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Correlation between Fast and Slow States Observed Post Substrate Hole Injection in P-MOSFETs

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Abstract**—**The recently reported post-stress degradation of MOSFETs is investigated in this paper. We found that during substrate hole injection fast and slow states are created. Once the injection is stopped and a positive gate voltage is applied, without injection, the slow states migrate toward the silicon silicon-dioxide interface and become fast states. This explains the previously reported increase in fast state density post Substrate hole injection.

Keywords**—** Interface states, Substrate hole injection, Slow states, Trapped holes

I. Introduction

FOR a submicron CMOS technology, the reliability of SiO_2 and the SiO_2/Si interface is one of the main factors limiting the maximum operating voltage. For example, for 0.25 µm MOSFETs, difficulties have been encountered to achieve a lifetime of 10 years under an operating voltage of 2.5 V with the standard LDD structure. During the operation, devices can experience voltage overshoots due to capacitive coupling and charge redistribution, which can significantly accelerate the degradation [1]–[7]. The lifetime can be extended by using lower operating voltage, but this will inevitably reduce the operation speed. The instabilities of MOSFETs have been extensively studied over the last decade [2]-[7] and it was found that the degradation arose from two sources: the charges trapped in the gate oxide and the interface states created. The relative importance of these two depends on the stress condition [2]-[7].

The attention of previous investigations was mainly paid to the oxide charges and interface states generated during the stress, It is generally assumed that they will not increase after the stress is terminated. This is true for oxide charges, which decrease with time due to detrapping post-stress [3]-[8]. However, the behavior of interface states is more complex. Depending on stressing conditions and the gate bias applied post-stress, the interface state density can either decrease [8], or increase [3]-[7], [9], [10] or be redistributed within the energy bandgap of silicon through transformation [11], [12].

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Holes can be introduced into the oxide during irradiation [13], [14] uniform [10], [15] and non-uniform [8] electrical stress along the channel. The interface state generation post-irradiation has been extensively studied and explained by a hydrogen transportation model [13], [14]. The generation post uniform hole injection has received much attention [2]-[7]. However, there is relatively less information available for the generation post-electrical stress. Recently, it has been demonstrated that the post- stress generation can reduce the device lifetime [4]. A clear insight in the physical mechanism was, however, not obtained. The objective of this paper is to investigate the observed increase in interface states post-electrical stress in more detail. New results are presented and compared with those in literature. A new explanation is proposed to explain the observed increase in the interface state density.

II. Devices and experiments

A. Devices

The devices used in this paper are p-MOSFETs fabricated by a 0.5 µm CMOS technology. The oxide was grown in dry O_2 to a thickness of 13.8 nm. heavily doped to a level of 2×10^{17} cm^{-3} and no threshold voltage adjustment implantation was carried out. The channel length is in the range of 5 to 20 µm and the channel width is 200 µm. The devices used here are passivated by a 1 µm layer of oxide.

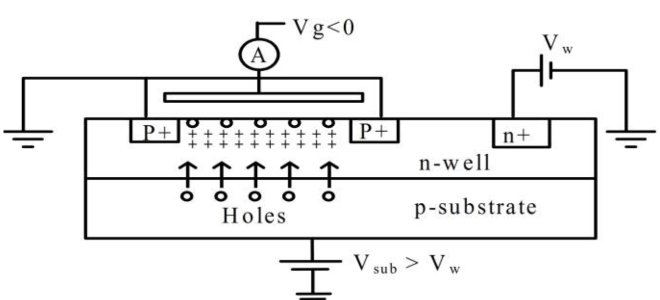

Fig. 1 Schematic illustration of the SHI measurement setup

B. Experiments

When devices are stressed by Fowler Nordheim "FN" injection, electrons and holes are introduced into the oxide. These electrons could recombine with the trapped holes. Therefore, it is difficult to determine the effect of trapped holes alone on the slow states creation. To simplify the experimental condition and to avoid uncertainties in the lateral distribution of trapped holes, holes were injected uniformly along the channel using the substrate hot hole injection "SHI" technique [10], [15]. Fig. 1 shows schematic illustration of SHI technique. Holes are supplied by forward biasing the p-substrate/n-well junction underlying the MOSFET. These holes are then accelerated towards the SiO_2/Si interface by the electric field of the space charge region. The majority of these holes are collected by the source and drain, while some of the most energetic ones can be injected into the oxide. The small amount of electrons generated in the oxide from electron-hole pairs through impact ionization will be repelled from the interface by the strong vertical electrical field. As a result, the damage studied here is dominated by hole bombardment.

