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Dopant Drive-in Path Analysis in Poly-silicon Filled in Trench type 3D-MOSFET using Atom Probe Tomography

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Abstract

Dopant drive-in path in n- and p-type poly-Si gate of trench structure, one of the 3D device structures, is investigated by atom probe tomography. In the case of P atoms, grain boundary diffusion is dominant. While in the case of B atoms, grain boundary diffusion coefficient seems to be almost same with bulk one.

1. Introduction

The continuous shrinking of the device dimension necessitates a shift from planar structure to complex geometrical designs including 3D-devices like FINFET or trench FET for MOS devices. Spatial distribution control of dopants with high accuracy becomes more difficult because of the complex geometrical designs. For example, in the trench structure, dopant atoms in the poly-Si gates are introduced from the surface but, in contrast to planar structure, diffusion of the dopant atoms from the surface to the gate-inside is more complicated due to the change of the poly-Si thickness and grain orientation by location as shown in scanning transmission electron microscopy (STEM) image of Fig. 1. Therefore it is needed to understand the dopant drive-in path in the poly-Si gates in order to optimize the implantation and the annealing conditions in the trench structure. In this work, dopant distribution in the poly-Si filled in the trench structure with different annealing condition is investigated by laser-assisted atom probe tomography (APT).

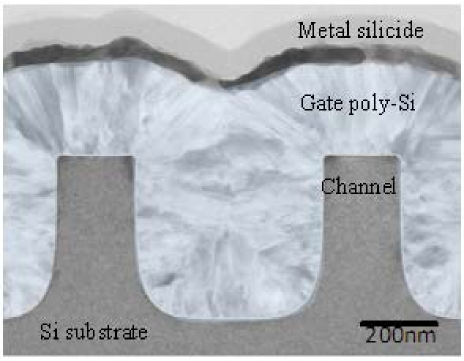

Fig. 1.Cross-sectional STEM image of trench structure. Orientations of the poly-Si grains can be seen.

2. Experimental

Samples are n- and p-type trench structure devices with 300 nm width and 270 nm depth trench which consist of poly-Si gate, gate oxide, and Si substrate. As gate doping, P atoms with a dose of 2×10^{15} cm^{-2} at 10 keV and B atoms with a dose of 5×10^{15} cm^{-2} at 2 keV were implanted in n- and p-type trench, respectively. Then, the samples were annealed at 900 °C with different annealing time to investigate dopant drive-in path. In this trench structure, grain orientation in poly-Si is characteristic and changed systematically by location as shown in Fig. 1, because the grain growth direction is basically perpendicular to the surface of the Si substrate.

Needle specimens for APT analysis were prepared using focused-ion-beam (FIB: FEI, Helios NanoLab600i) system. To protect the device structure from Ga damage during FIB processing, sample surfaces were coated with about 100 nm of Pt. As the result, we obtained Ga-free atom maps. The samples were sharpened by an annular milling technique in which the outer and inner diameters of a circular mask were decreased progressively. The final stage of the milling was performed by low accelerating voltage.

We employed laser-assisted local electrode atom probe (Cameca, LEAP4000X HR) [1,2]. In this work, the pulsed laser with a 355 nm wavelength was irradiated to needle specimen under condition of 200 kHz repetition rate with 20 pJ laser-pulse energy. The base temperature of needle specimen during the measurement was 50K.

3. Results and Discussion

Figure 2(a) shows dopant (P) map in n-type poly-Si filled in the trench structure after annealing at 900 °C for 120 sec. Iso-concentration surface of oxygen are also shown in order to see relationships of the position between the atom map and the trench structure. Figure 2(b) shows 10 nm-thick slices map downward from the top of the needle specimen. In the topmost 20nm region, high density distribution of P was observed, which is due to the as-implanted state. Going to deeper region from the surface, grain boundary segregation was observed. This is due to the rapid diffusion of P along grain boundaries. After annealing at 900 °C for 600 sec, P atoms diffuse into the deeper region from the surface as shown in Fig.3 (a), compared with Fig. 2(a). Segregation of P atoms at the grain boundaries and the interface with silicon dioxide are clearly observed, which is consistent with our previous work [3]. In relatively large grains, the dopant concentration is low. This shows that P atoms diffuse along grain boundaries rapidly and then diffuse into the grain inside.

