Extended Abstracts of the 1993 International Conference on Solid State Devices and Materials, Makuhari, 1993, pp. 829-831

Investigations on Hole Trapping and Detrapping Phenomena in Thin Oxide Films

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Hot hole induced damage of SiO_2 and the trapping characteristics of hole traps present in the oxide of MOS structure have been investigated using thin oxides p-channel MOS transistors. In contrast to the effect of hot electron, oxide damage is rather less severe as no new traps were generated during hot hole injection. The concept of thin oxide films for better device reliability was found to be limited for small injection as the trapped hole density approaches that for thick oxides with the increase of injected hole density. Intrinsic hole trap has got retrapping capability and the capture cross-section was found to have distributed values in the range from 10^{-12} to 10^{-17} cm^2. Detrapping of trapped holes is strongly dependent on oxide field polarity and magnitude. Negligible discharging for negative polarity suggests that detrapping is dominant at the Si/SiO_2 interface.

1 Introduction

Hot carrier injection and trapping phenomena in the oxide of MOS structures are being studied for decades due to its active involvement in the degradation of device characteristics, which has now become a major reliability concern as the high damage rate caused by hot electron results in short device lifetime. Accordingly, massive investigations on hot electron induced degradations of MOS devices have been carried out during previous decades.[1-9] Although the role of hot holes in device degradation has long been discussed, investigations on the matter started lately as holes were found responsible for interface trap formation at the Si/SiO_2 interface.[10-13] A number of reports on hole trapping phenomena in the oxide of MOS structures are published during recent years with controversies indicating the necessity and scope for more investigations on the matter.[13-19] In this connection, we investigate the nature and trapping characteristics of hole traps present in the oxide through charging, discharging and subsequent recharging experiments. Charging and recharging of hole traps are achieved by uniform hole injection from Si substrate into the gate oxide, while discharging is done by applying positive bias to the gate.

2 Experimental

The samples used in this study are p-channel MOSFETs fabricated in CMOS process. Gate oxide is grown at 850°C in dry O_2 and annealed in N_2 at 900°C. Samples with oxide thickness in the range from 4.6 to 15nm are fabricated to study hole trapping and detrapping phenomena in very thin oxide films. Uniform hole injection into the oxide is achieved through substrate hole injection technique. Biasing conditions during substrate hole injection has been illustrated elsewhere.[13] Gate current during injection is monitored to obtain injected hole density, while $I_d - V_g$ characteristics are measured periodically to investigate threshold voltage shift and thereby trapped charge density in the oxide. The sample is allowed to relax under a fixed *positive* oxide electric field for long time ($\sim 2 \times 10^5$s) after injecting 10^{16} holes/cm^2. In order to investigate the nature of hot hole induced damage, we repeated the experiment twice on the same sample through reinjection of holes from the substrate.

3 Results and Discussion

3.1 *Trapping characteristics*

A semilog plot between trapped and injected hole densities with oxide thickness as a parameter is shown in Fig. 1. Although hole trapping in thin oxides for small injected hole density ($N_{inj} \leq 5 \times 10^{13}cm^{-2}$) has been reported before,[17,19] hole trapping rate in very *thin* oxide for *high injection* has not so far been reported. Figure 1 supports less degradation in very thin oxides for small injected hole density but demonstrates that the damage approaches that in thick oxides for high injected hole densities. Thus the concept of thin oxide films for better device reliability[18] is limited to low carrier injection only. No oxide thickness dependence (for $t_{ox} \geq 6$ nm) of hole trapping demonstrates that the nature and spatial position of hole traps in the oxide are identical.

3.2 *Detrapping characteristics*

Figure 2 illustrates the detrapping characteristics in logarithmic time scale under a fixed oxide field as mentioned in the figure. No significant dependence on *oxide thickness* demonstrates that the nature, energy and spatial position of hole traps that undergo

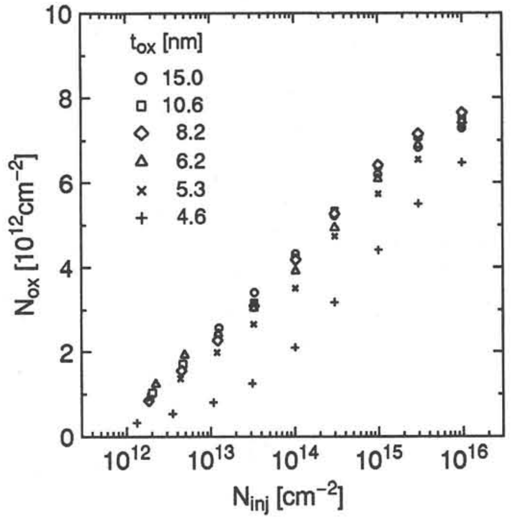

Fig. 1 Trapped hole density as a function of injected hole density with oxide thickness as a parameter.

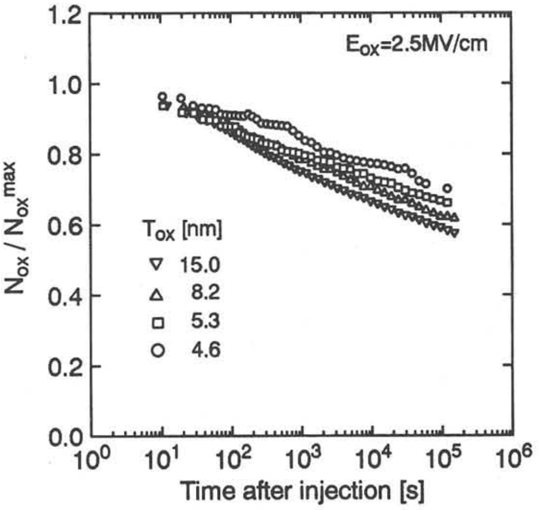

Fig. 2 Normalized detrapping characteristics for samples with various oxide thicknesses.

discharging under a certain oxide field are similar regardless of oxide thickness. In this connection, we also investigated the *oxide field* dependence of detrapping characteristics. The results thus obtained are presented in Fig. 3. A systematic variation with the same discharging rate can be seen which indicates strong initial influence of oxide field on detrapping phenomena. Negligible detrapping for negative oxide field suggests that detrapping through the SiO_2/Gate interface hardly occurs, while high detrapping for positive oxide fields indicate considerable discharging through the Si/SiO_2 interface. It also indicates the presence of different detrapping mechanisms with respect to oxide field polarity.

