Similarities between Ionizing Radiation Effects and Negative-Bias Temperature Instability (NBTI) in MOSFET Devices

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The equivalent role of hydrogen cracking in radiation effects and Negative Bias Temperature Instability (NBTI) is described. A prediction concerning thickness dependence is compared with data. The temperature dependence of interface trap density is explained.

Introduction

The demand for advanced, radiation hard silicon-based MOSFETs for space based applications is increasing. The quality of the dielectric- Si interface plays an extremely important role in the development process [1] and much of the success of MOS devices has followed from improvements in this interface. As a result of this evolution, work continues on primary degradation process such as negative-bias temperature instability (NBTI) [2] and radiation effects [1]. In this paper, we focus on the common features of these phenomena and show that physically they have many similarities. These similarities allow us to use NBTI data to develop models that apply to both NBTI and radiation effects. For both cases here, we focus on the creation of interface traps. As will be shown, injected holes start the processes that create the interface traps both for radiation and NBTI mechanisms. In the case of NBTI, an electric field leads to injection of the holes. This mechanism involves tunneling of holes from the Si substrate to traps near the interface in the oxide. In the case of radiation effects, the holes are released by ionizing radiation throughout the dielectric.

For both radiation effects and NBTI, the holes cause the release of atomic hydrogen in the form of a proton which reacts with the hydrogen-passivated interface traps to create depassivated interface traps. Thus, for both mechanisms, the end result is the creation of interface traps. The understanding and control of these phenomena has received much attention.

Theory

The physics is illustrated in Fig. 1, which shows the temporal evolution of the key phenomena. For the case of the NBTI, the trap density is very high because the region accessible by tunneling is the highly defective region near the interface. Furthermore, as shown in Fig. 1, the accessible portion of this region has defined end points. The nearest end point is a consequence of the energy restrictions given by the electric field and the band bending. Thus the oxide region nearest the interface is inaccessible. Furthermore, for any given amount of time, the deepest point reached by the tunneling front is also a well-defined demarcation. An equivalent figure for radiation effects would show the entire dielectric region as accessible to hole trapping.

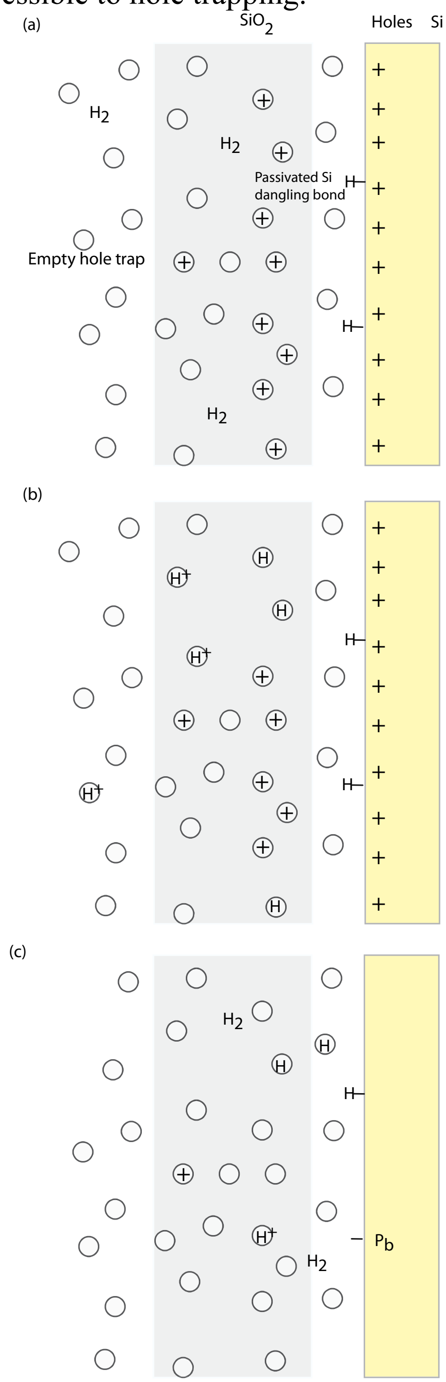

Figure 1 Sequence of events during NBTI.

