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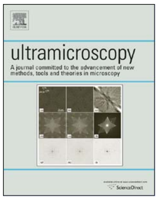

Influence of laser power on atom probe tomographic analysis of boron distribution in silicon

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ABSTRACT

The relationship between the laser power and the three-dimensional distribution of boron (B) in silicon (Si) measured by laser-assisted atom probe tomography (APT) is investigated. The ultraviolet laser employed in this study has a fixed wavelength of 355 nm. The measured distributions are almost uniform and homogeneous when using low laser power, while clear B accumulation at the low-index pole of single-crystalline Si and segregation along the grain boundaries in polycrystalline Si are observed when using high laser power (100 pJ). These effects are thought to be caused by the surface migration of atoms, which is promoted by high laser power. Therefore, for ensuring a high-fidelity APT measurement of the B distribution in Si, high laser power is not recommended.

1. Introduction

Boron (B) is the most common *p*-type dopant used in silicon (Si)-based semiconductor devices, and its behavior determines the device performance. For example, transient enhanced diffusion of B atoms during the post-implantation annealing process is an obstacle for achieving an ultra-shallow junction [1], and B interstitial clustering has been put forward to explain the low activation rate of dopants [2]. In addition, B segregation at a grain boundary or interface has been proposed as one of the reasons for threshold voltage variability [3,4]. Therefore, understanding the behavior of B atoms in Si-based devices is of great importance for the development of next-generation microelectronic technologies. Atom probe tomography (APT) has emerged as a powerful technique for its capability of obtaining three-dimensional elemental distribution maps with near atomic-scale resolution, which makes it distinguished from other techniques in materials science research [5]. Because the primary mechanism of APT is electric-field ionization and evaporation, it was originally utilized to study metals and alloys. However, the implementation of pulsed lasers in combination with APT has enabled its application for studying semiconductor materials and devices [6–9].

Although the behavior of B atoms in Si has recently been intensively investigated using APT, some inconsistent results have been reported. For example, Takamizawa et al. [7] did not observe B diffusion from the source/drain extension region to the single-crystalline Si (*c*-Si) substrate of field-effect transistors, which is inconsistent with the work of Grenier et al. [10]. Moreover, Inoue et al. [11] did not observe B segregation in the grain boundaries of the gate polycrystalline Si (poly-Si), which differs from the reports of Thompson et al. [12] and Jin et al. [13]. These inconstancies may originate from both sample fabrication and APT measurement conditions. Sample fabrication conditions, such as the dopant dose, acceleration energy, annealing temperature, and annealing time could influence the actual dopant distribution, whereas the measurement conditions, such as the base temperature, laser wavelength, and laser power would only have an impact on the APT data. Here, we focus on the effect of laser power on the B distribution measured by APT because the laser conditions employed in such measurements vary widely. In the previously mentioned APT studies on B distribution in Si, when a UV laser (343 nm) with its pulse duration of 450 fs is used, the laser power is 35 nJ [10]; when a green laser (532 nm) with its pulse duration of ~10 ps is used, laser power is 0.5 nJ in Ref. [7] and Ref. [11], 1.0 nJ in Ref. [13], and not specified in Ref. [12], respectively.

The exact role of laser assistance in field evaporation is complex, but the most common explanation is the thermal heating effect, which results in significant temperature rise and the observation of surface

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diffusion of atoms [14–17]. In general, high laser power is helpful for reducing the probability of sample fracture and improving the signal-to-noise ratio in the mass spectrum, but it can result in poor spatial resolution in the reconstruction [18]. Previously, Liu and Andrén studied the influence of laser irradiation on the elemental distribution, and found that it led to an electric field gradient from the incident side to the shallow side of the specimen, thus resulting in a non-uniform distribution for certain ions [19]. Gault et al. discussed the degeneration of the spatial resolution in the lateral plane, which is due to laser-promoted surface migration [20]. Finally, Müller et al. demonstrated that laser illumination changed the apex morphology and led to inaccuracies in the analysis of Group III–V semiconducting compounds [21]. Due to the clear influence that laser irradiation has on APT measurements, in this study, we investigate the effects of laser power on the measured B distribution in Si to help ensure reliable measurements. It turns out the high power laser can lead to non-homogenous distribution of B in Si, which is probably induced by migration of ions over the surface of needle specimen. This migration process consists of a serial of short-range directional motions of ions prior to their evaporation [22,23], which is different to the classical surface diffusion which occurs at low field and on a static surface [15,24].

2. Experimental

To study the effect of laser power on the B distribution in c-Si, we employed a line-and-space patterned sample, with which we previously demonstrated the origin of the difference in threshold voltage variability between *p*-type and *n*-type transistors [7]. As shown in Fig. 1(a), the B-doped poly-Si (gate) and c-Si (source/drain) regions were isolated using SiO_2. After gate patterning, implantation in the source and drain extension was performed at an acceleration energy of 2.5 keV to a dose of 3×10^{14} atoms/cm^2. The samples were processed by rapid thermal annealing at 900 °C for 10 s and then laser annealed at 1310 °C. An amorphous Si layer was then deposited to protect the implanted region from being damaged during fabrication of the needle-shaped specimen.

