Extended Abstracts of the 16th (1984 International) Conference on Solid State Devices and Materials, Kobe, 1984, pp. 99-102

Interface-Trap Generation Modeling of Fowler-Nordheim Tunnel Injection into Ultrathin Gate Oxide

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Two mechanisms for interface-trap generation during Fowler-Nordheim tunnel injection into ultra-thin gate oxide are described. One mechanism is independent of the gate bias polarity during injection, and is explained using a broken-bond model by taking account of electron heating due to an oxide field during injection. The other mechanism is present only in negative gate bias injection, and is explained by a model in which electrons, heated by the oxide field, generate interface-trap when the electrons cross the interface between the SiO_2 and the Si substrate.

1. Introduction

The degradations of bulk SiO_2 and the interface between SiO_2 and Si substrate are the main causes of instability in MOS devices. As the demand for thinner SiO_2 film has increased along with higher integration of Si LSI, the role of the interface becomes increasingly important. However, the degradation mechanism of the interface remains poorly understood.

This paper describes two mechanisms for interface-trap generation during Fowler-Nordheim tunnel injection into ultra-thin gate oxide. One mechanism is independent of the gate bias polarity during injection, and the other mechanism is present only in negative bias injection. Models for the two mechanisms are also proposed taking account of electron heating by an oxide field during injection.

2. Experimental procedures

The devices measured were MOSFETs fabricated using n-channel Si gate technology. The impurity concentration in the p-type (100) Si substrate was 3.5×10^{16} cm^{-3}. The gate oxide of 54 Å thick was grown in dry O_2 at 800°C and the gate oxides of 107 Å and 148 Å thick were grown at 900°C; thicknesses were estimated by ellipsometric technique. H_2/N_2 annealing was carried out at 400°C for 30 minutes.

Fowler-Nordheim tunnel current was injected under the condition that the gate electrode was either positively or negatively biased, and the source, the drain and the substrate electrodes were grounded. The interface-trap density change ΔD_{it} during the injection was estimated from the subthreshold current slope [1].

3. Comparison of interface-trap generation for positive and negative biases

The ΔD_{it} for 54 Å gate oxide MOSFETs is shown in Fig. 1 as a function of the density of electrons injected into the gate oxide N_{inj}, with gate bias V_G during injection as a parameter. For positive V_G, ΔD_{it} saturates with N_{inj} to 3.6 x $10^{12} eV^{-1}cm^{-2}$ independent of V_G [1]. For negative V_G, ΔD_{it} increases with N_{inj} above 6 x 10^{12} $eV^{-1}cm^{-2}$, while it is almost equal to that in the corresponding positive case up to about 10^{12} $eV^{-1}cm^{-2}$ (Compare data for V_G = -7V and 6V, and for V_G = -7.5V and 6.5V; absolute oxide field for each pair is almost the same.).

In order to investigate the discrepancy between positive and negative biases, the difference between ΔD_{it} for a negative bias and that for a corresponding positive bias, $\widetilde{\Delta D_{it}}$, will be discussed. $\widetilde{\Delta D_{it}}$ is shown in Fig. 2 as a function of N_{inj}, with negative gate bias V_G during injection and gate oxide thickness t_{ox} as parameters.

The solid lines in the figure are calculated

results using the following equation:

$$\Delta\widetilde{D_{it}} = \widetilde{D_{it,sat}}(1-\exp(-\widetilde{\sigma} \times N_{inj})), \qquad (1)$$

with saturation value $\widetilde{D_{it,sat}}$ = 4.7 x $10^{12}eV^{-1}cm^{-2}$, and cross section $\widetilde{\sigma}$ indicated in the figure. Eq. (1) is obtained by solving the following equation:

$$d\widetilde{D_{it}}/dt = (\widetilde{D_{it,sat}} - \widetilde{D_{it}})\widetilde{\sigma}J/q, \qquad (2)$$

with the relation $N_{inj} = Jt/q$ and $\widetilde{D_{it,sat}} \gg \widetilde{D_{it}}(t = 0)$, where q is electronic charge and J is the density of the injected Fowler-Nordheim current.