At the top of Fig. 1a, the neutral hole traps are predominantly neutral oxygen vacancies. These exist in the puckered and dimer forms, but this distinction will not be considered in the physics to be discussed [3]. Some holes h^+ are shown as trapped by the neutral oxygen vacancies $V_O{}^0$

$$V_O{}^0 + h^+ \leftrightarrow V_O{}^+ \quad (1)$$

In the NBTI case, the holes reach these sites by tunneling. In the case of radiation, the migrating holes released by the ionizing radiation are captured at these sites. The key reaction that unites the radiation and NBTI effects is the cracking of molecular hydrogen at the charged vacancy site:

$$V_O{}^+ + H^0{}_2 \leftrightarrow V_O H^0 + H^+ \quad (2)$$

This reaction releases protons H^+ that create interface traps (states). In the case of radiation effects, holes can also release protons from source sites. These sites are thought to be oxygen vacancy sites. Making this assumption, this reaction

$$V_O H^0 + h^+ \leftrightarrow V_O{}^0 + H^+ \quad (3)$$

also governs the release of protons.

Fig. 1b illustrates the cracking reaction and its consequences. These reactions tend to consume the molecular hydrogen shown in Fig. 1a. Given the large electric field, the protons tend to move away from the interface towards the gate. They can be trapped at more distant oxygen vacancies. The net effect is to increase the effective distance that is reached by tunneling. Furthermore, these protons can be released again, migrate further into the oxide and be trapped again.

Finally, Fig. 1c shows the phenomena after the negative bias is removed. The nearest trapped holes immediately tunnel back to the substrate, and the more distant holes tunnel back more slowly. Given the absence of the large electric field, the protons tend to diffuse back to the interface. Some get trapped again. Some of these trapped protons lose their charge through tunneling, but others are released and migrate closer to the interface. Those that are neutral but trapped can now react with a proton to release molecular hydrogen again; a reverse of the cracking reaction. Thus the effect is to consume a proton. The net effect of the complicated reactions that are tending to be reversed is the migration of positive charge closer to the substrate. This migration may increase the rate at which charge goes back to the substrate for the most distant trapped charge because the diffusion of protons will be faster than tunneling of holes beyond some critical distance.

A small fraction of the protons will reach the defective region and also the interface. Some will hydrogenate oxygen vacancies. These proton reactions will lead to a charged trap whose hole will tunnel to the interface.

In both radiation effect and NBTI, some portion of the protons will create interface traps. These interface traps, known as Pb-centers, have three charge states P_b^-, P_b^0 and P_b^+. Most have been made inactive by hydrogen passivation. These passivated traps $P_b H^0$ can react with protons to form interface traps:

$$P_b H^0 + H^+ \leftrightarrow P_b^+ + H_2 \quad (4)$$

The protons can also repassivate the interface traps:

$$P_b^- + H^+ \leftrightarrow P_b H^0 \quad (5)$$

These phenomena are cyclical in an NBTI experiment. When the bias is applied, all the molecular hydrogen may be consumed in producing protons. When the bias is reduced, the reactions are reversed. Thus molecular hydrogen tends to be created again. These reactions reach an approximate steady state but some fraction of the interface traps are created in an irreversible way. Thus the interface trap density rises with time in agreement with the data to be discussed.

In the next section, this physics will be applied to understanding NBTI data in which the thickness of the gate dielectric is varied. More detailed physics and calculations will be presented in the presentation. Although not discussed in this abstract, this physics also provides a new mechanism as an explanation for Enhanced Low Dose-Rate Sensitivity (ELDRS) [4,5,6].

