Extended Abstracts of the 2013 International Conference on Solid State Devices and Materials, Fukuoka, 2013, pp18-19

Mechanism of Low-Temperature Activation of B in Si by Soft X-ray Irradiation

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Abstract

Mechanism of novel activation method of B dopant using a soft X-ray undulator was investigated. The activation energy of B activation by soft X-ray irradiation was lower than that of B activation by an annealing. As the irradiated photon energy closed with the core level of Si2p, the activation ratio increased. This related to the enhancement of electron excitation as a base on Felmi golden rule. At low temperature, the B activation occurred by the atomic migration of Si atoms due to Coulomb force via the electron excitation.

1. Introduction

Fabrication method of an ultra-shallow junction lower than 10nm is required. We proposed a novel activation method of B dopant at low temperature by using a soft X-ray undulator [1]. The photon energy dependence of sheet resistance and the B depth profile were investigated. In addition, the mechanism of soft X-ray activation was discussed in comparison with a conventional thermal activation.

2. Exprimental

B ions were implanted to Si (100) wafer (n-type, 8-12 Ωcm) with an energy of 5 keV and a dose quantity of 2×10^{15} cm^{-2}. The irradiation of soft X-ray was carried out at BL07A of NewSUBARU[1]. The photon energy was changed from 50 to 250 eV, with the dose quantity of 50 mA h. In addition, to reduce the sample temperature, the storage-ring current decreased from 250 to 50 mA. The gas pressure during irradiation was 6×10^{-5} Pa. The surface temperature of Si substrate during soft X-ray irradiation was measured by thermocouple and via a ZnSe window by a thermo-viewer. For the comparison, the annealing in N_2 atmosphere was carried out in the range of 100 to 1000°C.

The sheet resistance was measured by a four-point probe method at room temperature. The activation ratio is given by Irvin curve and dopant dose quantity. Activation energy of B activation (E_a) was estimated by Arrhenius plot of activation ratio. The B depth profile was evaluated by secondary ion mass spectroscopy (SIMS).

3. Results and discussion

The sheet resistance and the temperature of Si wafer as a function of photon energy are shown in Fig. 1. The temperature at the photon energy of 100 eV, which corresponds to the energy level of Si 2p core-electron (99.8 eV), shows the highest value. The Si 2p core-electrons of Si atom are excited by soft X-ray irradiation and they relax resulting in a temperature increase of Si wafer. The activation was enhanced at 100 eV. According to Felumi golden role, the electron excitation is enhanced by closing to energy of core level. It is found that the sheet resistance after soft X-ray irradiation strongly depended on the irradiated photon energy.

As the storage ring current decreased, the sample temperature decreased to 110°C and the sheet resistance was increased to 3.1 kΩ/□ (Fig. 2). The sheet resistance of annealed sample at 100°C was 8.0 kΩ/□. It shows that the activation was enhanced by the electron excitation during the soft X-ray irradiation.

The sheet resistance as a function of sample temperature and the relationship between the activation ratio and the reciprocal absolute temperature are shown in Figs. 3 and 4, respectively. The sheet resistance of soft X-ray irradiated Si was lower than that of annealed Si below 400°C. The E_a for the soft X-ray activation was smaller than that for the annealing. The discrepancy of E_a between the soft X-ray irradiation and annealing indicates that the soft X-ray activation occurred by not only the thermal effect but also the excitation of the core electrons followed by the atomic migration.

The B depth profiles in Si substrate irradiated at 115 and 250 eV at storage-ring current of 200 mA are shown in Fig. 5. Dopant diffusion of both samples irradiated with soft X-ray was suppressed in comparison with thermal annealed sample in the range of 40 to 130 nm.

The activation mechanism of B by soft X-ray irradiation is considered as follows (Fig. 6). The activation by annealing generally occurs by movement of dopant atoms to lattice sites of Si. This process corresponds to the Arrhenius plot for thermal annealing in high temperature range. The soft X-ray irradiation enhances the atomic migration via excitation of Si2p core-electrons of Si. During the recovery of crystallinity in amorphizated Si surface by atomic migration via electron excitation, B atom can shift to the lattice site of Si atom. Because the size of B atoms is smaller than that of Si atom, the B activation is influenced by atomic migration of Si such as “knock-on” effect.

4. Conclusions

1) The activation of B dopant occurs at 110°C, although the activation ratio shows small value of 6.2×10^{-3}. The B activation ratio of Si wafer subjected to photon with an energy of Si2p and B1s were 1.8×10^{-2} and 5.7×10^{-3}, respectively. Because the size of B atoms is smaller than that of Si atom, the enhancement of Si migration by soft X-ray irradiation triggers the movement of B atoms.

