Influence of interfacial nitrogen on edge charge trapping at the interface of gate oxide/drain extension in metal–oxide–semiconductor transistors

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In this work, the edge charge trapping at the interface of gate oxide/drain extension caused by Fowler–Nordheim injection is determined quantitatively by using a simple approach to analyze the change of the drain band-to-band tunneling current. For both pure and nitrided oxides with an oxide thickness of 6.5 nm, positive edge charge trapping is observed while the net charge trapping in the oxide above the channel is negative. It is found that the nitrogen at the interface can enhance the edge charge trapping. The results could be explained in terms of the creation of positive fixed oxide charges at the interface as a result of the electrochemical reactions involving holes and hydrogen ions. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1572471]

Nitrogen incorporation in gate dielectric films has been widely employed in deep submicron metal–oxide–semiconductor (MOS) devices.[1] There have been many studies on the charge trapping in the nitrided oxides, and both positive and negative charge trapping have been observed.[2–4] However, these studies were mainly concerned with the charge trapping in the oxide above the channel, and less studies have been reported on the charge trapping in the oxide edge overlapping the drain extension. The edge charge trapping at the interface of this overlap region has a strong influence on the gate-induced drain leakage current resulting from the drain band-to-band tunneling because the band-to-band tunneling current has an exponential dependence on the silicon surface electric field in the overlap region.[5–8] As a small change in the electric field due to the edge charge trapping could cause a significant change in the band-to-band tunneling leakage current, the edge charge trapping could be a reliability concern for MOS transistors and flash memory devices. Obviously, a study on the influence of the nitridation of the gate oxide on the edge charge trapping and thus on the band-to-band tunneling current is necessary. In this work, we used a simple approach to quantitatively examine the influence of interfacial nitrogen concentration on the edge charge trapping.

The devices used in this study were n^+-polycrystalline-silicon (polysilicon)-gate n-channel MOS field-effect transistors (MOSFETs) with a channel length/width of 0.5/20 μm and a gate oxide thickness of 6.5 nm. Either pure SiO_2 or nirided oxides were used as the gate dielectrics. The pure SiO_2 was grown using partial-wet process, and further, *in situ* NO nitridation and N_2/O_2 annealing were carried out for nitrided oxides. The secondary ion mass spectroscopy measurement showed the nitrogen piling up at the SiO_2/Si interface for the nitrided oxides, and two nitrogen concentrations (1.8 and 4.0 at. % at the interface) were used in this study. The devices were stressed under a constant gate current (10 mA/cm^2) with either substrate or gate FN injections. The drain band-to-band tunneling current was measured with a gate-controlled-diode configuration[9] in which the drain was kept at a constant positive voltage while the gate voltage was varied in a sufficiently negative range corresponding to the band-to-band tunneling. The gate current was also monitored to ensure that the contribution of the gate oxide leakage was insignificant.

When the surface electric field (E_s) in the silicon of the drain extension under the gate is strong enough, a band-to-band tunneling will occur in this silicon region, giving rise to a drain current.[5] The band-to-band tunneling current can be expressed as[6,10]

$$J = A E_s^2 \exp(-B/E_s), \tag{1}$$

where A and B are two constants[6] which can be determined experimentally from the plot of $\ln(J/E_s^2)$ versus $(1/E_s)$. If there is an electric charge trapped at or very close to the SiO_2/Si interface in the drain extension overlap region (i.e., the edge charge trapping mentioned herein) as a result of electrical stress, the silicon surface electric field will change, and the electric field is now $E_s = E_{s_0} + \Delta E$ where E_{s_0} is the surface field without charge trapping (i.e., the electric field before stress, which can be calculated with the formulas given in Ref. 5) and ΔE is the surface field change. Thus, the influence of the edge charge trapping on the band-to-band tunneling current can be described in terms of ΔE by

$$J = A(E_{s_0} + \Delta E)^2 \exp\left(-\frac{B}{E_{s_0} + \Delta E}\right). \tag{2}$$