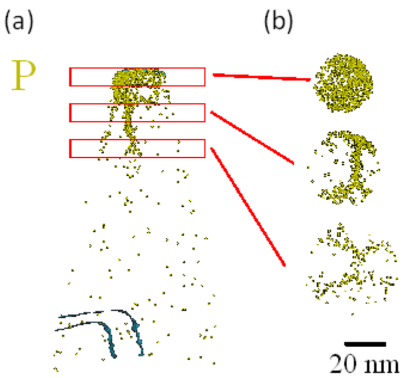

Fig. 2. (a) P map of trench structure after annealing at 900 °C for 120 sec. Iso-concentration surface of the oxygen is also shown. (b) 10 nm-thick slices map.

Figure 3(b) shows 10 nm-thick slices map in the depth where the interface of poly-Si and gate oxide can be seen. In the two figures, same P maps are shown but iso-concentration surface of oxygen is not shown in the lower maps. Paying attention to the interface, low concentration regions on the interface can be seen, which is shown as circle in the lower Fig. 3(b). This low concentration region is apart from grain boundaries.It is indicated that interface diffusion of P is slower than that along grain boundaries. Therefore, main drive-in path of P in the poly-Si of the trench structureis expected to be grain boundary.

Figure 4(a) shows B map in p-type poly-Si after annealing at 900 °C for 600 sec. B atoms are almost uniformly distributed in 10 nm-thick slices map as shown in Fig. 4(b). Neither the grain boundary segregation of B atoms nor rapid grain boundary diffusion in the deeper region is observed. It is indicated that, in the case of B atoms, there is no large difference between grain boundary diffusion coefficient and bulk diffusion one. By comparing the B

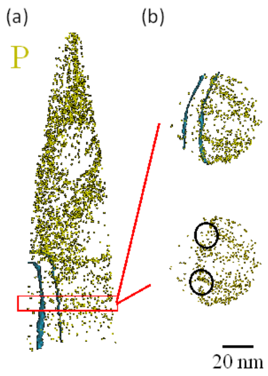

Fig. 3. (a) P map of trench structure after annealing at 900 °C for 600 sec. (b) 10 nm-thick slices map.

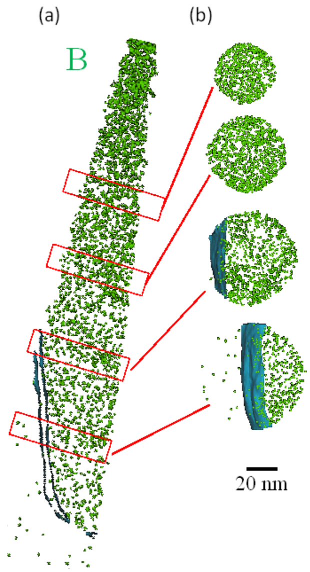

Fig. 4. (a) B map of trench structure after annealing at 900 °C for 600 sec. (b) 10 nm-thick slices map.

distribution in Fig. 3(a) and the P one in Fig. 4(a) in the same annealing condition, B atoms reach the deeper region. Therefore, the bulk diffusion coefficient of B is larger than that of grain boundary diffusion of P in the poly-Si gate.

After annealing under the same condition, the distribution of P and B in the poly-Si gate of the trench structure is quite different. Especially P diffuses mainly via grain boundary. Therefore it is desired to optimize the implantation and annealing conditions considering P diffusion characteristics depending on the grain size and grain orientation in the poly-Si gate.

4. Conclusions

Atom probe tomography reveals P and B drive-in process in poly-Si gate of the trench structure. Rapid grain boundary diffusion of P is clearly observed. In the case of P, the grain boundary diffusion is the fastest, and interface diffusion between the gate and gate oxide is slower than the grain boundary diffusion. Bulk diffusion is the slowest. While in the case of B, grain boundary diffusion of B is similar to the bulk diffusion. B diffusion is faster than the grain boundary diffusion of P.

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