ELSEVIER

Journal of Non-Crystalline Solids 187 (1995) 165–169

JOURNAL OF NON-CRYSTALLINE SOLIDS

Section 6. Silicon dioxide, charge trapping

Interface traps induced by hole trapping in metal-oxide semiconductor devices

Y. Roh[a], L. Trombetta[a,*], D.J. DiMaria[b]

[a] *Electrical Engineering Department, University of Houston, Houston, TX 77204-4793, USA*
[b] *IBM TJ Watson Research Center, Yorktown Heights, NY 10598, USA*

Abstract

Interface traps near the Si–SiO_2 interface induced by hole trapping *alone* are reported. It is found that interface traps are generated directly due to the presence of trapped holes in metal-oxide-semiconductor devices, and that the loss of trapped holes due to annihilation by electron injection is accompanied by a reduction of interface traps. This observation is distinct from previous reports of a 'conversion' of trapped holes to interface traps or a process of interface trap generation in which the presence of trapped holes is required in an intermediate step. It is shown that the origin of these interface traps is not the P_b center, nor a recombination center in general; thus the phenomenon may help to explain the discrepancy between the density of electrically measured interface traps and P_b center densities measured using electron paramagnetic resonance.

1. Introduction

Interface traps at the Si–SiO_2 interface in metal-oxide semiconductor (MOS) devices have been extensively investigated for improving device reliability. For example, mobility degradation and threshold voltage shifts are known to be caused by electron trapping at the Si–SiO_2 interface. Further, it has been recently suggested that interface-trap creation by hot electrons and by trapped holes during device operation will eventually lead to destructive breakdown of the SiO_2 [1]. Consequently, understanding and control of these defects have been at the core of research among semiconductor interface specialists, and represent a critical step in the fabrication of integrated circuits.

Interface traps play a central role in the degradation and breakdown of the Si–SiO_2 interface. They are generated during electrical stress by both hot electron-related mechanisms [1] and by trapped hole-related mechanisms [2,3]. During Fowler–Nordheim tunnel (FNT) injection, for example, electrons with energy greater than about 2 eV above the SiO_2 conduction band edge cause the release of hydrogen at the anodic interface. The hydrogen then diffuses to the cathodic interface where it is believed to depassivate ≡Si–H bonds, leaving dangling-bond defects. This process takes place at the Si–SiO_2 interface if electrons are injected from the Si substrate. However, substantial hydrogen release is observed only after a threshold electron injection fluence of approximately 0.001 C/cm^2.

* Corresponding author. Tel: +1-713 743 4424. Telefax: +1-713 743 4444. E-mail: ltrombetta@uh.edu.

0022-3093/95/$09.50
SSDI 0022-3093(95)00131-X

The trapped hole is also known to create interface traps *indirectly*. Specifically, it can serve as a cracking site for hydrogen, thereby generating H^+, which will drift to the Si–SiO_2 interface under positive gate bias and depassivate $\equiv$Si–H bonds after capturing an electron at the interface [3]. It has also been shown that annihilation of trapped holes via recombination with electrons introduced using photoinjection at low electric fields generates interface traps in Al-gate MOS capacitors [2]. The mechanism of trap generation is believed to involve the release and/or dissociation of hydrogen by energy released in the recombination event; the hydrogen then forms interface traps via a depassivation process.

In many cases following hot carrier or radiation damage processes, the energy distribution of interface traps (D_{it}) in the Si band gap shows a peak at 0.8 eV above the valence band edge. This peak is frequently observed when D_{it} is obtained from capacitance–voltage measurements, and is often regarded as being due to the P_b center, or more generally, to a dangling bond defect. In FNT and hole annihilation experiments described above, electrically measured interface trap spectra show such a peak. However, it is not always true that electrically measured interface defects can be assigned to P_b centers. Several cases involving hot electron damage have been reported in which interface states have been observed electrically but epr experiments do not show P_b-like signals [4,5].

In this work, we report interface traps near the Si–SiO_2 interface induced by hole trapping *directly*. We find that interface traps are generated due only to the presence of trapped holes in MOS devices, and that the loss of trapped holes by annihilation with injected electrons is accompanied by a reduction of interface traps.