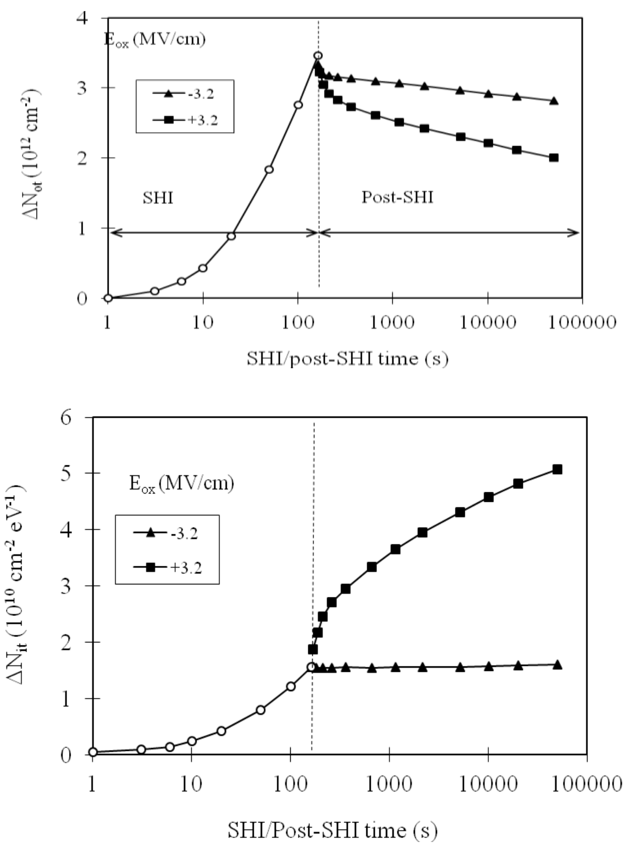

Fig. 2 Typical behavior of trapped holes (a) and measured fast interface states (b) during SHI and post-SHI under different oxide field polarities. The SHI was carried out at Eox = −6 MV/cm for 5000 s.

After devices were stressed for a preset time, the stress was terminated and a positive gate bias (Vg) was applied with the other terminals grounded. Both during and post-stress, both fast "ΔN_{it}" and slow interface states as well as trapped holes were monitored. The variable frequency two-level charge pumping (2LCP) technique [2] was used to monitor fast and slow interface state density. The fast states are considered to be the states that respond to 10^5 Hz in agreement with previous work [4]-[6], [11], [16]. The oxide charges density "ΔN_{ot}' was measured from the shift in the subthreshold region of the transfer characteristics. The contribution of interface states to this shift is generally negligible. Since the charge centroid is unknown, an effective charge density is obtained by assuming the centroid is at the SiO_2/Si interface, to comply with the previous work in this area [11], [16]. Unless otherwise specified, the SHI was carried out at an oxide field strength of -6 MV/cm. The n-well and p-substrate were biased at 8.8 V and 10 V, respectively. All experiments were carried out at room temperature.

