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Boron Penetration Enhanced by Gate Ion Implantation Damage in PMOSFETs

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1. Introduction

Boron penetration from p^+-polysilicon gate electrodes through thin gate oxides to the substrate is a serious problem in surface-channel pMOSFETs. This boron penetration is often enhanced by process conditions for device fabrication [1]. B^+ ions are primarily used in gate ion implantation instead of BF_2^+ ion, because boron penetration is enhanced by fluorine [2]. The projected range (R_p) of B^+ ion is deeper due to its smaller mass. Thus, the ion-implanted B^+ often reaches the gate insulator, resulting in damaged gate SiO_2. In addition, the channeling effect increases the penetrating ions. In Fig. 1, implanted B^+ ions with an energy of 7-keV reached gate SiO_2 and its concentration near the gate SiO_2 was 10^{18} cm^{-3}. This ion implantation damage may enhance boron penetration. Therefore, we studied the ion implantation damage effect on boron penetration.

2. Experiments

We fabricated pMOS structures having gate SiO_2 damaged by ion implantation. The gate SiO_2 thickness used in this experiment was 5.6 nm. We used Ar^+ or Si^+ ions to induce the damage. The reason that we did not use B^+ ion is to prevent influencing boron diffusion. Ar^+ ions were implanted with an energy of 10 keV (R_p: 5 nm) with a dosage of 10^{11} to 10^{14} cm^{-2} just after gate oxidation. Si^+ ions were implanted through the amorphous Si gate with an energy of 130 keV (R_p: 200 nm) with a dosage of 10^{11} to 5×10^{12} cm^{-2}. To prevent damage by B^+ ion implantation, we used a 200-nm-thick amorphous Si gate. B^+ ions were implanted into the amorphous Si with an energy of 7 keV with a dosage of 5×10^{15} cm^{-2}. After the pMOS samples were annealed at 750 to 1000°C, we measured the boron penetration profiles in the substrate using secondary ion mass spectroscopy (SIMS). We analyzed the SIMS data using a process simulator to estimate boron diffusivity in SiO_2 (D_{ox}) [3].

3. Results and Discussion

Fig. 2 shows the boron penetration profiles for Ar^+-damaged samples annealed at 800°C for 1000 hours. Boron penetrated more in the damaged sample than in the non-damaged one. The penetration depth at a boron concentration of 10^{17} cm^{-3} in the sample damaged by Ar^+ of 10^{14} cm^{-2} dose is 0.04 μm deeper than that in the non-damaged one. Fig. 3 shows Ar^+ ion dose dependence on the penetration depth. Boron penetrated more in the higher Ar^+ dose sample. In contrast to samples annealed at 800°C, boron penetration profiles were the same between the damaged and non-damaged samples annealed at 1000°C (Fig. 4, Fig. 3). This is because ion implantation damage recovers with annealing, and the recovery is faster during annealing at 1000°C than at 800°C [4]. This phenominon was similarly observed in a sample damaged by Si^+ ion (not shown). Fig. 5 shows annealing time (t) dependence on the the difference in the integrated product of boron diffusivity in SiO_2 and annealing time ($\Delta\int D_{ox}dt$), which implies an amount of enhanced diffusion by ion implantation damage. $\Delta\int D_{ox}dt$ was saturated for a long annealing time, meaning that the ion implanted damage was recovering with a D_{ox} decrease during annealing. This saturated $\Delta\int D_{ox}dt$ for various temperatures was plotted in Fig. 6 (Arrehenius plot). Below 900°C, the saturated $\Delta\int D_{ox}dt$ increased slightly with annealing temperature. The slope corresponds to 0.3 eV. The saturated $\Delta\int D_{ox}dt$ is very large, since the $D_{ox}t$ of the non-damaged sample annealed at 1000°C for 10 seconds was 1.4×10^{-16} cm^2 (Fig. 6). Above 1000°C, the saturated $\Delta\int D_{ox}dt$ is small compared with temperatures below 900°C, indicating rapid damage recovery. In Fig. 6, data at 1000°C is a possible maximum value calculated from SIMS data which shows no difference between damaged and non-damaged samples. Therefore, it is effective to use rapid thermal annealing (RTA) above 1000°C for damaged samples, in order to suppress boron pentration.