To study the effect of laser power on the B distribution in poly-Si, particularly at the grain boundaries, we employed a simplified laterally uniform structure on account of the high probability of sample fracture during measurements of complex structures. As illustrated in Fig. 1(b), a 140-nm-thick poly-Si layer was fabricated on a c-Si wafer with a 2-nm-thick native oxide layer on the surface. The poly-Si was B doped by ion implantation to a dose of 2×10^{15} atoms/cm^2 at 3 keV and then rapidly thermally annealing at 900 °C for 30 s, followed by a second ion implantation to a dose of 4×10^{15} atoms/cm^2 at 2 keV and spike annealing at 1025 °C and laser annealing at 1310 °C. Finally, a protective amorphous Si layer was deposited.

The doping and annealing conditions for both samples are consistent with practical industrial device fabrication process. The region of interest was extracted from the sample using a conventional lift-out method, milled into a fine needle shape using a dual-beam focused ion beam (FIB) system (Quanta200, FEI), and finally modified with a low-voltage Ga shower to limit the damage induced by FIB [25,26]. The prepared needle specimens were measured using a laser-assisted local electrode atom probe (LEAP 4000XHR, CAMECA). The laser had a fixed wavelength of 355 nm and a repetition rate of 200 kHz. The base temperature was set to 50 K for all of the measurements. The line-and-space patterned specimens were measured with laser powers of 40, 70, and 100 pJ, and the laterally uniform specimens were measured with laser powers of 10, 20, 40, 70, and 100 pJ. Corresponding averaged intensities of the Gaussian-beam laser are calculated to be 6.37×10^{-4}, 1.27×10^{-3}, 2.55×10^{-3}, 4.46×10^{-3}, and 6.37×10^{-3} J/cm^2, respectively.

3. Results and discussion

Fig. 2(a)–(c) show cross-sectional projected elemental maps corresponding to a selected region (white rectangle in Fig. 1(a)) of the line-and-space patterned specimens, measured with 40, 70, and 100 pJ of laser power, respectively. The B tail is much longer for the 100 pJ measurement than for the other two. In addition, in the lateral distribution map presented in Fig. 2(d), which was obtained from the region marked by the red rectangle in Fig. 2(c), the B atoms are localized near the center of the specimen, where the Si atoms are distributed with low density as a low-index (001) pole of the Si lattice. The accumulation of B at the low-index pole can be explained by the surface migration of atoms prior to evaporation from the surface. In the atomic map of c-Si, the low-index pole corresponds to the [001] crystallographic direction protruding onto the specimen surface; thus, a large electric field gradient exists between the edge and center of the pole [27]. The migration of atoms toward the pole is electric-field driven and thermally assisted process previously observed by field ion microscopy [28]. It is worth mentioning that the surface migration we discussed here is more of a serial of short-range directional motions of ions prior to their evaporation, such as rolling and jumps [22,23], rather than the classical surface diffusion which occurs at low field and on a static surface [15,24]. Similar accumulation effect of carbon in the poles of steel [29,30] was also reported, in which the measurement was conducted in voltage mode and at low temperature, which proved that this mechanism is not a simple surface diffusion. Fig. 3 shows generated B concentration profiles corresponding to the region marked by the blue dashed rectangle in Fig. 2(c) for 40, 70, and 100 pJ of laser power. The total amount of B (integral of the concentration curve) is clearly much larger for the 100 pJ case than for the other two. In general, the atoms on the outer surface of the region remote from the apex of the specimen are projected out of the range of detection; therefore, the region actually detected is narrower than the specimen [31]. The outer region of the specimen that evaporates out of the range of detection is regarded as lost, or undetectable. This phenomenon was also reported in Ref. [32], in which the APT-detected region was much narrower than the specimen as measured by transmission electron microscopy (TEM), with respect to the excellent matching of microstructures observed by two techniques. However, B has a high thresh-

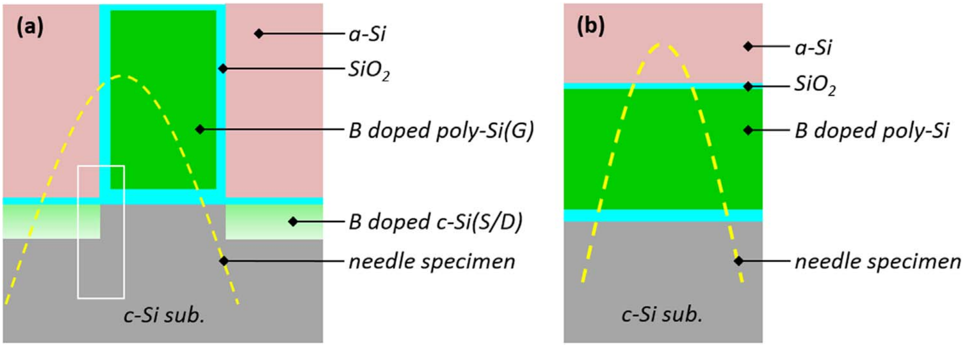

Fig. 1. Schematic illustration of sample structure for investigating B distribution in (a) c-Si and (b) poly-Si.