3.3 *Retrapping characteristics*

Figure 4 shows the trapping characteristics obtained from charging, discharging and recharging experiment carried out sequentially on the same sample. About 50% of the trapped charge are discharged nearly $2 \times$

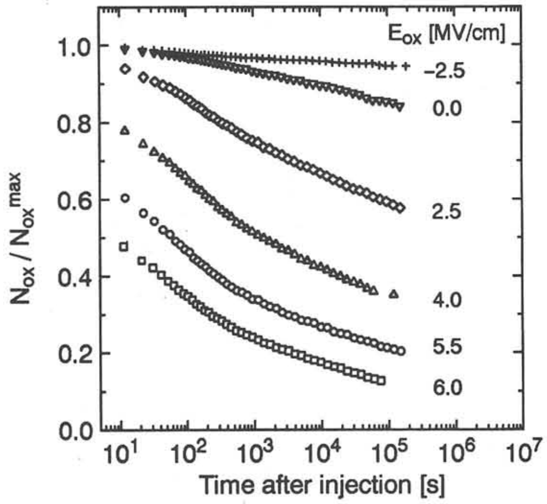

Fig. 3 Oxide electric field dependence of detrapping of holes trapped in the oxide during substrate hot hole injection.

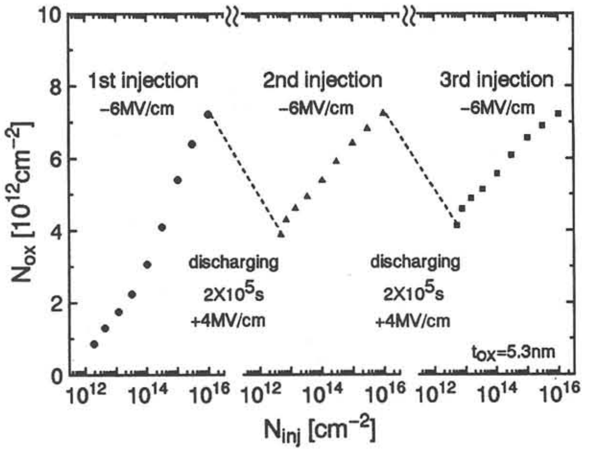

Fig. 4 Injection, relaxation and reinjection characteristics.

10^5s after injection under an oxide field of +4MV/cm. As shown in Fig. 4, reinjections resulted in trapping characteristics with a unique gradient. It is interesting to note that the total charged traps after $N_{inj} = 10^{16}$cm^{-2} are exactly the same for all the three cases. This happened regardless of oxide thickness. These can be interpreted as recharging of the same traps discharged during relaxation i.e. unlike trap generation due to Fowler-Nordheim stress,[20] neither generation nor destruction of hole traps occur due to hot hole injection. The curve for first injection can be analyzed as charging of traps with various capture cross sections as has been illustrated in Fig. 5. Moreover, as depicted in Fig. 5 by hatched lines, most of the traps with large as well as very small capture cross-sections get discharged during relaxation, while medium range capture cross-section traps are reluctant to be discharged and thereby can be considered as deep traps.

4 Conclusions

Hot hole induced degradation caused by the structural defects present in the oxide of MOS structure

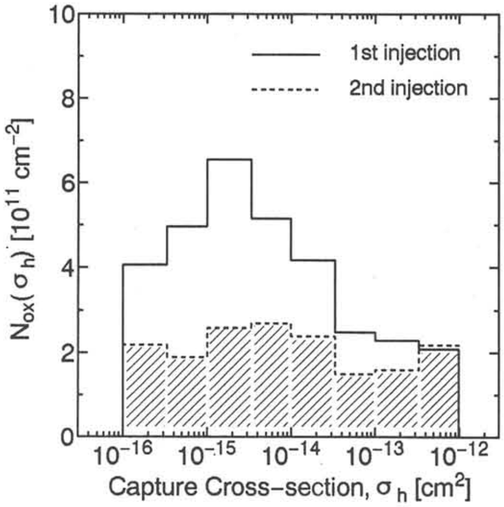

Fig. 5 Relative amount of trapped holes as a function of capture cross-section. Hatched portion represents the traps that take part in charging, discharging and recharging cycle.

have been investigated through alternate charging and discharging of hole traps by substrate hole injection experiments, using thin oxides p-channel MOS transistors. In contrast to the effect of hot electron, oxide damage is rather less severe as no new traps were generated during hot hole injection. The concept of thin oxide films for better device reliability was found to be limited for small injection as the trapped hole density approaches that for thick oxides with the increase of injected hole density.

Intrinsic hole trap has got retrapping capability and the capture cross-section was found to have distributed values in the range from 10^{-12} to 10^{-17} cm^2. Detrapping of trapped holes is strongly dependent on oxide field polarity and magnitude. Negligible discharging for negative polarity suggests that detrapping is dominant at the Si/SiO_2 interface and discharging through the SiO_2/Gate interface hardly occurs.

5 Acknowledgements

The authors are thankful to Dr. K. Iguchi, Sharp Corporation, for providing the experimental samples.

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