2. Experimental details

Polycrystalline-silicon (poly-Si) gate MOSCs and MOSFETs were used in this work. The gate oxides for MOSCs were grown on n-type (100) 0.1 Ω cm Si wafers at 1000°C, resulting in an oxide thickness of 675 Å and with a gate area of 1×10^{-3}–1×10^{-2} cm^2. Details of the fabrication process have been discussed in a previous publication [6]. Data on MOSFETs were obtained on n-channel devices with an oxide thickness of 245 Å. Hole trapping was performed using avalanche hole injection (AHI) and FNT injection for MOSCs and MOSFETs, respectively. The average current density for AHI was 1.9×10^{-8} A/cm^2 with various injection fluences. Holes previously trapped in the oxide were annihilated using either FNT injection or substrate hot electron injection (SHE) to explore the consequences of removing trapped holes. High frequency (HF) and quasi-static (QS) capacitance–voltage (C–V) techniques were used to measure D_{it} in MOSCs. Charge pumping (CP) and HF C–V techniques were used to measure the densities of trapped holes and interface states in MOSFETs [6]. The possibility that lateral nonuniformities (LNU) were responsible for experimental artifacts mimicking interface traps was investigated using a procedure described by Brews and Lopez [7]. Finally, possible contributions to D_{it} from anomalous positive charge (APC) were investigated.

3. Results

Hole trapping and interface trap generation in MOSCs are illustrated in Fig. 1. In Fig. 1(a), the C–V curves are shifted in the direction of negative voltage after AHI (thick, unbroken lines), indicating that hole trapping has occurred. In addition, interface traps are induced by AHI as is clear from the QS C–V curve and from the corresponding D_{it} spectrum in Fig. 1(b). Annihilation of trapped holes using FNT electron injection from the gate electrode to a fluence of 8×10^{-4} C/cm^2 results not only in a shift of the C–V curves in the direction of positive voltage (dashed lines), but also in recovery of the QS C–V curve to nearly its original shape. The corresponding D_{it} spectrum shows that most interface traps have been removed.

The fluence used for FNT electron injection in Fig. 1 was not sufficient to initiate interface trap creation by hydrogen, but was enough for both impact ionization [1] and electron–hole recombination [2]. Fig. 1(a) indicates only a partial annihilation to a steady-state density of trapped holes due to the competing effects of electron–hole recombination and impact ionization.

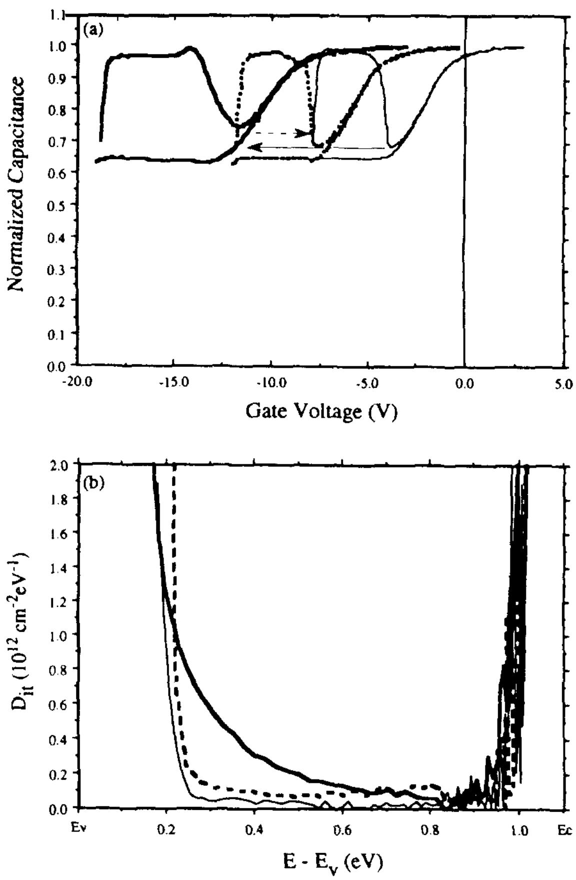

Fig. 1. (a) Reversible interface traps induced by hole trapping in MOSCs: (a) HF/QS C–V curves before (solid line) and after (thick solid line) AHI to a trapped hole fluence of 3×10^{-5} C/cm^{-2}. Trapped holes are annihilated using FNT electron injection from the gate electrode to an injection fluence of 8×10^{-4} C/cm^2 (thick broken line). (b) D_{it} derived from Fig. 1(a).

