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Experimental proof of direct correlation between hydrogen migrated to SiO_2/Si interface and MOSFET characteristics using high energy $^{15}N^{2+}$ ion beam

Masamichi Suzuki[1], Riichiro Takaishi[1], Yusuke Higashi[1], Mitsuhiro Tomita[1], Yuichiro Mitani[1], Masuaki Matsumoto[2], and Katsuaki Fukutani[2]

[1] R&D Center, Toshiba Corporate
1, Komukai Toshiba-cho, Saiwai-Ku, Kawasaki 212-8582, Japan
Phone: +81-44-549-2075 E-mail: masamichi2.suzuki@toshiba.co.jp
[2] Institute of Industrial Science, University of Tokyo
4-6-1, Komaba, Meguro, Tokyo 153-8505, Japan

Abstract

High energy $^{15}N^{2+}$ ion beam was used not only as NRA (Nuclear Reaction Analysis) for the estimation of hydrogen depth profile but also as the measure to migrate hydrogen to the SiO_2/Si interface. In the case of SiO_2 formed by wet oxidation (WO), the leakage current and interface trap density (Nit) were dramatically degraded after ion beam irradiation due to the depassivation of hydrogen in the bulk followed by hydrogen migration to the interface. As for SiO_2 formed by radical oxidation (RO), the significant hydrogen migration to the interface was not observed and the increased Nit value was almost the same as that of constant current stress case. The direct correlation between hydrogen at the interface and MOSFET degradation was successfully demonstrated.

1. Introduction

The scaling of CMOS transistors has been associated with an adverse effect of the reliability deterioration of gate dielectric. For instance, threshold voltage (Vth) shift caused by negative bias temperature instability (NBTI) have become obvious with the scaling [1]. The cause of this phenomenon has been considered to be hydrogen release followed by its diffusion [2]. On the other hand, it is revealed by first principle calculation that negatively charged hydrogen atoms in SiO_2/Si system migrate to the interface, resulting in the generation of dangling bonds at the interface through H_2O molecule desorption[3]. Although hydrogen has close relationship with MOSFET performance as mentioned above, accurate estimation of hydrogen depth profile is very difficult.

Resonant Nuclear Reaction Analysis (NRA) using ^{1}H (^{15}N, $\alpha\gamma$)^{12}C reaction with the resonant energy of 6.5 MeV is one of effective method for the analysis of hydrogen profile because of its narrow resonant width (1.86 keV) [4,5]. However, when the ion exposures exceed a threshold of $3x10^{15}/cm^2$, the detachment of hydrogen atoms in SiO_2/Si system by energetic secondary electrons occur, resulting in migration of hydrogen to the SiO_2/Si interface [6]. In this paper, using this hydrogen redistribution behavior during NRA measurement, we demonstrate the direct correlation between hydrogen migrated to SiO_2/Si interface and MOSFET characteristics.

2. Experimental

Blanket samples with SiO_2(6 nm)/Si and nMOSFETs with Poly-Si(125 nm)/SiO_2(6 nm)/Si were fabricated, in which two kinds of SiO_2 were applied. One SiO_2 was fabricated by wet oxidation (WO); the other was fabricated by radical oxidation (RO). These SiO_2 were expected to contain different hydrogen concentration. Hydrogen depth profile of blanket samples were determined by NRA using $^{15}N^{2+}$ ion beam (6.356~6.464 MeV). Incident angle was 17^{o} with respect to the sample surface. The same condition of $^{15}N^{2+}$ ion beam except ion beam energy (6.528~6.674 MeV) was also irradiated to nMOSFETs for the estimation of impact of hydrogen migration to the interface on MOSFET performance. In our experiments, the ion exposures were designed to cause the hydrogen migration. The damage in SiO_2 such as a bond breakage stem from an atomic collision is considered to be negligible because nuclear stopping power in SiO_2 region is nearly zero at this energy. On the other hand, because the electron stopping power is dominant, the energetic secondary electrons are created by the ion beam irradiation, resulting in hydrogen migration. Therefore, the change of MOSFET performance is considered to be mainly due to the hydrogen migration. Fig.1 represents the evaluation concept of this study.

3. Results and Discussion

3.1 Hydrogen redistribution by high energy $^{15}N^{2+}$ ion beam

Figs.2 show the hydrogen depth profile estimated by (a) High-resolution Elastic Recoil Detection Analysis (HERDA) and (b) NRA using each blanket sample. As expected, WO-SiO_2 contained higher concentration of hydrogen (Figs.2 (a)) and hydrogen migration to the interface by ion beam irradiation was observed characteristically in WO-SiO_2 (Fig.2 (b)).

