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Dopant-atom distribution measurement at *p-n* junctions on wet-prepared Si(111):H surfaces by scanning tunneling microscopy

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1. Introduction

The feature size of integrated circuits is now becoming a few tens of nanometer. At these dimensions, fluctuations in dopant distribution may impose serious problems on device performance and yield. This has motivated research in recent years to develop a reliable technique to profile dopant distributions with a sufficient spatial resolution. One of the promising techniques is Scanning Tunneling Microscopy (STM) that can detect not only surface electronic states with atomic scale resolution but also individual dopant atoms beneath the surface.[1-4]

In order to image individual dopant atoms with STM, it is indispensable to prepare an atomically flat surface. Recently, we developed a method to make Si(111) surfaces atomically flat and hydrogenated, which is well suited for STM detection of dopant atoms beneath (111) cross sections of fabricated MOSFETs.[5] This method consists of an aqueous NH_4F treatment and subsequent low temperature annealing up to 700 K in vacuum.

Using this surface preparation, we have succeeded in detection of dopant atoms beneath *p*-, *n*- and codoped Si(111) surfaces.[5] Since these surface layers were homogeneously doped, it is unclear whether STM can detect dopant atoms in a depletion region, where charge carriers do not exist.

In this article, we report on STM measurements of dopant-atom distributions at *p-n* junctions fabricated on Si(111) substrates. We show that acceptors and donors can be distinguishably detected in depletion regions as well as *p*- and *n*-type regions.

2. Experiment

Fig. 1(a) shows a schematic cross section of *p-n* junction array fabricated in a *p*-type Si(111) wafer (B-doped, 10 Ω cm). B ions of 1.5×10^{13} cm^{-2} at 10 keV were implanted onto the whole surface and n-type regions were fabricated by an As-ion implantation of 5×10^{13} cm^{-2} at 10 keV through line-and-space masks defined by electron beam lithography (EB). An activation annealing was performed at 1273 K for 10 s. B and As concentrations near the surface measured by secondary ion mass spectroscopy were N_a = 1-2$\times10^{18}$ cm^{-3} and N_d = 2-5$\times10^{19}$ cm^{-3}, respectively.

The Si(111) samples were dipped into a 5% HF solution for 1 min, and then immersed in a 40% NH_4F solution for 4 min at room temperature in an N_2 ambient resulting in atomically-flat and hydrogenated surfaces. Since this treatment deactivates dopant atoms by hydrogenation, the sample was gradually heated up to 685 K to reactivate dopant atoms after being loaded into an ultrahigh-vacuum (UHV) chamber. STM tips used were fabricated from <111> single-crystal rods of W. The STM was operated with constant-current mode at room temperature.

3. Results and Discussion

Figure 1(b) shows a STM image of a *p*-type stripe taken with a positive sample bias voltage. We see that the almost entire area is composed of a single terrace. Many triangles seen are etch pits with a step height of 0.32 nm that corresponds to one bilayer height of Si(111) surfaces. The *p*- and *n*-type regions are observed as dark and bright areas on a single atomic terrace. When we measured the surface with an opposite negative sample bias voltage, the height contrast between the two regions was reversed (see Fig. 3). These results reveal that the height contrast arises

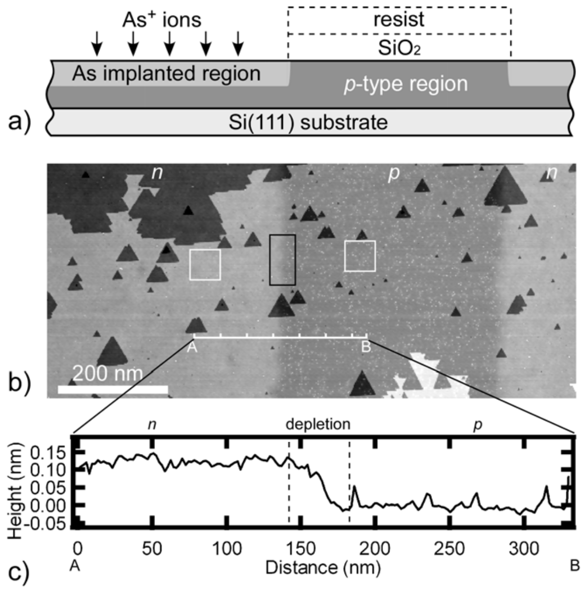

Fig. 1. (a) Schematic cross section of fabricated *p-n* junctions. (b) STM image of parallel *p-n* junctions. The sample bias voltages (V_s) and the tunnel current (I_t) were +2.5 V and 6 pA. White and black rectangles show regions at which the STM images in Fig. 2 and Fig. 3 were acquired, respectively. (c) Height profile along the line A-B.