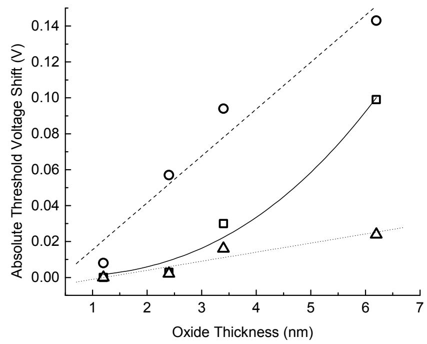

Figure 2 Thickness dependence of threshold voltage shifts.

Experiments

The threshold voltages were measured as a function of time in response to cyclical biases [7]. These measurements were performed on 130 nm channel length p-channel MOSFETs manufactured using a proprietary technology, the gate dielectric being SiON with [N] ~ 0.5 atomic percent. In order to enhance the degradation effect, devices were stressed at 120^{o}C with the gate biased at -3.25 V with respect to the source, drain and body contacts; relaxation at 0 V was also carried out at 120^{o} C. Details of the stress/relaxation and measurement methodology and the conversion of measured source-drain current variations into threshold voltage shifts can be found elsewhere [7].

Three different contributions to the threshold voltage shift ΔV_{th} are found in the data. The portion recovered during the zero volt bias relaxation phase is the recoverable charge component (RC). The component that can be cycled by application of potentials too small in themselves to generate we call the field recoverable charge ΔVth(FRC).

The remaining component ΔVth(IS)is attributed to interface states,. By suitable choice of duty cycle in a pulsed stress/measurement mode, the time dependent growth of the interface term can be extracted [3]. The data reduction process has been applied to other devices having a range of gate dielectric thicknesses, and the results are shown in Fig. 2 for the unique case of a total bias time of 500 s. Note that the stressing potential bias was adjusted for each oxide thickness to maintain as near as possible the same electric field in the gate dielectric for all cases.

The data in Fig. 2 show both a linear and quadratic dependence on sample thickness. The linear term arising from the linear dependence of the threshold voltage shift on sample thickness explains the linear relationship detected for the ΔVth(RC) and ΔVth(FRG) components, and this linear relation suggests the charge trapping does not depend upon oxide thickness. The quadratic dependence of the interface state ΔVth(IS) indicates that the IS trapping density increases approximately linearly with dielectric thickness. A similar observation has been made [1] for interface state build-up and for "oxide trapped charge" build-up resulting from irradiation. We assume that in the radiation case oxide trapped charge engulfs both the RC and FRC terms used in this work.

Figure 3 shows the temperature dependence of the interface trap density as a function of temperature. This data is compared with similar data obtained from a radiation effects experiment. In both cases, the interface trap density is controlled primarily by Eq. (4). At the lowest temperatures, the forward reaction dominates. However, depassivation only takes place after the electrical stress is removed. At the highest temperatures, the reverse reaction tends to dominate. For NBTI, this reaction is very effective because all the traps tend to me positively charged. Furthermore, the electric field drives the protons away from the interface, preventing the forward reaction. Calculations for the temperature dependence show that the temperature dependence can be explained by a rate constant and Arrhenius energy obtained from hydrogen annealing experiments.

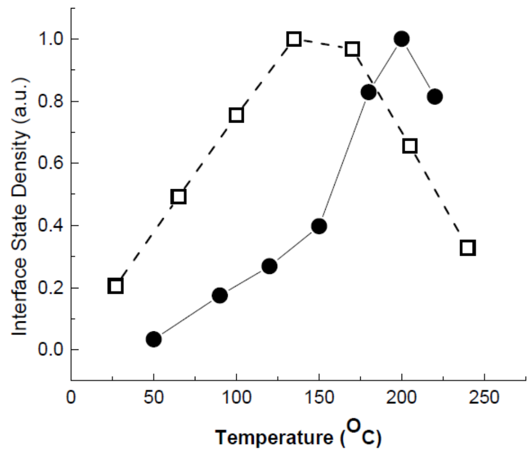

Figure 3 Temperature dependence of the interface trap density for NBTI (solid circles) and radiation effects (open squares).