3.2 Direct correlation between migrated hydrogen to the interface and MOSFET characteristics

Fig.3 shows gate current(Ig)-gate voltage(Vg) curves for two nMOSFETs *without* ion beam irradiation. Because they had the same SiO_2 thickness, the curves showed quite the same behavior dominated by Fowler–Nordheim (FN) tunnel current. Fig.4 shows the Ig-Vg curves *with and without* ion beam irradiation. Ig for nMOSFET with WO-SiO_2, in which hydrogen was supposed to migrate to the interface, dramatically increased with ion beam irradiation as compared with the case of RO-SiO_2. The dramatic increase in WO-SiO_2 is thought to be caused by the defects due to the depassivation of hydrogen in bulk stem from energetic secondary electrons generated with ion beam irradiation. Moreover, oxygen vacancies might be subsequently created by hydrogen condensation around the defects[7] due to depassivation of hydrogen, and the vacancies might also increase the Ig.

The interface trap density (Nit) was also strongly associated with the migrated hydrogen. While charge pumping curves (CP) for two nMOSFETs *without* ion beam irradiation are quite the same (Fig.5(a)) as is the case with Ig-Vg, the Nit for WO-SiO_2 case increased dramatically by ion beam irradiation (Fig.5(b)). Then, the conventional electrical stress (constant current stress) with the positive gate bias and ion beam irradiation were compared about Nit. The behaviors of Nit under constant current stress for both samples are almost the same and saturated at the lower Nit than that of WO-SiO_2 with ion beam irradiation as shown in Figs.6. We infer that, in the case of constant current stress, hydrogen has little to do with the Nit increase, because *negatively charged hydrogen* move away from SiO_2/Si interface under the stress condition with the *positive* gate bias[3]. The saturated Nit values in Figs.6 (b) are considered to depend on the number of pre-existing Si-H bonds at SiO_2/Si interface. The pre-existing Si-H bonds are broken by electron injection under constant current stress followed by formation of H_2 molecule[3], and Nit increases up to the saturated value. It should be noted that the saturated Nit value of RO-SiO_2 in figs.6(b) is equivalent to the value with ion beam irradiation shown in figs.6(a). These results can be explained as shown in Fig.7. Nit increase of RO-SiO_2 case in figs.6(a) is caused by breakages of pre-existing Si-H bonds due to energetic secondary electrons generated with ion beam irradiation as is the case of constant current stress, while the additional Nit increase occur in WO-SiO_2 case due to migration of hydrogen atoms from bulk to the interface followed by H_2O molecule desorption [3] with ion beam irradiation.

4.Conclusions

The direct correlation between hydrogen migrated to SiO_2/Si interface and MOSFET characteristics was demonstrated using high energy $^{15}N^{2+}$ ion beam. It was experimentally proved that the degradations of Ig-Vg and Nit have a strong correlation with hydrogen migrated to the interface. We expect this evaluation method, which can control the amount of hydrogen migration to the interface, will be helpful for the resolution of hydrogen-associated MOSFET degradation.

Acknowledgements

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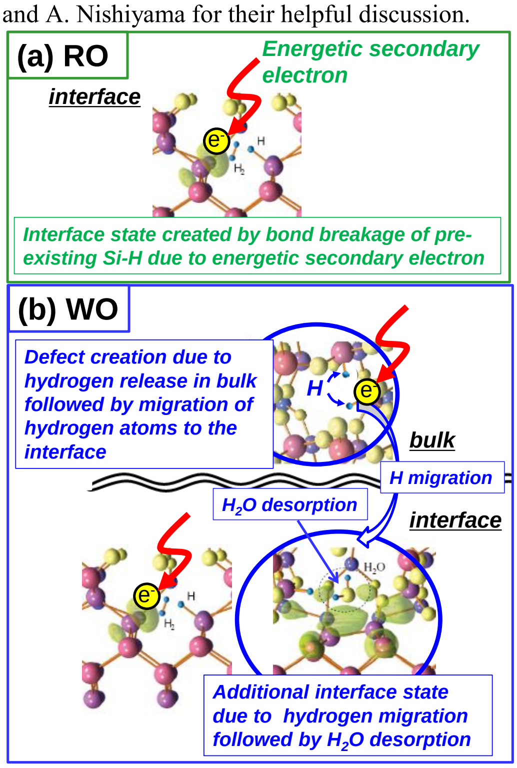

Figs.7 Schematic of interface state formation for (a)RO-SiO_2 and (b)WO-SiO_2 with ion beam irradiation. Large balls represent Si atoms from red to blue according to the depth. Small blue and white balls represent H and O atoms, respectively. Yellow isosurfaces represent the electronic charges of the expelled electron and dangling bonds. These lattice models are cited from [3].

