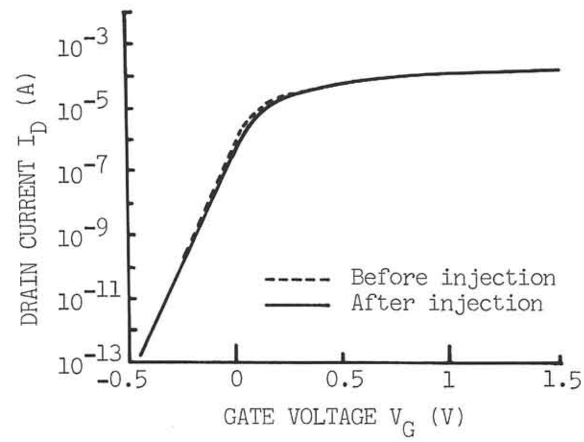

Fig.3 Subthreshold characteristics for a 1.3μm channel length MOSFET with 54 A gate oxide, before and after Fowler-Nordheim gate current injection.

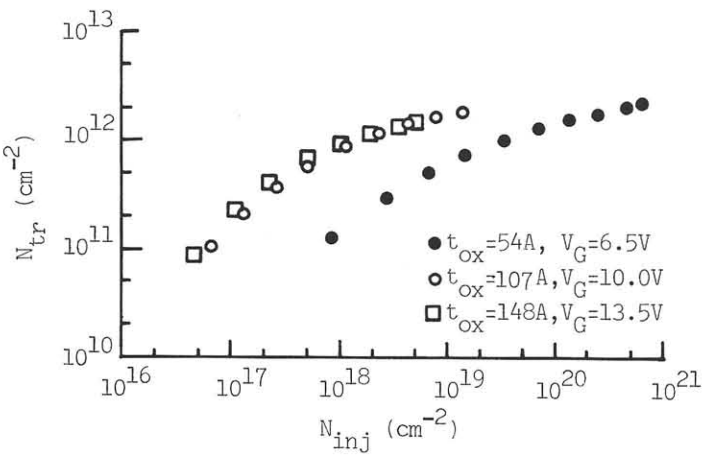

Fig.5 N_{tr} as a function of N_{inj} for MOSFETs with 54 A, 107 A and 148 A gate oxide.

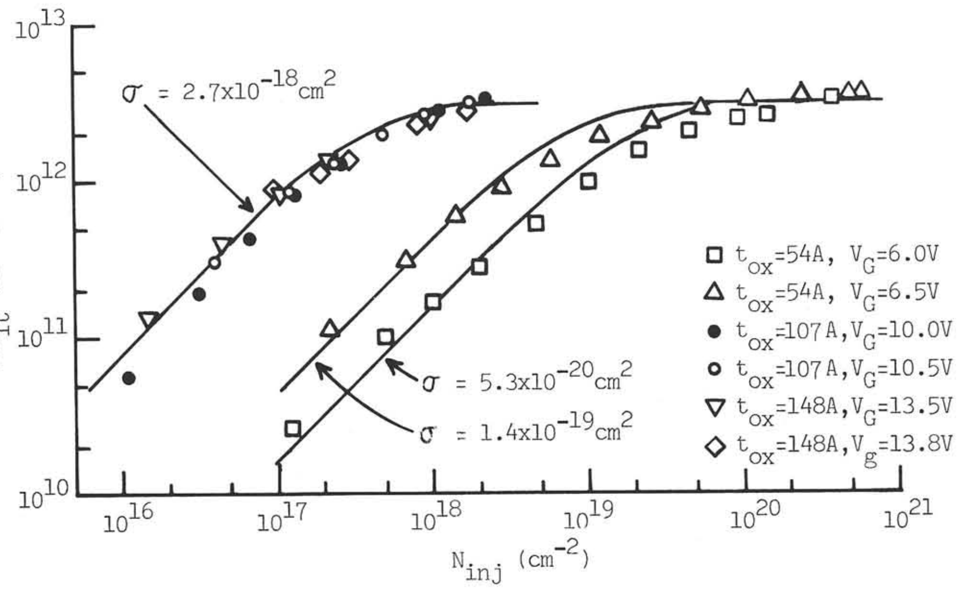

Fig.6 ΔD_{it} as a function of N_{inj} for MOSFETs with 54 A, 107 A and 148 A gate oxide.