Generation of trapped holes and interface traps during 11 MV/cm FNT electron injection on n channel MOSFETs is shown in Fig. 2. The generation of interface traps (open circles) tracks that of trapped holes (open inverted triangles); both charge species were monitored using C–V techniques, as indicated on the figure by (C–V). In agreement with the results of Fig. 1, interface states disappear after total annihilation of the trapped hole distribution using SHE injection (solid circles). Most interestingly, interface traps generated at fluences less than 0.01 C/cm^2 are detected in substantially fewer numbers using CP techniques

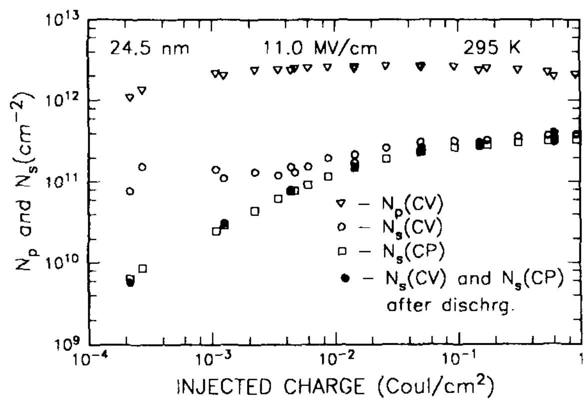

Fig. 2. Number of interface states N_s and trapped positive charge N_p generated during high field stress (11 MV/cm) as a function of injected electron fluence determined using C–V and CP techniques. The curves labeled 'dischrg.' correspond to the number of interface states remaining after total annihilation of the trapped holes using SHE at low field (1.5 MV/cm) and fluence (1×10^{-6} C/cm^2).

(open squares). Charge pumping is sensitive to the capture cross section of interface traps and, in fact, measures recombination currents at the defect center. On the other hand, C–V techniques are dependent only on the charge states of the defect. The discrepancy in the number of interface traps detected using these techniques thus suggests that the hole induced interface trap is not a recombination center. At fluences beyond 0.01 C/cm^2, however, CP and C–V measurements detect equal densities of interface traps. In this fluence range, interface trap creation is dominated by hydrogen diffusion; at least some component of traps generated by this mechanism is evidently due to the P_{bo} center [4], which is a recombination center and therefore detectable by CP techniques. Note also that following hole annihilation, C–V and CP techniques detect the same density of interface traps at all injection fluences.

4. Discussion

4.1. Nature of interface traps induced by hole trapping

An important result of the present work is that interface traps induced by hole trapping, as illustrated in Fig. 1, are not due to P_b centers. Spectral features of the defects observed here are decidedly different from the doubly peaked structure of the P_b center as observed on as-grown samples [8]. The spectra observed in Fig. 1 are also clearly different from the ubiquitous 0.8 eV peak observed following FNT injection and radiation damage; this peak, as we have suggested, may or may not be related to the P_b center. Additionally, although interface trap peaks in Al gate MOSCs have been reported to develop over time after AHI has stopped [9], we observe no such development in the present spectra. We have, however, observed the 0.8 eV peak following substrate FNT injection in our samples, demonstrating that the failure to develop a peak is not sample dependent.

The discrepancy in the measured density of interface traps observed by CP and by C–V (see Fig. 2) is quite interesting, and demonstrates that the hole induced interface traps observed here are not recombination centers, or else that their interaction with the substrate is too slow to be detected using CP. This assertion is supported by recent work by Stathis and DiMaria monitoring interface trap generation in MOSFETs during hot electron injection using spin-dependent recombination (SDR) [4], which is also sensitive to recombination currents at the defect site. In that work, hot electron injection at fluences less than 0.001 C/cm^2 resulted in interface traps which were observed using C–V techniques but not using SDR. Hot electron injection generates holes via impact ionization; the holes are subsequently trapped at the $Si–SiO_2$ interface and, we suggest, induce defect states having the energy distribution seen in Fig. 1. In Ref. [4] an SDR signal was observed, however, for fluences larger than 0.001 C/cm^2. In this fluence range, interface trap generation is dominated by depassivation of Si–H bonds by hydrogen, resulting in interface traps which were identified as the P_{bo} variation of the P_b center.

We note that similar effects have been observed following radiation damage [10]. In these studies, near-interface oxide traps (referred to as 'border traps') were detected using current–voltage techniques but not using CP. In addition, changes in oxide charge were observed to correlate with changes in interface trap density in a manner consistent with our observations. It is thus reasonable to suggest that defects observed here are similar in nature to those observed in the radiation work, and may be properly categorized as border traps.

