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Distribution of Trapped Electron and Hole in Thin SiO_2 Film

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We investigated the spatial distribution of trapped hole in thin SiO_2 film induced by Fowler-Nordheim (F/N) injection. F/N stress induced leakage current was measured and used to determine the spatial distribution of trapped hole. 1/t time dependence of leakage current was exactly modeled by the determined distribution of trapped charges.

1. Introduction

There has been many researches on the understanding of thin SiO_2 degradation by F/N injections for about a decade.[1],[2],[3] But, some problems are still remained open for further study. One of them is trapped electron and hole distributions in thin SiO_2 film induced by F/N injection.

In ref.[4] and [5], F/N stress induced leakage currents are explained by trap filling and detrapping process. Also, 1/t time dependence of leakage current is utilized to extract the density of generated traps in the oxide film.[6] However, 1/t leakage current formulation has a singularity as $t \to 0^+$, that has needed some corrections. That kind of corrections should involve the spatial distribution of trapped charge. In this paper, we show the experimental results pertinent to determine the spatial distribution of trapped charge. Also we present a new formalism which can explain the time dependence of leakage current.

2. Experimental

We use the n^+ poly gate MOS capacitor with gate area of 50000 μm^2, which has 100 $\AA$ thick thermal oxide grown at dry O_2 ambient on (100) p-type Si substrate. During measurements on the MOS capacitor, electrons are injected from the n^+ poly gate and the p-substrate is in accumulation, for the convenience of analysis. 5 V pulse response of stressed oxide with electron fluence of 20 C/cm^2 is shown in Fig.1(a). In Fig.1(b), we compare the leakage(discharge) currents of differently charge-fluenced oxide films. The more stressed the oxide film, the larger leakage curerent is. However, it is ambiguous whether this leakage currrent is due to electon or due to hole. In Fig.2, we show the gate voltage shift of MOS capacitor under constant stress of 2x10^{-5} A/cm^2. The initial decrease of gate voltage due to hole trapping lasts till 2x10^3 sec. After 2x10^3 sec, gate voltage increases due to electron trapping at the interface. It reveals that we are able to observe only hole-related leakage current during the initial 2 x 10^3 sec. In Fig.3, the gate voltage shift under current stress of 8x10^{-3} A/cm^2 is shown. Hole trapping is overwhelmed by electron trappings at interface and bulk oxide film. In this stress condition, leakage currents are due to both hole and elec-

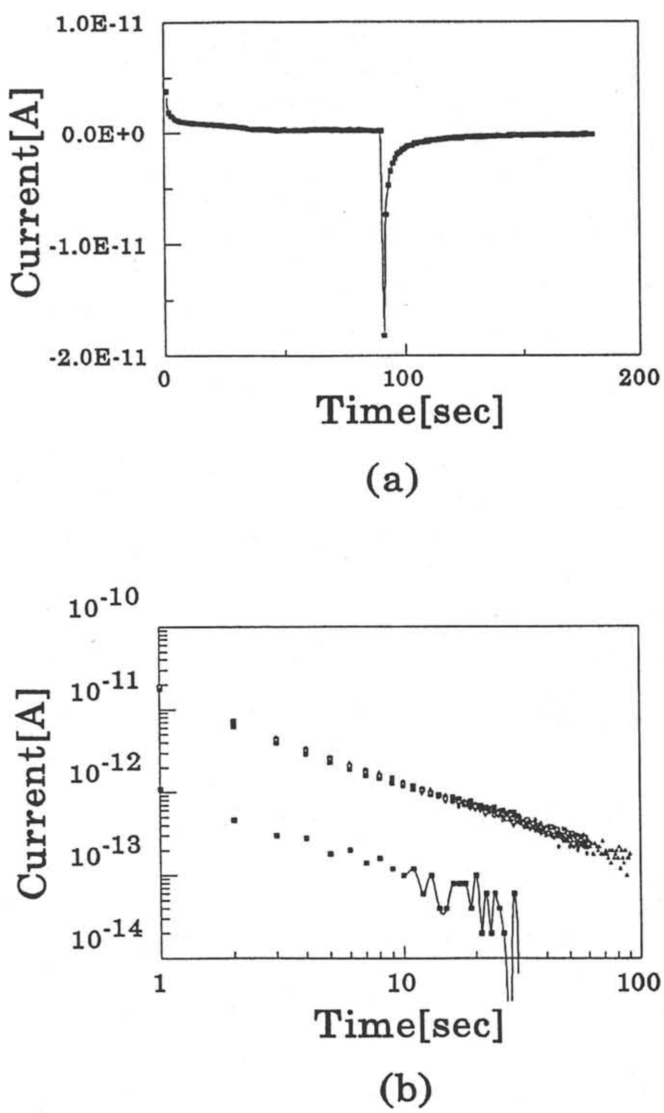

Fig.1(a) shows the 5 V pulse response of stressed oxide with electron current fluence of 20 C/cm^2. At the input transitions, large leakage current is measured. Leakage current at $E_{ox} = 0$, i.e. discharge current, has the 1/t time dependence. Fig.1(b) shows leakage currents as the oxide film is forced to more electrical stress of V_{str} =13 V.

