Extended Abstracts of the 2012 International Conference on Solid State Devices and Materials, Kyoto, 2012, pp36-37

Ultra-High Resolution Depth Profiling of Carrier Concentration in P-implanted Silicon by HREELS

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1. Introduction

The miniaturization of silicon (Si) devices such as metal-oxide-semiconductor field-effect transistor (MOSFET) and their performance improvement require the well-control of the dopant profile in depth. To reduce contact resistance due to Schottky barrier height (SBH), it is crucial to keep high dopant concentration at the interface between the source/drain region and the metal contact electrodes. There have been, however, many difficulties to characterize the carrier density profile at shallow surface region due to limitation in sensitivity.

High resolution electron energy loss spectroscopy (HREELS) gives us the information on the near-surface electronic structure (e.g., surface plasmon) as well as adsorbed molecules without sample destruction and with more surface-sensitive way. The incident energy change in HREELS allows us to obtain a tunable effective probing depth and the observed surface plasmon energy is proportional to the free carrier density [1-3]. This enables us to evaluate the carrier concentration in depth.

In this work, we present the carrier density depth profile in a shallow region (less than 20 nm in depth) for heavily doped Si with H-termination using HREELS.

2. Experiments

Si (100) wafer was heavily doped (3 x 10^{15} /cm^2) with phosphorus (P) using ion implantation (30 keV) and annealed at 1000 °C for 20 seconds to activate the dopants. This P-doped Si was immersed in a 0.5 % hydrofluoride (HF) solution for 3 minutes to avoid surface effects such as surface-band bending. HREELS measurements were carried out at different incident electron energies (1.5 – 70 eV) and in-specular angles in the range from 53° to 75° ($\theta_i = \theta_d$, θ_i and θ_d are the incident and detection angles, respectively). The schematic diagram of the HREELS measurement is shown in Fig. 1. For comparison of depth profile, secondary ion mass spectroscopy (SIMS) was also measured for P atom. The sample was annealed at 300 °C for 30 min in UHV condition to reactivate the H-induced deactivated dopant.

2. Results and Discussion

For P-doped Si (100) after HF-treatment, HREELS spectra are shown as a function of the incident electron energy at 60° in-specular angle in Fig. 2 (a). Apart from the peaks at ~50 and 279 meV, which are surface phonon and plasmon, respectively, all other peaks are mainly related surface molecules.

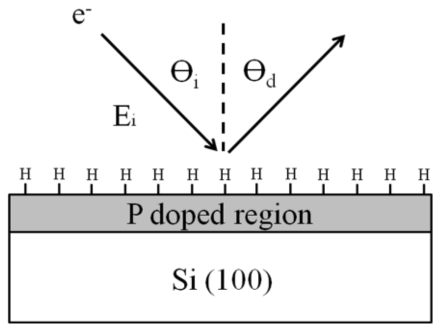

Fig. 1 Schematic diagram of HREELS mesurament in specular condition ($\theta_i = \theta_d$). θ_i and θ_d are the incident and detection angles, respectively.

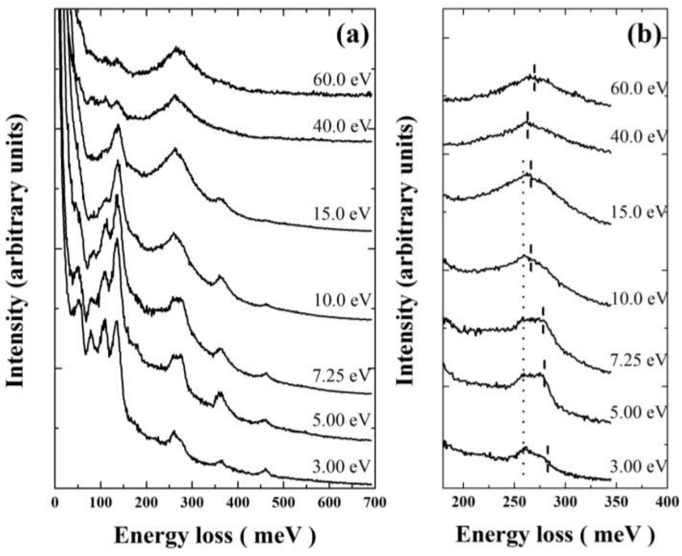

Fig. 2 HREELS spectrum of P-doped Si (100) after HF treatment at 60° in-specular angle and different incident electron beam energies (a), Zoomed in plasmon peak region. Si-H stretching mode at 260 meV and surface plasmon mode are denoted as dotted and dashed lines, respectively (b).