The physics of the damage-induced diffusion in SiO_2 is not known. We propose a possible model to explain our data (Fig. 7). In the non-damaged sample (Fig. 7a), boron diffuses to the next stable position by overcoming the normal 3.8-eV diffusion barrier [2]. In the damaged sample (Fig. 7b), the diffusion barrier between stable positions is partly destroyed, and so boron can move freely to each position. With the annealing process (Fig. 7c), some destroyed diffusion barrier is recovered with a recovery speed (R_r). In this model, the enhanced diffusion is expressed using an increment of the pre-exponential factor of diffusivity (Eq. 1 in Table I) [2]. Its recovery time constant τ (=$1/R_r$) is expressed as Eq. 2 (Table I), assuming a single acvtivation energy process. The activation energy of damage recovery (E_a^r) is calculated as appoximetly 3.5 eV using the equations in Table I and 0.3 eV in Fig. 6. This E_a^r is close to that of silica self-diffusivity (3.1 eV) [5].

4. Conclusion

We showed that ion implantation damage in gate SiO_2 enhanced boron penetration in pMOS devices. Because the damage amount caused by B^+ gate ion implantation is not known now, we cannot calculate its exact enhancement factor. However, our data indicated that it is possible for the ion implantation damage to easily enhance boron diffusion in SiO_2 by 10 times or more. It is effective to use RTA above 1000°C for damaged samples in order to suppress boron pentration.

References

[1] T. Aoyama et al., Ext. Abst. SSDM'98 p16.
[2] T. Aoyama et al., J. Appl. Phys. **77**, 417 (1995).
[3] SSUMPEM IV Users' Manual.
[4] A. Stesmans et al, J. Appl. Phys. **55**, 1551 (1984).
[5] N. J. Chou et al., J. Appl. Phys. **41**, 1731 (1970).

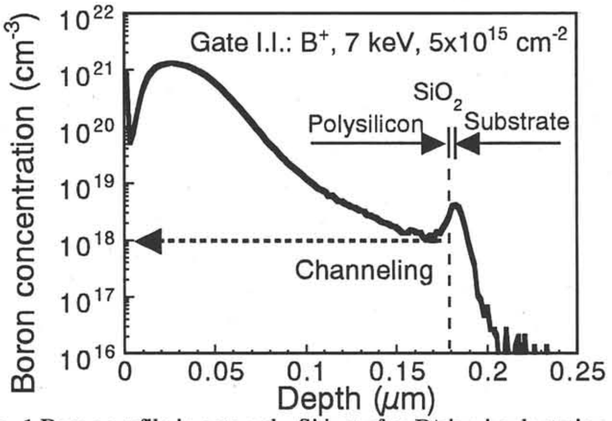

Fig. 1 Boron profile in gate poly-Si just after B^+ ion implantation.

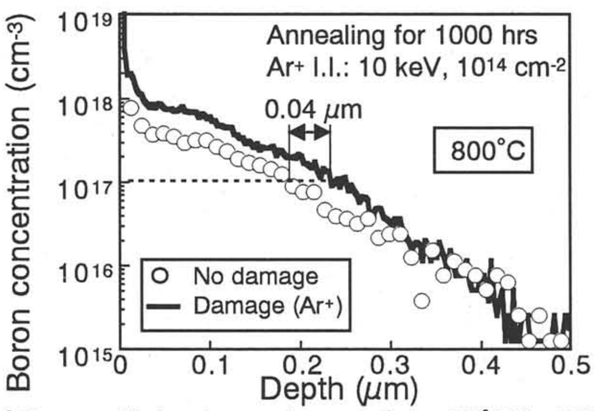

Fig. 2 Boron profile in substrate after annealing at 800° C for 1000 h.

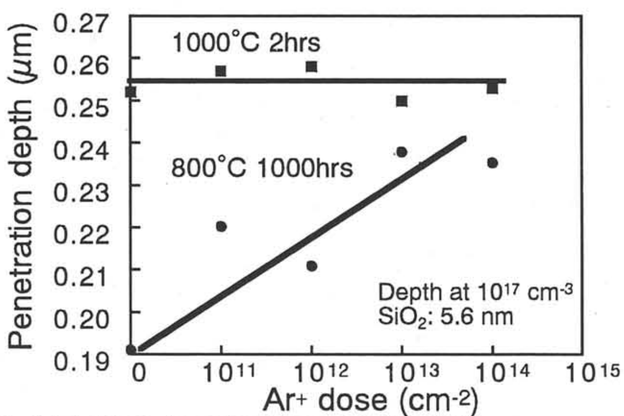

Fig. 3 Ar+ dosage dependence on penetration depth .