ΔE can be calculated easily by using[11]

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$$\Delta E=\frac{\sum_{i=1}^{n}\left[\ln\left(\frac{J_m(i)}{E_{s_0}(i)^2}\right)-\ln A+B\frac{1}{E_{s_0}(i)}\right]\left[\left(2\frac{1}{E_{s_0}(i)}+B\left(\frac{1}{E_{s_0}(i)}\right)^2\right]}{\sum_{i=1}^{n}\left[\left(2\frac{1}{E_{s_0}(i)}+B\left(\frac{1}{E_{s_0}(i)}\right)^2\right]^2}, \tag{3}$$

where $J_m(i)$ is the poststress band-to-band tunneling current measured at a different applied surface field E_{s_0}(i) (i $=1,2,...n$, n is the number of the data points).

Figure 1 shows that the electrical stress leads to a reduction of the silicon surface electric field (i.e., $\Delta E<0$) and thus a reduction of the band-to-band tunneling current. On the other hand, the reduction of the electric field (and thus the band-to-band tunneling current) is enhanced with a higher nitrogen concentration at the interface, as shown in Fig. 2. The reduction of the electric field means a net positive edge charge trapping in the drain extension region. The edge charge trapping can be determined with $Q_T=\epsilon_{\mathrm{Si}}\Delta E$ where ϵ_{Si} is the Si permittivity and Q_T is the areal density of the edge charge trapping at the interface in the drain extension region. Figure 3 shows the edge charge trapping as a function of stress time for different interfacial nitrogen concentrations. For the gate oxide thickness of 6.5 nm used in this study, a net positive edge charge trapping is always observed. As shown in Fig. 3, the stress time dependence of the edge charge trapping follows a power law, i.e., $Q_T\propto t^n$, where t is the stress time and n is an exponent. In addition, a larger interfacial nitrogen concentration leads to a larger edge charge trapping (n is also larger), indicating that the interfacial nitrogen can enhance the positive charge trapping.

In contrast to the positive edge charge trapping shown in Fig. 3, a net negative charge trapping above the channel region is observed. Figure 4 shows the threshold voltage shift (ΔV_T) as a function of stress time for different interfacial nitrogen concentrations. The positive ΔV_T indicates a net negative charge trapping in the gate oxide above the channel region. It has been clear that electron trapping throughout the oxide is the dominant charge trapping in a thick gate oxide for sufficient long stress time. Therefore, the net negative charge trapping shown in Fig. 4 is understandable.

The positive edge charge trapping could be explained as described next. In the gate oxide overlapping the drain extension region, only those charges trapped at the interface or very close to the silicon surface will affect the silicon surface electric field and thus affect the band-to-band tunneling. It is well accepted that high field stress leads to both electron and hole trapping in the gate oxide and the release of hydrogen ions (H^+). In addition, holes are induced at the interface of the drain extension as the gate is strongly biased with negative voltage during the tunneling current measurement. At the interface, the following electrochemical reactions may take place[12,13]

$$O_3\equiv \mathrm{Si—H}+h^+\rightarrow O_3\equiv \mathrm{Si}^+ +\mathrm{H}^0, \tag{4}$$

$$\equiv\mathrm{Si—}\overset{\|}{\mathrm{N}}+\mathrm{H}^+\rightarrow\equiv\ \mathrm{Si—}\overset{\|}{\mathrm{N}}\mathrm{H}^+. \tag{5}$$

A positive fixed oxide charge is thus created from Eqs. (4) and (5). On the other hand, high field stress leads to electron trapping throughout the gate oxide. In the gate oxide overlapping the drain extension region, only the positive fixed oxide charge and the electron trapping at the interface or very close to the silicon surface can affect the silicon surface electric field. For the 6.5 nm gate oxides used in this study, the electron trapping that can affect the silicon surface electric field is less significant than the positive fixed oxide charge, and thus the net charge trapping leading to the