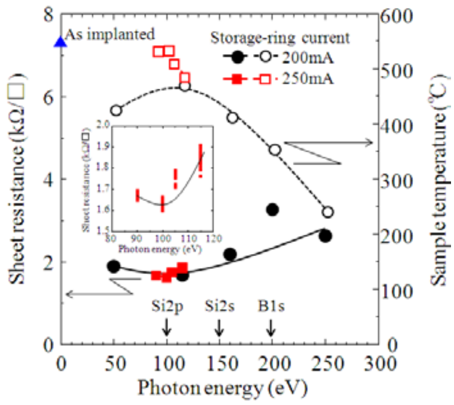

Fig. 1. Sheet resistance (closed symbol) and temperature of Si wafer (open symbol) as a function of photon energy of soft X-ray. The insert shows the sheet resistance of Si wafer for the photon energy from 90 to 115eV.

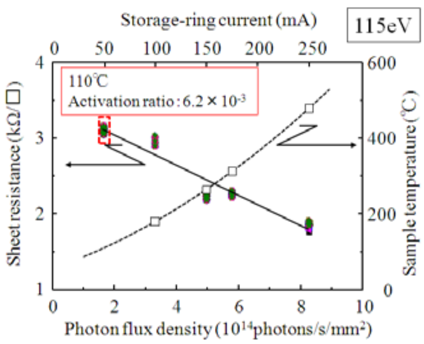

Fig. 2. Sheet resistance and sample temperature as a function of photon flux density (storage-ring current) at photon energy of 115 eV. The B activation occurs at 110°C, although the activation ratio shows small value of 6.2×10^{-3}.

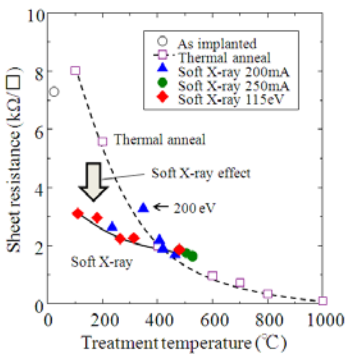

Fig. 3. Sheet resistance as a function of treatment temperature. The soft X-ray effect was confirmed at temperatures lower than 400°C.

2) The B activation energy for the soft X-ray irradiation was smaller than that for the annealing. The soft X-ray activation occurred by not only the thermal effect but also the excitation of the core electrons followed by the atomic migration.

References

[1] A. Heya, K. Kanda, K. Toko, T. Sadoh, S. Amano, N. Matsuo, S. Miyamoto, M. Miyao, and T. Mochizuki: Thin Solid Films 534 (2013) 334.

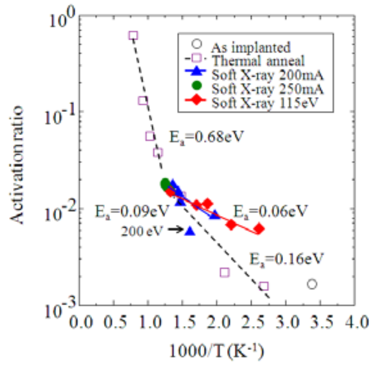

Fig. 4. Relationship between the activation ratio and reciprocal absolute temperature. Activation energy of B dopant activation was estimated from the slope. The E_a for the soft X-ray activation (0.06 and 0.09 eV) was smaller than that for the annealing (0.16 eV).

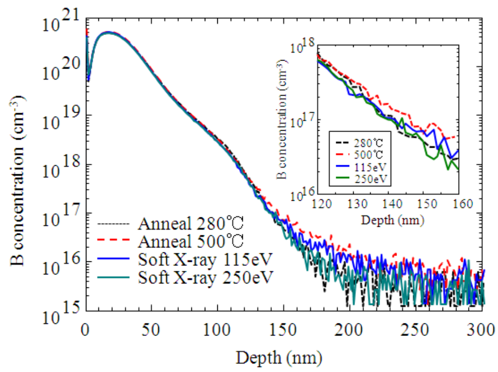

Fig. 5. B depth profile in Si wafer. The B depth profiles in the range of 120 to 160 nm are enlarged in the insert.

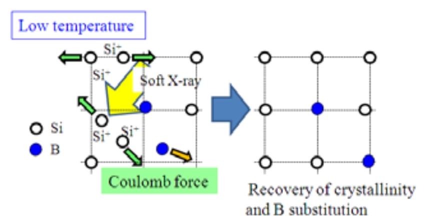

Fig. 6. Schematic diagram of mechanism of low-temperature activation by soft X-ray irradiation. The soft X-ray irradiation enhances the atomic migration via excitation of Si2p core-electron. During the recovery of crystallinity in amorphizated Si surface by the atomic migration via the electron excitation, B atom can shift to the lattice site of Si atom.