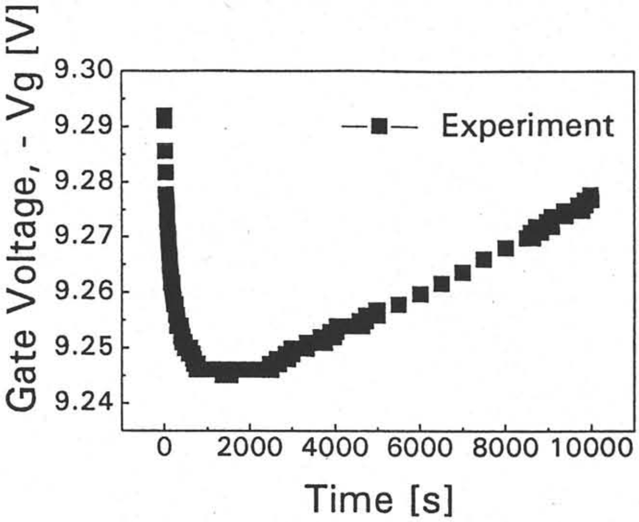

Fig. 2. The gate voltage shift under current stress of $j_e = 2 \times 10^{-5} A/cm^2$ is measured for 1×10^4 sec(filled square). The initial decrease of gate voltage is due to hole trapping. After $\sim 1 \times 10^3$ sec, electron trapping at the interface contributes to the gradual gate voltage increase.

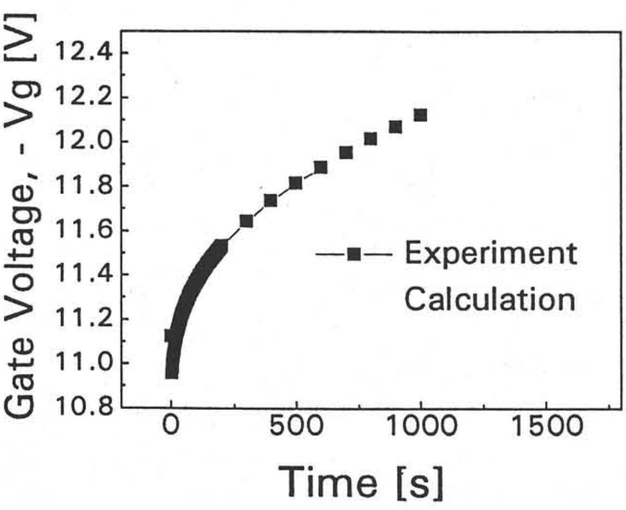

Fig. 3. Under current stress of $j_e = 8 \times 10^{-3} A/cm^2$, gate voltage shift is measured. The turn-around time is reduced and interface-electron trapping and neutral-electron trap generation dominantly contribute to the gate voltage shift.

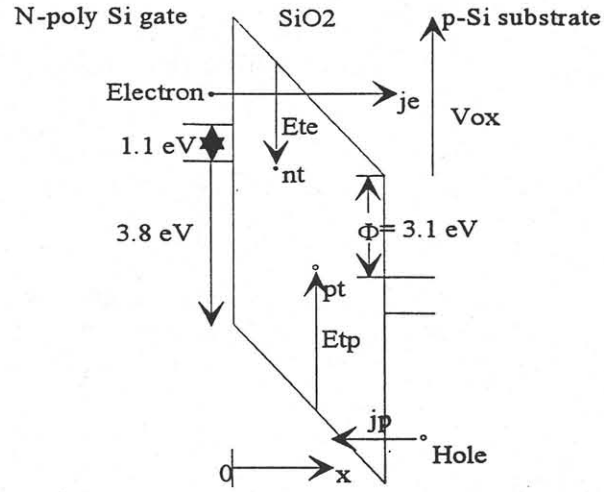

Fig. 4. Thin SiO_2 film capacitor on p-Si substrate with n-poly gate is biased into the F/N regime, where p-Si substrate is in accumulation mode and electrons are injected from the n-poly gate. Holes are generated from the anode, Si substrate.

tron, which makes analysis difficult. So we concentrate on the small current stress data.