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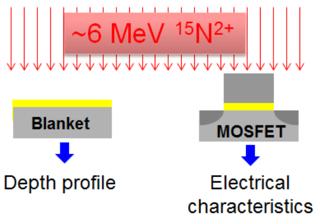
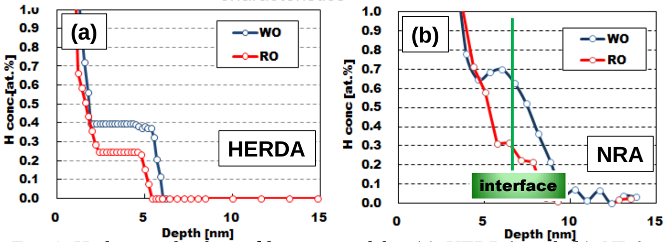


Fig.1 Schematic of evaluation concept of this study. $^{15}N^{2+}$ ion beam with almost the same condition was irradiated to both blanket and nMOSFET samples. The beam energy for nMOSFET was set to be slightly high considering energy loss at Poly-Si layer region.



Figs.2 Hydrogen depth profile estimated by (a) HERDA and (b) NRA using blanket samples. Large signals at 0 nm in both figures are due to surface adsorbed species. During HERDA measurement, hydrogen migration is not observed, because the energy of the irradiated ion beam is relatively low (480 keV) and the spectra are constructed by summing up the data from various measurement points.

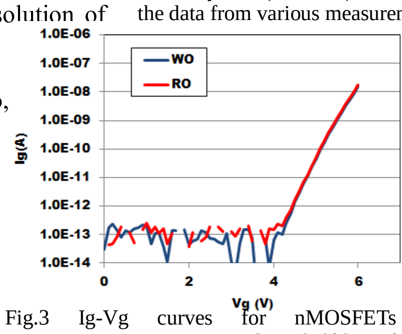


Fig.3 Ig-Vg curves for nMOSFETs (L/W=100 μm/100 μm) with WO-SiO_2 and RO-SiO_2 *without* ion beam irradiation.

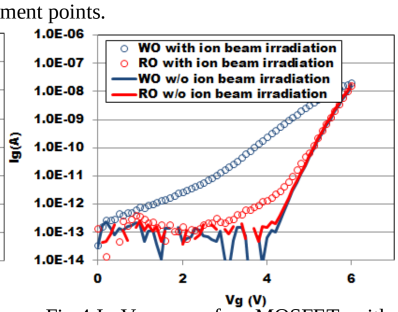


Fig.4 Ig-Vg curves for nMOSFETs with WO-SiO_2 and RO-SiO_2 *with and without* ion beam irradiation.

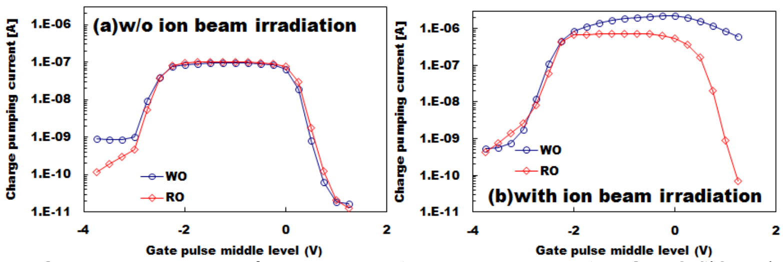
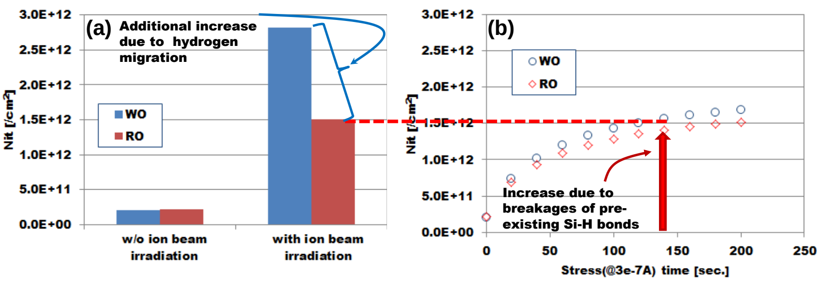


Fig.5 Charge pumping curves for nMOSFETs (L/W=50 μm/100 μm) with WO-SiO_2 and RO-SiO_2 (a) *with and* (b) *without* ion beam irradiation. The amplitude of the gate pulse was set to 3.5 V.



Figs.6 (a) Bar graph representing the change of Nit due to ion beam irradiation (hydrogen migration to the interface) and (b) dependence of Nit on duration of constant current ($3X10^{-7}$ (A)) stress for nMOSFETs with WO-SiO_2 and RO-SiO_2.