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Interface State Generation and Annihilation in Thin Film p-Channel MOSFETs

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Interface state generation in thin film p-MOS transistors due to hot hole injection is investigated. The generation is found to have a saturating tendency after an incoming hole density of $1 \times 10^{16}\text{cm}^{-2}$. A new model for the generated interface trap is proposed with a Lognormal distribution of capture cross section. No significant oxide field dependence of the generation is found experimentally, while remarkable oxide thickness dependence is observed for very thin oxide thicknesses ($t_{ox} \leq$ 8nm). Active involvements of hole trapping and subsequent detrapping in the formation and annihilation of interface traps respectively, is observed. It suggests a reversible atomic structure at the Si/SiO_2 interface with respect to trapping and subsequent detrapping of holes.

1 Introduction

Interface state generation in MOS structures was identified as one of the major factors behind device degradation more than twenty years ago. Massive research have been carried out over the years to unveil the mechanism of radiation as well as hot-carrier induced interface state generation. However, no unique mechanism could be established owing to the complex response of MOS oxides to damaging causes. As a consequence, despite extensive investigations, the physical mechanism of interface state formation in MOS structures is still controversial, needing even further research and more acute analysis. In a broad sense, the mechanisms of interface state generation, reported so far, are based on two basic conceptions: involvement of hydrogen species and hole trapping at the interfacial region. The models based on trapped holes state that the holes generated by ionizing radiation drift to the Si/SiO_2 interface. Some holes are trapped near the interface and eventually get converted to interface traps.[1-4] The conversion mechnism is not however described clearly. On the other hand, models based upon hydrogen involvement describe that radiation induced holes react in the oxide to produce hydrogen species which move to the interface and ultimately produce interface traps.[5-9]

The aim of this paper is to investigate the generation mechanism, post injection behavior and oxide thickness dependence of hot hole induced interface states in thin film p-channel MOSFETs. The relationship between trapped-holes and generated interface states is discussed as well. Instead of radiation induced degradation, which is considered to involve complex interaction between electrons and holes produced by radiation, we carried out uniform hole injection into the gate oxide from the substrate. The experimental technique we used ensures more direct investigation as the complicacy due to the presence of electrons could totally be avoided.

2 Experimental

The p-channel MOSFETs used in this study are fabricated in CMOS process with an average channel doping density of $2 \times 10^{17}\text{cm}^{-3}$ and a gate area of $100 \times 100\mu m^2$. Gate oxide is grown at 850 ℃ in dry oxygen ambient and annealed in N_2 at 900 ℃. Hot-hole injection into the gate oxide is achieved by applying a reverse bias voltage to n-well satisfying a forward bias condition between the n-well and p-substrate. Bias conditions during the injection is schematically illustrated in Fig. 1. Gate current during injection

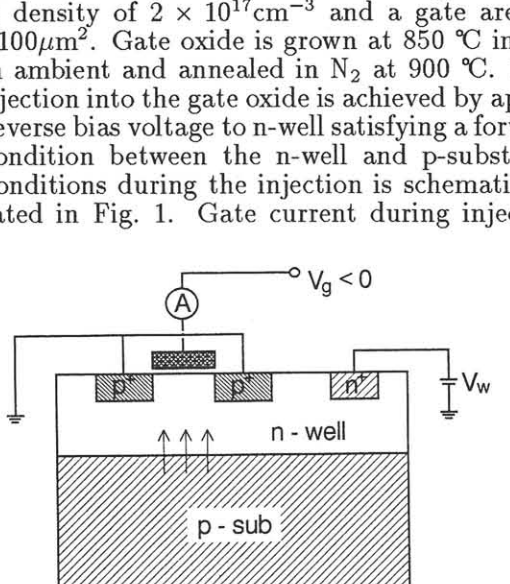

Fig. 1 Schematic illustration of the bias conditions during hot-hole injection.

is monitored to obtain the number of injected hole. Oxide degradation due to hole trapping is characterised periodically interrupting the hole injection.