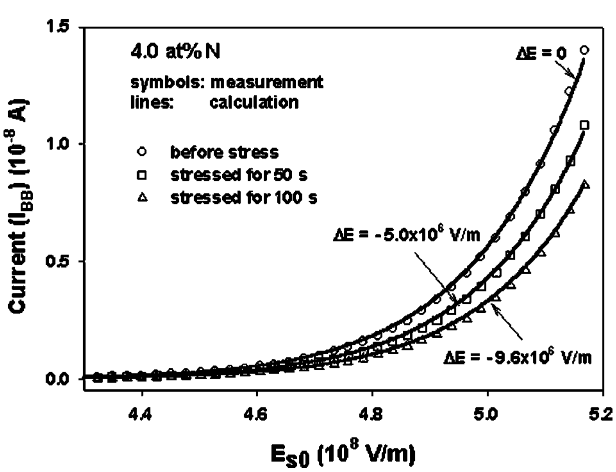

FIG. 1. An example showing the stress effect on the drain band-to-band tunneling current as a result of the positive edge charge trapping. The curves in (b) represent the calculated band-to-band tunneling current with Eq. (2) using the ΔE values determined with Eq. (3).

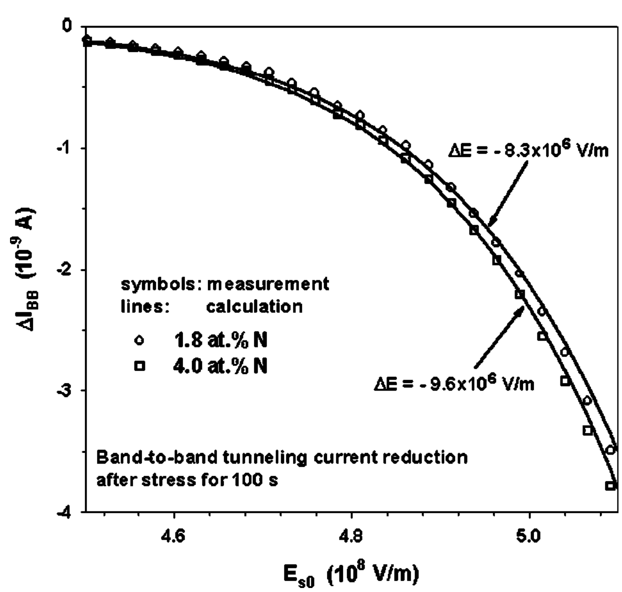

FIG. 2. Comparison of the band-to-band tunneling current reduction after a 100 s stress between the two nitrided oxides with 1.8 and 4.0 at. % N. $\Delta I_{\mathrm{BB}}=I_{\mathrm{BB}}(\text{after stress})-I_{\mathrm{BB}}(\text{before stress})$ where I_{BB} is the band-to-band tunneling current.

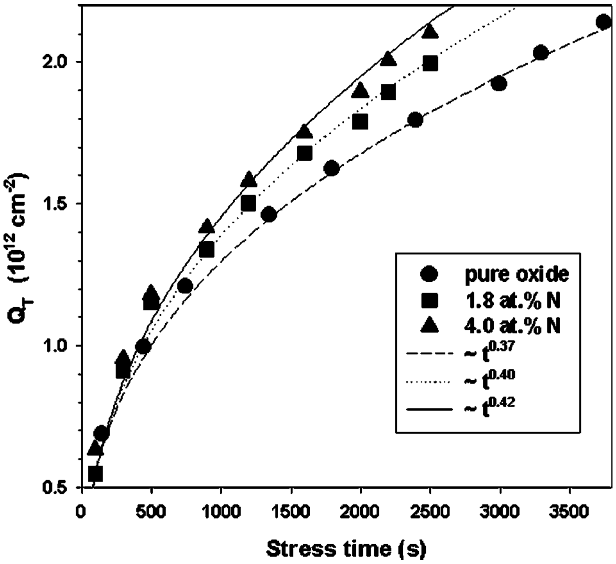

FIG. 3. Edge charge trapping as a function of stress time for different interfacial nitrogen concentrations.