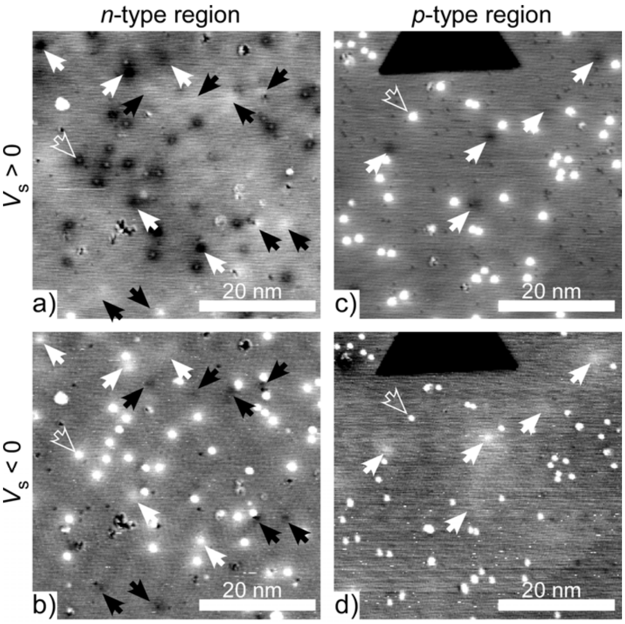

Fig. 2. STM images of *n*- and *p*-type regions taken with both polarities of bias voltages. (a) V_s = +1.7 V, (b) V_s = -2.1 V, (c) V_s = +2.2V, (d) V_s = -1.5 V. I_t = 6 pA.

from potential difference.

Figure 1(c) shows a line profile of the *p-n* junction. From this graph, the depletion region of ~50 nm width can be identified. This value agrees with the depletion width estimated from the dopant concentrations.

Figure 2 shows STM images of dopant features observed in *n*- and *p*-type regions. White and black arrows indicate subsurface acceptor and donor atoms, respectively. Open arrows show surface dangling bonds that are left after desorption of surface hydrogen atoms. The acceptor atoms in the *p*-type region appear as dark spots at $V_s > 0$ V and as bright ones at $V_s < 0$ V, while for the donor atoms in the *n*-type region, the appearance is reversed in both bias polarities. The acceptor atoms in the *n*-type region, which exist because of the co-implantation for *n*-type region, have the same contrast as that in the *p*-type region. These dopant appearances are consistent with our previous results.[5]

Figure 3 shows dopant features observed in the depletion region. We can recognize the acceptor and donor atoms with the same contrasts as those in the *n*- and *p*-type regions. This result clearly indicates that STM can detect dopant atoms distinguishing between acceptors and donors even in depletion regions. Furthermore, we can identify the edge of donor distribution as shown by white broken curves. These curves show that the donor atoms distribute with a spatial amplitude more than 10 nm. We suppose that the observed edge fluctuation arises from a combination of the line edge roughness of the EB resist pattern and the statistical distribution of donor atoms. In this case the statistical distribution seems to be the major origin, because the same degree of edge fluctuation is reproduced in random dot distributions with the same density as the measured donors.

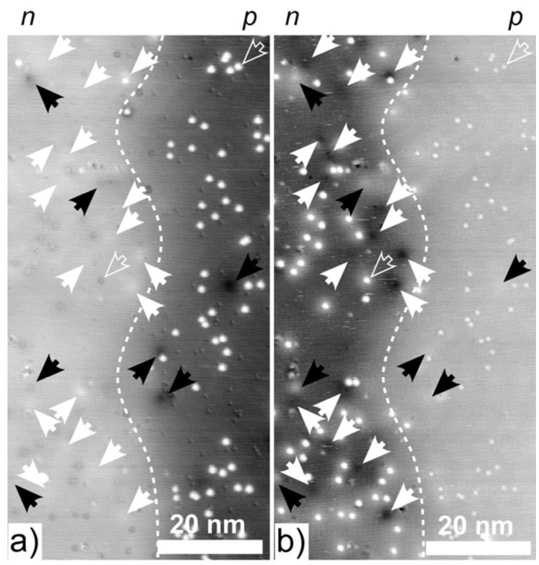

Fig. 3. STM images of depletion region. (a) V_s = +1.7 V, (b) V_s = -1.9 V. I_t = 6 pA. White and black arrows indicate subsurface acceptor and donor atoms. Open arrows show Si dangling bonds on the surface. Broken curves are guide for the donor distribution edge.

4. Conclusion

We have succeeded in measurement of both donor- and acceptor- atom distributions at *p-n* junction regions on wet-prepared Si(111) surfaces by STM. The acceptor and donor atoms were distinguishably observed in the whole surface including depletion regions. From the measured dopant-atom distribution, the donor-atom distribution edge was identified. The observed donor-distribution edge fluctuated with an amplitude more than 10 nm. These results clearly demonstrate the ability of STM as a powerful technique to measure dopant distributions in Si devices with a high spatial resolution.

Acknowledgements

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