The charge pumping current[10] is measured in succession to the $I_d - V_g$ characteristics to investigate the interface state generation. The generated interface traps is calculated using the increase in the charge pumping current in the flat region. Similar measurements are also carried out after injection for about 40 hours to monitor the behavior of trapped holes as well as the annihilation of the generated interface states. All the MOSFET terminals except the gate are grounded during relaxation. Number of holes trapped in the oxide is determined from the experimental data of gate voltage shift in threshold region at a given drain current.

3 Results and Discussion

A semilog plot of generated interface trap density (ΔN_{it}) *vs* injected hole density ($\log N_{inj}$) is shown in Fig. 2 (circles). The curve shows a saturating tendency with increasing injected hole density above $1 \times 10^{16}\text{cm}^{-2}$. It suggests that the interface states are not generated monotonically with injected holes which has been reported for the case of electron injection,[11,12] *i.e.*, the equation $\Delta N_{it} = A N_{inj}^{\alpha}$ does not hold good for hole injection. In order to formulate the relationship between ΔN_{it} and N_{inj}, we suggest the following equation considering a Lognormal distribution of the capture cross-section:

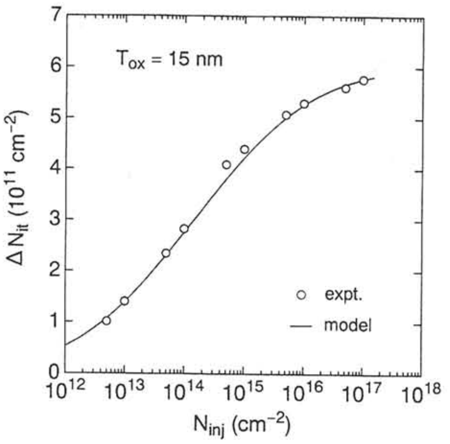

Fig. 2 Generated interface state density as a function of injected hole density. Circles are the experimental data and solid line represents the proposed model.

$$\Delta N_{it} = N_s \int f(\sigma_h)\left[1 - \exp(-\sigma_h N_{inj})\right] d\log\sigma_h; \quad (1)$$

with

$$f(\sigma_h) = \frac{1}{\sqrt{2\pi}\Delta\log\sigma}\exp\left[-\frac{1}{2}\frac{(\log\sigma_h - \log m)^2}{(\Delta\log\sigma)^2}\right]. \quad (2)$$

Where σ_h is the hole capture cross-section of interface trap. Figure 2 illustrates a good agreement between the proposed model (solid line) and the experimental results (circles) for a mean $\sigma_h = 2 \times 10^{-15}\text{cm}^2$ and $\Delta\log\sigma = 1.47$.

A logarithmic plot of ΔN_{it} *vs* N_{inj} with oxide electric field as a parameter is shown in Fig. 3. In contrast to that for electron injection,[12] we observe that the interface state formation hardly depends on oxide electric field. It indicates that the interface states due to hot-hole injection has got a single generation mechanism rather than two as has been reported for electron injection.[12] The mechanism can briefly be described as the formation of silicon dangling bonds by hydrogen species created by holes trapped near the Si/SiO_2 interface. In this connection, we investigate the relationship between trapped-holes and generated interface states to clarify the influence of the trapped-holes on interface state generation. Figure 4 suggests that a linear relationship exists between the two with nearly 10% generation efficiency, regardless of oxide thickness. It also demonstrates that trapped holes play a significant role in the formation of the interface states. We also investigate the post-injection behavior of oxide and interface degradations. An interesting gate voltage polarity dependent recovery is observed as illustrated in Fig. 5. Again, a linear relationship between detrapped holes and annealed interface states suggests a reversible atomic configutaion

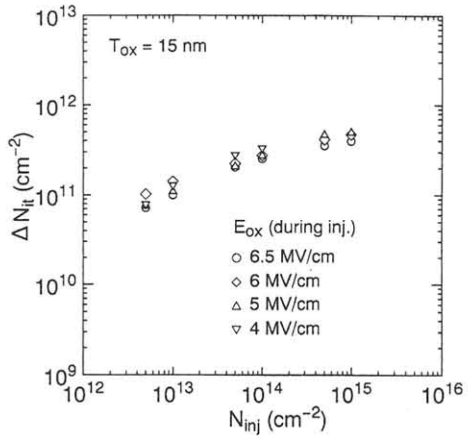

Fig. 3 Oxide electric field dependence of hot-hole induced interface state generation.