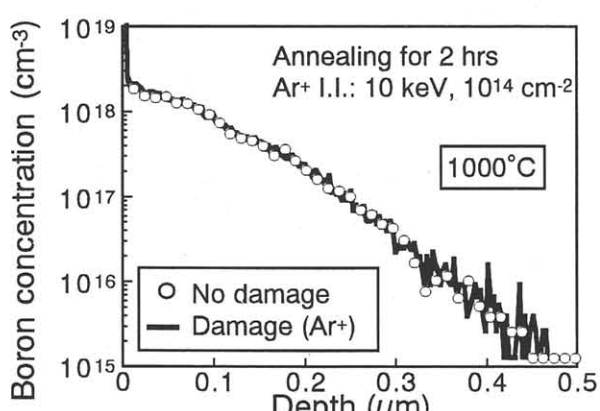

Fig. 4 Boron profile in substrate after annealing at 1000° C for 2 h.

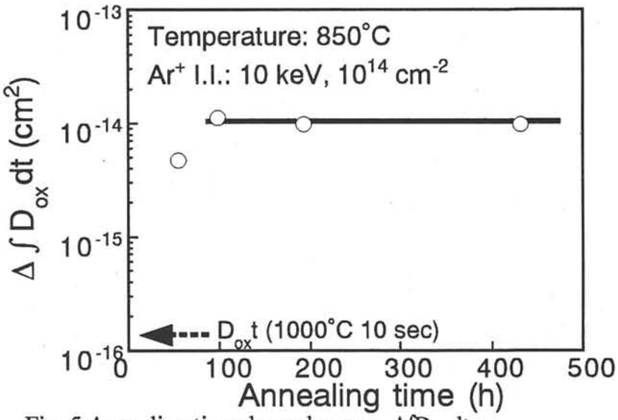

Fig. 5 Annealing time dependence on $\Delta\int D_{ox}dt$.

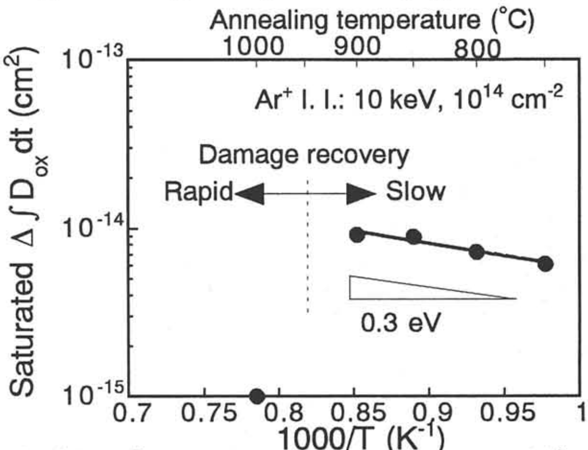

Fig. 6 Annealing temperature dependence on saturated $\Delta\int D_{ox}dt$.

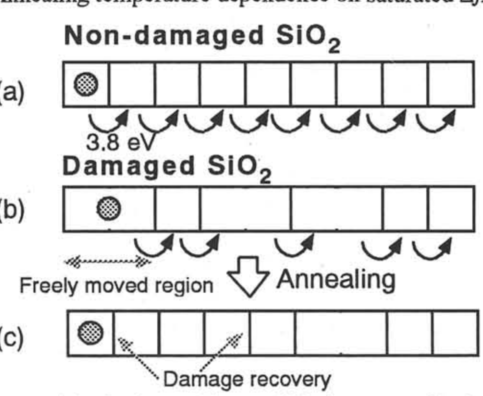

Fig. 7 A model of enhanced boron diffusion caused by ion implantation damage.

Table I Equations

Boron diffusivity in damaged SiO_2:

$$D'_{ox}(t) = D_{ox}\{1+A\exp(-t/\tau)\}$$

$$= 0.0183\exp(-3.8\text{eV}/kT)\{1+A\exp(-t/\tau)\} \quad (\text{cm}^2/\text{s}) \quad (1)$$

(A is constant corresponding to damage amount.)

Damage recovery speed (below 900°C):

$$R_r = 1/\tau = R_0\exp(-E_a{}^r/kT)$$

$$\approx (10^{-11}/A)\exp(-3.5\text{eV}/kT) \quad (\text{s}^{-1}) \quad (2)$$