Good agreement between the measured and calculated results confirms that there are two mechanisms for interface-trap generation during Fowler-Nordheim tunnel injection. One is common to both biases and the other is peculiar to a negative bias.

4. Interface-trap generation modeling

4.1 Modeling of mechanism common to both bias injections

Generation cross section σ for the mechanism common to both bias injections is shown in Fig. 3 as a function of the oxide electric field E_{ox} during injection for both bias injections, with t_{ox} as a parameter. σ was estimated by the following equation:

$$\sigma = \Delta D_{it}/D_{it,sat}N_{inj}, \qquad (3)$$

with saturation value $D_{it,sat}=3.6\times10^{12}eV^{-1}cm^{-2}$, in the region where ΔD_{it} depends linearly on N_{inj} [1].

It is obvious that this mechanism can not be explained by a hydrogen model [2,3], hole capture model [4], electron impact model [4] nor an impact ionization model [5], because these models are not responsible for both biases.

To explain this mechanism, we propose a new model based on a broken-bond model [6,7,8]. First, electrons injected into the gate oxide are accelerated by the oxide field and obtain electron temperature T(x) and energy $E_{el}(x)$ at a point x from the tunneling point. Second, the accelerated or heated electrons interact with strained bonds in the bulk SiO_2 with stopping power S(x), and break these strained bonds. In this process, the broken bonds' density is assumed to be proportional to S(x), which means that the threshold energy required for breaking strained bonds is small compared with the energy given by the applied voltage. Finally, the structural modifications of SiO_2 due to broken bonds in bulk SiO_2 causes many of the bonds at the Si-SiO_2 interface to break, and these broken bonds in turn act as new surface states [8].

Based on this model, ΔD_{it} can be obtained as follows, in the region where ΔD_{it} is proportional to N_{inj}:

$$\Delta D_{it} \propto N_{inj}\int_0^{\widetilde{t_{ox}}} f(x)S(x)v(x)/v_d(x)dx, \qquad (4)$$

where f(x) is the probability that bonds at the Si-SiO_2 interface are broken by the broken bonds at point x in the bulk SiO_2, and v(x) is the electron velocity of motion including thermal and drift components, while $v_d(x)$ is the electron drift velocity. The factor $v(x)/v_d(x)$ is used to take electron thermal motion into account. In Eq. (4), $\widetilde{t_{ox}}$ is the passing-through distance of electrons in the SiO_2 conduction band ($\widetilde{t_{ox}} = t_{ox} - \phi/E_{ox}$, where ϕ is the oxide potential barrier height for electrons (3.2eV [1]) and ϕ/E_{ox} is the tunneling distance.).

Then, the generation cross section σ for this mechanism is obtained using Eqs. (3) and (4) as:

$$\sigma = A\int_0^{\widetilde{t_{ox}}} f(x)S(x)v(x)/v_d(x)dx, \qquad (5)$$

where A is a proportional constant.

The lines in Fig. 3 are calculated results of Eq. (5), where A was determined so as to fit the calculated results to the measured ones. In the calculation, f(x) was regarded as a constant, because σ is almost independent of gate bias polarity which causes the different distribution of broken bonds in bulk SiO_2. This means that the structural modifications of SiO_2 propagate without decay at least within about 150 Å. We used the the following equation: [9]

$$S(x) \propto E_{el}^{\ 2}(x), \qquad (6)$$

for low energy electron stopping power S(x), and the equations:

$$E_{el}(x) = m_c^* v_d^2(x)/2 + 3kT_e(x)/2, \quad (7)$$

$$v(x) = \sqrt{2E_{el}(x)/m_c^*}, \quad (8)$$

for calculation of $E_{el}(x)$ and $v(x)$, where m_c^* is effective mass of electrons in the SiO_2 conduction band and k is Boltzmann constant. $v_d(x)$ is obtained as a function of x by solving the equation: [10]

$$x = q\tau_m^2(x)E_{ox}(-\ln(1-v_d(x)/v_m(x)) - v_d(x)/v_m(x))/m_c^*, \quad (9)$$