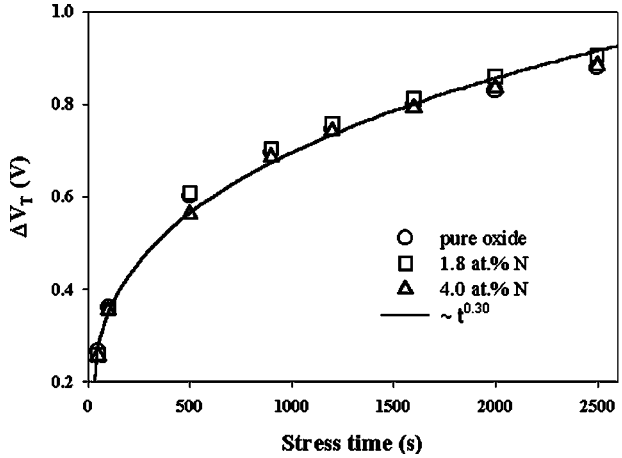

FIG. 4. Threshold voltage shift as a function of stress time for different interfacial nitrogen concentrations.

change of the electric field is positive. However, in the gate oxide above the channel, electron trapping throughout the oxide contributes to the threshold voltage (V_T), and thus the net charge trapping is negative leading to a V_T shift to a more positive voltage. This explains why the net edge charge trapping that affects the band-to-band tunneling is positive while the net charge trapping above the channel that affects the threshold voltage is negative. In addition, the aforementioned electrochemical reactions [Eqs. (4) and (5)] show that the edge charge trapping due to the positive fixed oxide charges depends on the nitrogen in the oxides, which explains the results of Fig. 3. However, in contrast to the positive edge charge trapping, the electron trapping in the oxides over the channel is insensitive or less sensitive to the nitrogen in the oxides. Therefore, there should be no obvious difference in the V_T shift between the pure and nitrided oxides as the V_T shift is mainly due to the electron trapping over the channel. This is the reason for the negligible difference in the V_T shift between the pure and nitrided oxides shown in Fig. 4.

Equations (4) and (5) have been used to explain the nitrogen-enhanced negative bias temperature instability (NBTI) effect.[13] We have also observed the nitrogen-enhanced positive fixed charge trapping above the channel from the NBTI experiments. It has been clear that for the nitrided oxides the nitrogen piles up at the interface and, therefore, a higher interfacial nitrogen concentration leads to a larger amount of positive charge trapping as a result of the H^+ trapping by nitrogen in the reaction of Eq. (5). The nitrogen-enhanced positive fixed charge trapping may be also related to the fact that the amount of interfacial Si—H bonds, which are involved in the reaction of Eq. (4), increases with nitrogen incorporation near the interface.[13] On the other hand, from first-principle calculations, we have also found that the reaction energy for the electrochemical reaction involving H^+ trapping is reduced in nitrided oxides. Therefore, the nitrogen-enhanced edge charge trapping can be explained in terms of the nitrogen-enhanced H^+ trapping and/or the increase of the amount of interfacial Si—H bonds with the interfacial nitrogen concentration.

In summary, we have conducted a study of the edge charge trapping in the gate oxide overlapping the drain extension caused by FN injection by using a simple approach to analyze the change of the drain band-to-band tunneling current. For both pure and nitrided oxides with an oxide thickness of 6.5 nm, positive edge charge trapping is observed while the net charge trapping in the oxide above the channel is negative. A higher interfacial nitrogen concentration leads to a larger edge charge trapping. The results can be explained in terms of the creation of positive fixed oxide charges at the interface as a result of the electrochemical reactions involving holes and hydrogen ions.

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