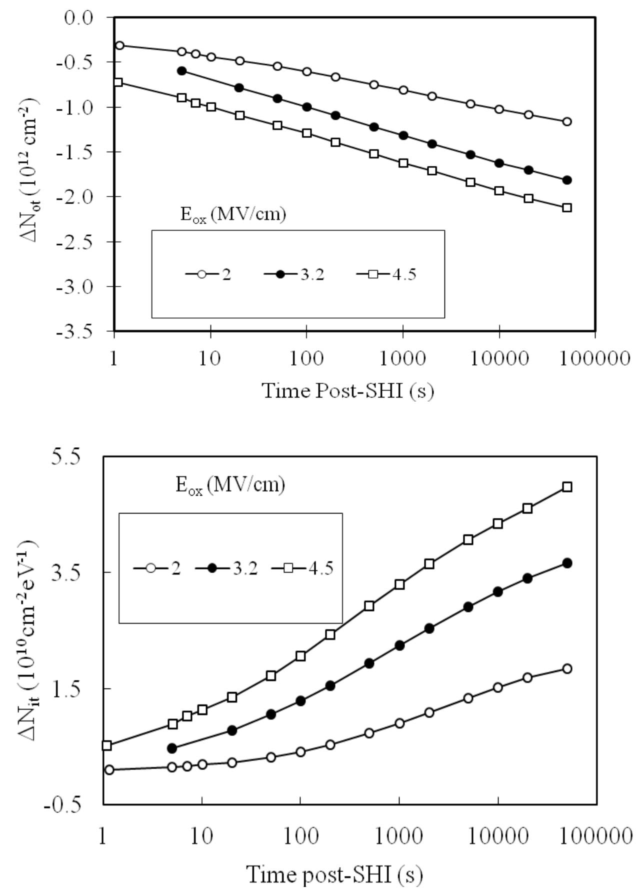

Fig. 3 The behavior of trapped holes (a) and fast state density (b) measured post-SHI as a function of Eox. The SHI was carried out under −6 MV/cm for 5000 s (injected holes density is 3.1×10^{14} holes cm^{-2}). The trapped holes density at the end of SHI was 7.2×10^{12} cm^{-2}.

III. Results And Discussion

A. Fast interface states and tarpped holes

The behavior of oxide charge density and fast interface state density during and post-SHI is shown in Fig. 2 (a) and Fig. 2 (b), respectively. As expected, both oxide charges and fast interface states build up during the injection. After the SHI is terminated, the oxide charge reduces with time due to detrapping which is a well-known phenomenon [4], [5], [9]. The detrapping rate under positive gate bias is higher because the trapped holes are located closer to the SiO_2/Si interface. Compared with oxide charges, interface states are much more strongly affected by the gate bias polarity. Under Vg>0, the interface state density increases with time, while it hardly changes when Vg<0 V. This observation is in agreement with previous results post-irradiation [14] and post-SHI [5], [6], [9]. A more detailed discussion of this phenomenon can be found in an early work [5], [6].

The dependence of ΔNot on the magnitude of electrical field is shown in Fig. 3 (a). It can be seen that an increase in electrical field enhances the hole detrapping. This indicates that the hole detrapping is dominated by charge carrier tunneling between the trapped holes and the substrate, rather than thermal emission at room temperature.

The dependence of ΔNit on the magnitude of electrical field is shown in Fig. 3 (b). It can be seen that an increase in electrical field enhances the measured interface stats density. This enhancement in the measured interface state density couldn't be explained by available models [5], [6] and a model was proposed to explain it [3]-[5].

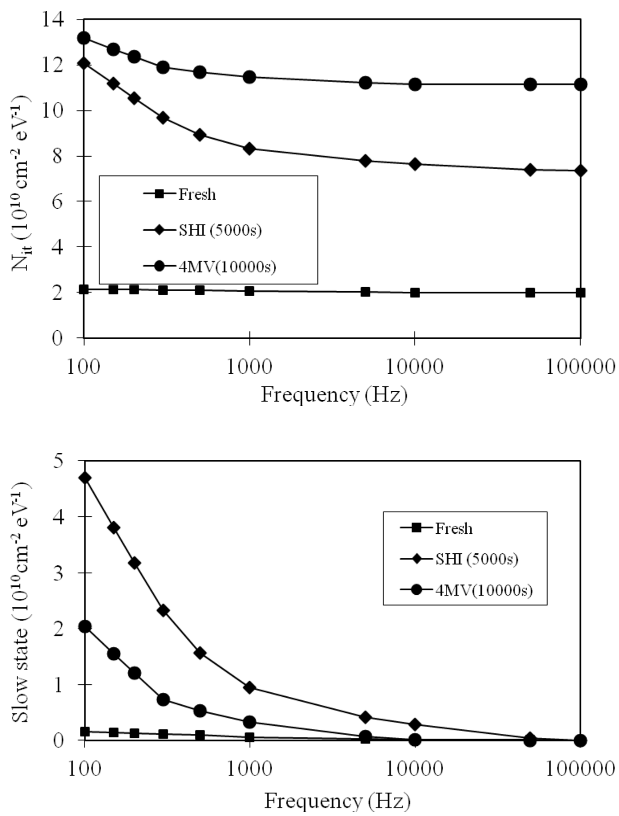

Fig. 4 The charge pumped per cycle to fast and slow states (a) and to slow states only (b) plotted as a function of frequency. The device was stressed under E_{ox} = -6 MV/cm for 5 × 10^3 s followed by post-SHI period under +4 MV/cm for 10^4 s. Fast interface states are assumed as the interface states that respond to 10^5 Hz.