where

$$\tau_m(x) = \mu(x)m_c^*/q, \quad (10)$$

$$v_m(x) = \mu(x)E_{ox}, \quad (11)$$

$$\mu(x) = \mu_0\sqrt{T_0/T_e(x)}, \quad (12)$$

and T_0 is lattice temperature and μ_0 is electron mobility at lattice temperature. $T_e(x)$ is given by the equation: [10]

$$T_e(x) = T_0(1+(\mu_0 E_{ox}/v_{sat})^2 \times (1-\exp(-(v_{sat}/\mu_0)^2 qx/2kT_0E_{ox}))), \quad (13)$$

where v_{sat} is the electron saturation velocity. We also used for calculation of Eq. (5), $m_c^* = 1.3m_0$ (m_0 is mass of free electron.) [11], $\mu_0 = 23$ $cm^2/Vsec$ and $v_{sat} = 1.5 \times 10^7$ cm/sec. The latter two values were determined so that the drift velocity dependence on oxide field for large x, derived from Eqs. (9) and (13), fitted the experimental results [12].

Noting the good agreement between the measured and calculated results in Fig. 3, it is apparent that the interface-trap generation common to both bias injections is explained using a broken-bond model [6,7,8] by taking account of electron heating during passage through the SiO_2 conduction band. Moreover, from the experimental results that ΔD_{it} saturates with N_{inj} to a constant value independent of t_{ox} [1], it is suggested that the number of weak bonds at the interface to be broken by the structural modifications is constant independent of t_{ox}.

4.2 Modeling of mechanism peculiar to negative bias injection

Generation cross section $\tilde{\sigma}$ for the mechanism peculiar to negative bias injection is shown in Fig. 4 as a function of E_{ox}. In the negative bias injection, the heated electrons pass through the interface between the SiO_2 and the Si substrate. Therefore, these heated electrons can directly break the bonds at the interface. For this mechanism, the following generation cross section $\tilde{\sigma}$ is obtained as:

$$\tilde{\sigma} = B \times S(x)v(x)/v_d(x) \quad (x = \text{Si-SiO}_2 \text{ interface}), \quad (14)$$

where B is a proportional constant. Eq. (14) can be derived similarly to Eq. (5), but in this case only the regions very close to the interface are taken into account.

The lines in Fig. 4 are calculated results estimated by Eq. (14). B in Eq. (14) was determined so as to fit the calculated results to the measured ones.

The good agreement between the measured and calculated results, especially for the dependence of $\tilde{\sigma}$ on oxide thickness t_{ox}, indicates that the mechanism peculiar to negative bias injection is explained using a model in which electrons heated by the oxide field generate interface-trap when electrons cross the interface between the SiO_2 and the Si substrate.

5. Conclusion

The comparison of the measured and calculated results for the difference between ΔD_{it} for a negative bias and that for a positive bias, $\Delta\tilde{D}_{it}$, confirms that interface-trap generation during Fowler-Nordheim tunnel injection consists of two mechanisms, one common to both biases and the other peculiar to a negative bias.

The good agreements between the measured and calculated results of the generation cross sections for both mechanisms indicate that (i) the former mechanism is explained using a broken-bond model [6,7,8] by taking account of electron heating due to an oxide field during injection, and (ii) the latter mechanism is explained using a model in which electrons heated by the oxide field generate interface-trap when electrons cross the interface between the SiO_2 and the Si substrate.

Acknowledgement

The authors would like to thank Prof. T. Sugano of the University of Tokyo and Dr. E. Arai for their helpful discussions. They are also grateful to Dr. M. Kondo for his encouragement.

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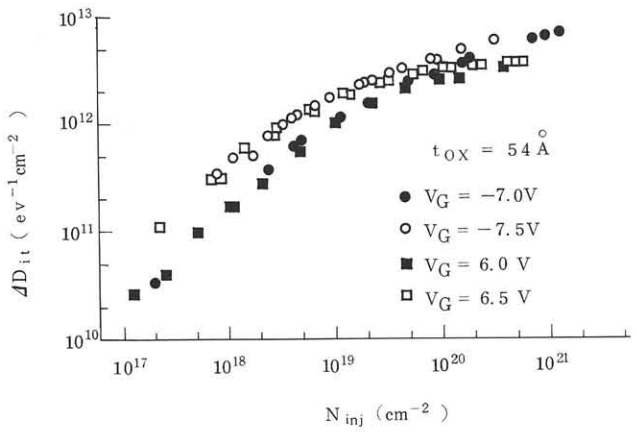

Fig. 1 ΔD_{it} as a function of N_{inj} for positive and negative injections.