It is well known that lateral non-uniformities in the density of trapped charge (LNU) can mimic the presence of interface traps. To explore this as a possible cause of apparent interface traps in our samples, we examined our HF C–V data using a method suggested by Brews and Lopez [7]. In this method, the surface potential, ϕ, is plotted as a function of substrate depletion depth, w, for the MOS capacitor before and after AHI. Because the depletion depth is uniquely determined by the substrate dopant distribution which is invariant, changes in w as a function of ϕ following AHI suggest the presence of lateral nonuniformities. Application of this test to our samples reveals little difference in the $\phi - w$ curves, suggesting very little contribution to interface trap spectra from LNU. In addition, comparison of charge densities detected using C–V and current-sensing techniques have been made on MOSFETs. These comparisons show similar results, again suggesting that lateral nonuniformities are not present in substantial quantities.

We also investigated a possible contribution to D_{it} from APC by the monitoring flatband voltage (V_{fb}) of injected MOS capacitors as a function of time under an applied bias of alternating sign; this test for APC is described in Ref. [9]. We find no evidence of APC generation in our samples following AHI.

4.2. Interface-trap generation mechanisms

Trapped holes have been reported to play a role in interface trap generation either by serving as a cracking site or via electron–hole recombination. The result of the former process is predicted to be a dangling bond defect which may be related to the P_b center, but at least is expected to be a recombination center. Ref. [4] shows that electron–hole recombination does not produce an SDR signal and is thus not a recombination center, but other work has shown that the process results in the 0.8 eV peak [2]. Finally, the disappearance of interface traps on removal of trapped holes is not consistent with either the hydrogen cracking or electron–hole recombination mechanisms. Thus we are led to conclude that a different mechanism leads to the interface trap spectra observed in Fig. 1. We suggest instead that interface traps are created as a direct result of the presence of trapped holes, and are removed along with them. We do not know the microscopic identify of such interface traps at present.

5. Conclusions

We report interface traps near the Si–SiO_2 interface induced by hole trapping alone. We find that interface traps are generated directly due to the presence of trapped holes in MOS devices, and that the loss of trapped holes due to annihilation by electron injection is accompanied by a reduction of interface traps. We do not believe the origin of these interface traps to be P_b centers. More generally, we find that these traps are not recombination centers; thus the phenomenon may help to explain the discrepancy between the density of electrically measured interface traps and P_b center densities measured using EPR. The underlying mechanism(s) for the current observations are still unknown, but there has been further understanding of interface trap generation mechanisms in terms of hot carriers involved in electrical stressing.

References

[1] D.J. DiMaria, E. Cartier and D. Arnold, J. Appl. Phys. 73 (1993) 3367.

[2] S.K. Lai, J. Appl. Phys. 54 (1983) 2540.

[3] D.L. Griscom, D.B. Brown and N.S. Saks, in: The Physics and Chemistry of SiO_2 and the Si/SiO_2 Interface, ed. C.R. Helms and B.E. Deal (Plenum, New York, 1988) p. 287 and references therein.

[4] J.H. Stathis and D.J. DiMaria, Appl. Phys. Lett. 61 (1992) 2887.

[5] L.P. Trombetta, D.J. DiMaria, G.J. Gerardi and E. Tierney, J. Appl. Phys. 64 (1988) 2434.

[6] D.J. DiMaria and J.W. Stasiak, J. Appl. Phys. 65 (1989) 2342.

[7] J.R. Brews and A.D. Lopez, Solid State Electron. 16 (1973) 1267.

[8] E.H. Poindexter, G.J. Gerardi, M.E. Rueckel, P.J. Caplan, N.M. Johnson and D.K. Biegelsen, J. Appl. Phys. 56 (1984) 2844.

[9] L.P. Trombetta, F.J. Feigl and R.J. Zeto, J. Appl. Phys. 69 (1991) 2512.

[10] D.M. Fleetwood, M.R. Shaneyfelf, L.C. Riewe, P.S. Winokur and R.A. Reber Jr., IEEE Trans. Nucl. Sci. NS-40 (1993) 1323; D.M. Fleetwood, M.R. Shaneyfelt and J.R. Schwank, Appl. Phys. Lett. 64 (1994) 1965.