Discussion

The linear growth of the interface state density is consistent with the hydrogen cracking mechanism because molecular hydrogen from the entire volume of the oxide contributes to this reaction. In fact, the molecular hydrogen density is assumed to be small enough that it is all consumed in the forward cracking reaction. After the bias is removed, the protons released by the cracking mechanism create the interface traps. Thus the linear dependence of molecular hydrogen density on thickness leads to a linear dependence of interface state density on thickness.

Thus our data and analysis indicate that the NBTI data can be interpreted in terms of the same defects identified in radiation studies [1]. Furthermore, these interface states charge positively in PMOS devices. Although not presented, measurements have shown they charge negatively in NMOS devices.

The data for recoverable charge can be interpreted in terms of trapping at neutral oxygen vacancies of the dimer type [3]. These recover rapidly because of their proximity to the Si/dielectric interface and the overall "thinness" of the dielectrics studied in NBTI (< 10 nm). The data for the field recoverable charge can be interpreted in terms of switching traps observed in electron spin resonance studies of irradiated MOS structures [8].

Recent attention has focused on the possible synergy between NBTI and radiation effects. The specific defect reactions presented in this paper do not provide any mechanisms for synergy.

Summary

The physics of radiation effects and NBTI have been shown to have similarities that arise from the common role of the hydrogen cracking reaction that releases protons as a consequence of trapped charge. The end result is the creation of permanent interface traps in both phenomena.

Acknowledgments

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References

1. J. R. Schwank, M. R. Shaneyfelt, D. M. Fleetwood, J. A. Felix, P. E. Dodd, P. Paillet and V. Ferlet-Cavrois, "Radiation Effects in MOS Oxides," IEEE Trans. Nucl. Sci. vol. 55, no. 4, pp. 1833-1853, Aug. 2008.

2. J. Franco, B. Kaczer, G. Eneman, Ph. J. Roussel, M. Cho, J. Mitard, L. Witters, T. Y. Hoffmann, G. Groeseneken, F. Krupi and T. Grasser,"On theRecoverable and Permanent Components of Hot Carrier and NBTI in Si pMOSFETs and Their Implication in Si0.45Ge0.55 pMOSFETs," IEEE Proc. IRPS11, pp. 624-629, 2011.

3. A. J. Lelis and T. R. Oldham, "Time Dependence of Switching Oxide Traps," IEEE Trans. Nucl. Sci., vol. 41, pp. 1835-1843, Dec. 1994.

4. R. L. Pease, R. D. Schrimpf and D. M. Fleetwood, "ELDRS in Bipolar Linear Circuits: a Review Mechanisms for Radiation Dose-Rate Sensitivity of Bipolar Transistors," IEEE Trans. Nucl. Sci., vol. 56, no. 4, pp. 1894-1908, Aug. 2009.

5. H. P. Hjalmarson, R. L. Pease, S. C. Witczak, M. R. Shaneyfelt, J. R. Schwank, A. R. Edwards, C. E. Hembree and T. R. Mattsson, "Mechanisms for Radiation Dose-Rate Sensitivity of Bipolar Transistors," IEEE Trans. Nucl. Sci., vol. 50, no. 6, pp. 1901-1909, Dec. 2003.

6. H. P. Hjalmarson, R. L. Pease, R. A. B. Devine, "Calculations of Radiation Dose-Rate Sensitivity of Bipolar Transistors," IEEE Trans. Nucl. Sci., vol. 55, no. 6, pp. 3009-3015, Dec. 2008.

7. D. D. Nguyen, C. Kouhestani, K. E. Kambour, H. P. Hjalmarson, and R. A. B. Devine, "Extraction of recoverable and permanent trapped charge resulting from negative bias temperature instability," Phys. Stat. Sol. (c), accepted, (2013).

8. J. F. Conley Jr., P. M. Lenahan, A. J. Lelis and T. R. Oldham, "Electron Spin Resonance Evidence that E'??Centers Can Behave as Switching Oxide Traps," IEEE Trans. Nucl. Sci. vol. 42, no. 6, pp. 1744-1749, Dec. 1995.