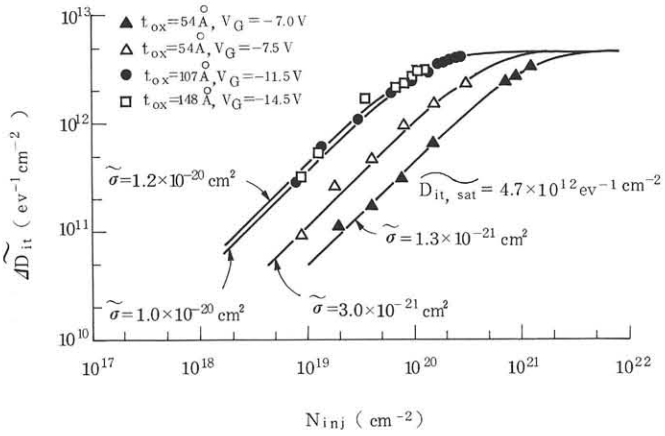

Fig. 2 Measured and calculated results for $\tilde{\Delta D}_{it}$ as a function of N_{inj}.

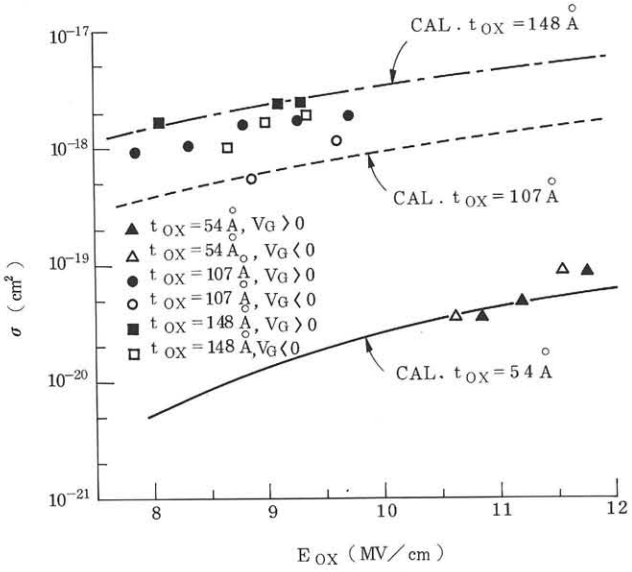

Fig. 3 Measured and calculated results for σ as a function of E_{ox}.

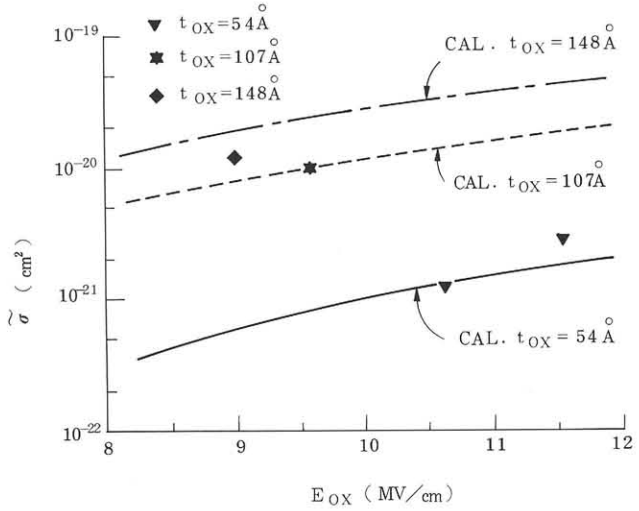

Fig. 4 Measured and calculated results for $\tilde{\sigma}$ as a function of E_{ox}.