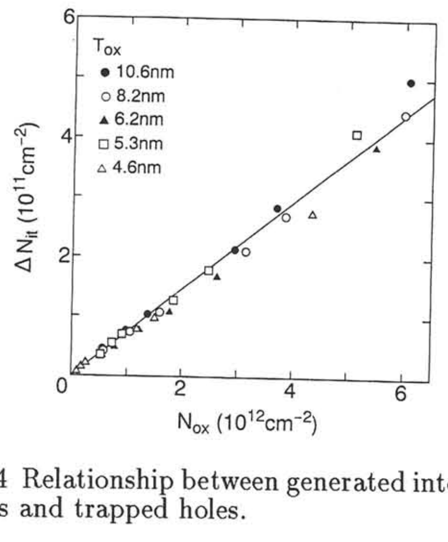

Fig. 4 Relationship between generated interface states and trapped holes.

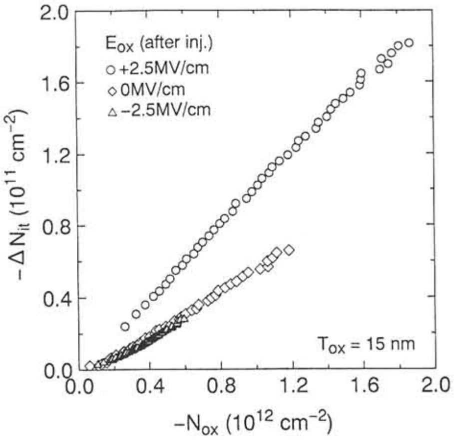

Fig. 5 Post-injection gate voltage dependence of the relationship between annealed interface states and detrapped holes.

at the Si/SiO_2 interface with respect to trapping and subsequent detrapping of holes.

A remarkable gate oxide thickness dependence of interface state generation is observed for very thin oxide thicknesses as illustrated in Fig. 6. This can be

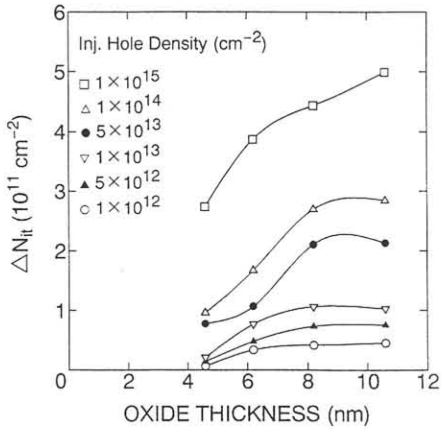

Fig. 6 Gate oxide thickness dependence of interface state generation.

explained on the basis of the spatial distribution of trapped-hole[13] in the oxide. It has been reported that the trapped-hole density decays exponentially with respect to the distance from the Si/SiO_2 interface and tends to zero over 6 nm from the interface.[13] Since interface trap generates in proportion to trapped-hole, it is expected that the generation should increase for oxide thicknesses upto 6 nm and be indifferent for oxide thicknesses thicker than that. Figure 6 demonstrates a good agreement with the conception stated above.

4 Conclusions

Hot-hole induced interface states as well as post injection behavior of the generated interface states is investigated for p-channel MOSFETs with very thin oxide thicknesses in the range of 4.6 to 15 nm. Oxide electric field dependence is examined to extract the mechanism of interface state generation. Our investigations can be concluded with the following statements:

(i) A new formula is established for hot-hole induced interface state generation in MOS structures. In contrast to two mechanisms of hot-electron induced interface state generation, a single mechanism is found to exist in this case.

(ii) A linear relationship exists between trapped-holes and generated interface states with nearly 10% generation efficiency.

(iii) An interesting gate bias dependent annihilation of the generated interface states is observed which also has got a linear relationship with detrapped holes. We believe that this is a new experimental result and has not been reported so far.

(iv) A remarkable oxide thickness dependence of interface state generation is observed for very thin oxide thicknesses ($t_{ox} \leq 8$ nm). One important inference can be drawn from this evidence that the device degradation caused by interface state generation would become an important point of consideration for future thin film MOS devices.

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