As shown in Fig. 2(b), the Si-H stretching mode is found at 260 meV being close to the surface plasmon mode. Those two peak positions were determined using Lorentzian fitting. The probing depth of the beam is proportional to the incident electron beam energy [1]. As a result, the plasmon peak becomes dominant as the electron energy increases, whereas the intensities of the surface molecular vibration peaks relatively decrease.

When zoomed in the plasmon peak region, it was found that the peak position of the Si-H stretching mode (dotted line) is not changed and hardly detected above the incident energy of 15 eV while the plasmon peak (dashed line) gets dominant and shifts down from 279 to ~265 meV as the incident electron energy increases up to 60 eV. This plasmon energy variation as a function of the incident energy suggests that the carrier density changes in depth because the plasmon energy is proportional to the carrier density.

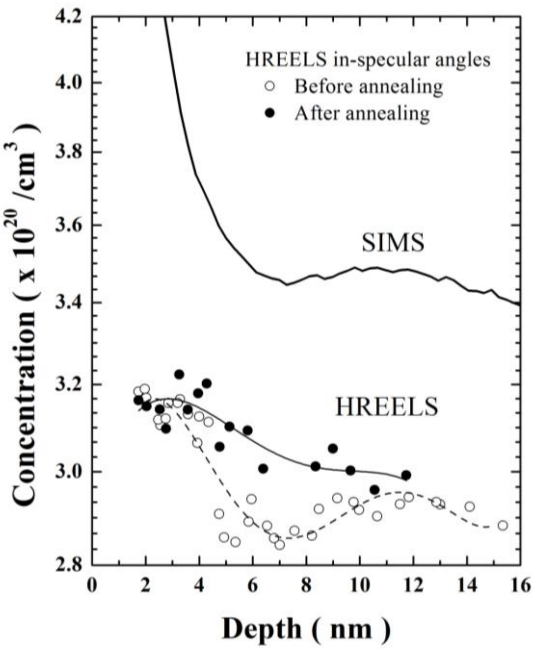

Fig. 3 For P-doped Si (100) after HF treatment, carrier concentration depth profile before and after annealing at 300 ^{o}C from HREELS analysis. SIMS data before HF treatment is displayed for comparison. The best-fit results (dashed and solid lines for before and after annealing, respectively) are plotted for a guide to the eye.

The surface plasmon frequency, ω_{sp} is given by

$$\omega_{sp} = \omega_p / (1+\varepsilon_\infty)^{1/2}, \qquad (1)$$

where ε_∞ is the background dielectric constant of 11.7 for Si [4] and

$$\omega_p = (4\pi n e^2 / m^*)^{1/2}, \qquad (2)$$

where electron density n, electric charge e, and effective electron mass (m^*) of 0.44 for Si [5].

The corresponding probing depth and free carrier concentration are approximately estimated as between 2 and 15 nm below the surface, and ~3.2 - 2.8 × 10^{20} /cm^3 as shown in Fig.3. From comparison with SIMS data, before annealing, the carrier density (hollow circles) corresponds to approximately 80 % of P atom density and its entire profile follows that of P throughout the measured range.

Fig. 3 also presents the HREELS spectra after annealing at 300 ^{o}C. All molecular peaks including Si-H were still detectable at low incident electron energy (≤ 15 eV, not shown here), indicating that the termination of Si surface retains even after annealing. It was also found that the plasmon peak position moved to higher energy. As a result, the corresponding carrier concentration (solid circles) slightly increased.

It was reported that dopants can be deactivated by diffused hydrogen, forming dopant-hydrogen complexes [6, 7]. So, this plasmon peak shift presumably means that the P dopants were deactivated by HF treatment and reactivated during annealing.

3. Conclusions

For P-doped Si (100) after HF treatment, the carrier density at surface-shallow region between 2 and 15 nm was estimated in depth by means of the surface plasmon measurements using HREELS. From comparison with SIMS, the activation efficiency at the near-surface can be estimated. This demonstration showed that HREELS technique can be used to obtain the carrier density depth profile near Si surface.

Acknowledgements

The authors would like to express sincere thanks to Dr. Y. Morita for the preparation of P-doped Si samples.

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