B. Slow interface state creation

The interface state density measured at different 2LCP frequencies for a fresh device and a device subjected to SHI and post-SHI is shown in Fig. 4 (a) (symbol '♦'). An increase in the charge pumped to the states increases with decreasing frequency. This indicates the creation of slow states in the device after SHI. The slow states are therefore created as a result of hole injection. The increase in slow states could be due to the trapped holes in the oxide, in agreement with previously reported results [8], or to the interface state generation. However, previous study [17] shows the absence of correlation between trapped holes and slow state generation. Therefore, slow state and interface state behavior during and post SHI needs further investigation.

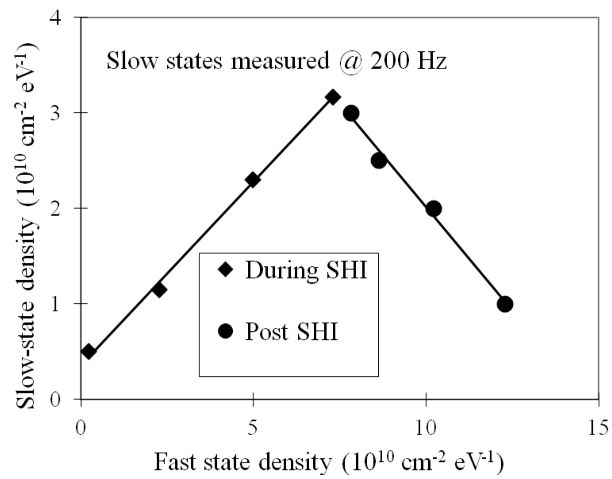

Fig. 5 The relation between fast and slow state densities during and post SHI. The device was stressed under Eox = -6 MV/cm for 5×10^3 s followed by post-SHI period under +4 MV/cm for 5 × 10^4 s. Fast interface states are assumed as the interface states that respond to 10^5 Hz.

To investigate this further, positive gate bias was applied for on a stressed for 10^4 s after SHI is terminated. This led to an increase in fast states and reduction in trapped hole density (see Fig. 2). However, the slow state density decreases as shown in Fig. 4 (b) (symbol '•'). The behavior of the slow state density with interface state density, as shown in Fig. 4 (b), may indicate that the two processes are correlated and the reduction in slow state density could be the reason for fast state formation. To investigate this further another experiment is carried out. In this experiment, a fresh device was subjected to SHI for 5000s, and followed by an E_{ox} = +4 MV/cm period for 5×10^4 s (post-SHI in Fig. 5). Throughout the experiment, fast interface and slow state densities were monitored. The slow sate densities, measured at 200 Hz, are plotted as a function of fast interface state density. The results in Fig. 5 clearly indicate that there is a linear correlation between fast interface state formation and slow state density.

Interface state creation was studied previously, and none of the available models [4], [5] could explain the formation of fast interface state post SHI. Al-kofahi et.al and others [4], [5] tried to explain this formation by proposing a model based on the formation of interface precursors [5], [18] which is generated during SHI and these precursors will be activated under positive oxide field. However, in these studies, the slow states density was not monitored. Fig. 5 clearly show a good correlation between slow and fast states. As shown in the figure, an increase in fast states is accompanied by a decrease in the slow state density. This results gave us the courage to suggest that fast interface states observed post SHI is not genuine but it is just a redistribution of the generated fast and slow states during SHI [12], [19]. The migration of slow states in the silicon dioxide towards the Si-Silicon dioxide interface reduces the slow state density and increases the fast state density. This suggestion needs further investigation and further work needs to done to clarify it.

IV. CONCLUSION

Hot hole injection creates slow and fast states and causes hole trapping. The observed increase in fast state density post SHI is believed not to be due to the generation of new interface states, but it is due to the migration of slow states, which are created during SHI in the silicon-dioxide towards the silicon silicon-dioxide interface.

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