3. Spatial Distribution of Trapped Hole

Holes are generated near the anode(Fig.4). Trapping in energetically deep traps is modeled using a first order rate equation [7] as follows.

$$\frac{\partial p_t}{\partial t} = \sigma_p \cdot j_p/e \cdot (P_t - p_t) - \sigma_{rp} \cdot j_n/e \cdot p_t - p_t/\tau_p(x) \quad (1)$$

The possibilities that a trapped hole is annihilated by a captured electron and a trapped hole is detrapped by tunneling process are included. P_t represents the density of hole traps, p_t is the trapped hole density, σ_p is the hole trapping cross section, σ_{rp} is the cross section for electron trapping by a trapped hole, τ_p is the detrapping time constant. j_n is the electron current density, j_p is the hole current density.

By taking $\partial/\partial t = 0$ in Eq.(1), we deduce the quasi steady-state trapped hole distribution p_{ts} as follows.

$$p_{ts}(x) = \frac{j_p/e \cdot \sigma_p \cdot P_t}{j_p/e \cdot \sigma_p + \sigma_{rp} \cdot j_n/e + \frac{1}{\tau_p(x)}} \quad (2)$$

Eq.(2) reveals that quasi steady-state hole distribution p_{ts} has the spatial distribution determined only by τ_p(x). Note that τ_p(x) is also related to the leakage current. We find that detrapping time constant is correctly determined using WKB approximation, which explains the 1/t time dependence of leakage current. In Fig.[5], the quasi steady-state hole distribution p_{ts} is calculated using WKB approximation. The trapped holes have uniform distribution from $t_{ox} - E_{tp}/qE_{ox} \equiv x_p$ to t_{ox}.

4. A New 1/t Leakage Current Formalism

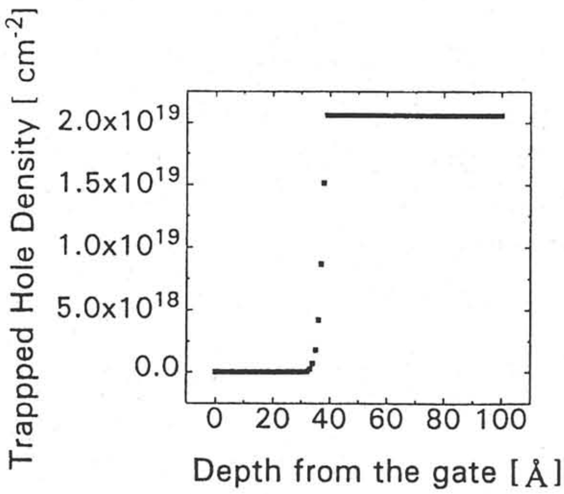

Fig. 5. The quasi steady-state hole distribution p_{ts} vs. oxide depth from the gate is calculated using WKB approximation. Trapped hole distribution at E_{ox}= 10 MV/cm is shown in this figure. The magnitude in the figure is arbitrary, only illustrating the spatial distribution of trapped hole.

When $j_n = 0$, $\tau_p = \tau_0 \cdot e^{\frac{2\sqrt{2m_pE_{tp}}}{\hbar}(t_{ox}-x)}$, τ_0=1.0 x 10^{-13} s by WKB approximation,[8] where E_{tp} is the hole trap energy level above the SiO_2 valence band, m_p is the tunneling effective mass of hole in SiO_2 film. Eq.(1) gives, $p_t(x) = p_{ts} \cdot e^{-\frac{t}{\tau_p(x)}}$. Therefore,

$$j_{leakage} = -q\int_{x_p}^{t_{ox}} \frac{p_t}{\tau_p(x)}dx \quad (3)$$

$$= -q\int_{x_p}^{t_{ox}} \frac{p_{ts}e^{-t/\tau_p(x)}}{\tau_p(x)}dx \quad (4)$$

$$= -q\int_{\tau_0}^{\tau_p(x_p)} \frac{p_{ts}}{\tau_p^2}\frac{e^{-t/\tau_p}}{\frac{2\sqrt{2m_pE_{tp}}}{\hbar}}d\tau_p \quad (5)$$

$$= -\frac{\hbar q p_{ts}}{2\sqrt{2m_pE_{tp}}}\frac{1}{t}(e^{-t/\tau_p(x_p)} - e^{-t/\tau_0}) \quad (6)$$

Eq.(6) implies no singularity and explains 1/t time dependence of leakage current due to trapped hole. Also, Eq.(6) enables us to determine E_{tp} and m_p by measuring leakage currents under small current stress, E_{tp}= 3.9 eV and m_p=0.4 m_0.[9]

5. Conclusions

The spatial distribution of trapped hole in thin SiO_2 is investigated by using 1/t time dependence of leakage(discharge) current. We find that the spatial distribution is well modeled by WKB approximation ,which allows us to present a new 1/t leakage current formalism.

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