MERIT Self-directed Joint Research

Electrical transport measurement of atmic layer superconductor Si(111)-($\sqrt{3} \times \sqrt{3}$)R30°-Sn

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Authors

Shunsuke Sato	He improved the *in situ* four-point transport measurement system installed in Hasegawa Laboratory and enabled to measure tunneling spectra. In this study, Shunsuke Sato performed *in situ* four-point probe transport measurements.
Xutao Wang	He developed an apparatus in which electrical transport, scanning tunneling spectroscopy (STS) and two-coil mutual inductance measurements can be performed in ultra high vacuum (UHV), and he has been doing a research on calsium intercalated graphene with it. In this study, Xutao Wang did the sample preparation in UHV.

1 Background

It is known that a superstructure Si(111)-($\sqrt{3} \times \sqrt{3}$)R30°-Sn, which is made by deposition of 1/3 monolayer (ML) of tin on Si(111), acts as a Mott insulator [2, 3]. By using a heavy-doped p-type Si(111) wafer, holes can be doped to the tin atomic layer and the system turns into metallic. In addition to this, the superconducting gap is observed by STS measurement in the temperature lower than 4.7 K [4]. It is predicted that the superconductivity is unconventional one, whose Cooper pairs are formed by strong electron correlation [5]. The scenario that the superconductivity is realized by hole doping to a Mott insulator is similar to high-T_{C} cuprates, but this system is much simplar than cuprates. The superconductivity of Si(111)-($\sqrt{3} \times \sqrt{3}$)R30°-Sn is attracting attention due to not only its probability of unconventionality, but also the expectation to giving a clue to understand high-T_{C} cuprates.

2 Purpose

In previous research [4], it is comfirmed by STS measurement that Si(111)-($\sqrt{3} \times \sqrt{3}$)R30°-Sn shows superconductivity. In this study, we aim to clarify the superconducting properties of the atomic layer superconductor Si(111)-($\sqrt{3} \times \sqrt{3}$)R30°-Sn by electrical transport measurement.

3 Method

We did sample preparation and electrical transport measurements using *in situ* four-point transport measurement system [1] installed in Hasegawa Laboratory. This equipment enables the sample preparation by molecular beam epitaxy while observing the reflection high-energy electron diffraction (RHEED) pattern, and the electrical transport measurement can be performed without taking out the sample from UHV. Since all processes are done in UHV environment, the possibility of getting damaged or change of the structure of the sample can be excluded. We can cool the sample down to $0.8\,\mathrm{K}$ and apply out-of-plane magnetic field up to $7\,\mathrm{T}$ during electrical transport measurements.

4 Sample preparation

In the previous research [4], ($\sqrt{3} \times \sqrt{3}$)-Sn superstructure was formed on boron heavy-dopoed Si(111) substrates and the superconducting gap was observed by STS measurements. To realize the superconducting transition, it was required to make the ($\sqrt{3} \times \sqrt{3}$)-B structure before the tin depositon by flashing the heavy-doped silicon substrate to segregate dopant. However, when a member of Hasegawa Laboratory tried to measure the electrical transport properties of this system, the behavior originated from the tin atomic layer could not be observed because the carrier density of the substrate was so high that its conductivity was dominant even in low temperature.

In this research, we used SOI (Silicon-On-Insulator) substrates which consist of a high-resistance handle layer (1–$100\,\Omega \cdot \mathrm{cm}$) and a heavy-doped p-type device layer whose dopant is boron (0.001–$0.005\,\Omega \cdot \mathrm{cm}$). Since the dopant of the device layer is boron (identical to the previous research), it is expected that ($\sqrt{3} \times \sqrt{3}$)-B superstructure can be formed. In addition to this, the substrate's contribution to the conductivity will be small for the handle layer becomes insulator at low temperature, and it is expected that the electrical transport properties of the tin atmic layer can be observed. The thicknesses of the handle layer and device layer of the SOI substrate which we used in this research were $(500 \pm 15)\,\mathrm{\mu m}$ and $(50.0 \pm 2.0)\,\mathrm{\mu m}$.

After installing a substrate to UHV chamber and degassing it, we annealed it at around $1250\,^{\circ}\mathrm{C}$ for $5\,\mathrm{s}$ to make its surface clean. Atomically clean Si(111) surface shows the superstructure with 7×7 periodicity. Corresponding to that, we obserced the RHEED pattern of Si(111)-(7×7) after annealing (figure 1(a)). Then we repeated the operation of heating up the substrate to $1250\,^{\circ}\mathrm{C}$ for $30\,\mathrm{s}$ several times. Si(111)-(7×7) became unclear and only 1×1 pattern remained(figure 1(b)). Further operations of annealing at $1250\,^{\circ}\mathrm{C}$ for $30\,\mathrm{s}$ made the dopant segregate at the surface and $\sqrt{3} \times \sqrt{3}$ RHEED patterns appeared(figure 1(c)).

By depositing 1/3 ML of tin to the substrate with keeping its temperature at approximately $600\,^{\circ}\mathrm{C}$, sharp $\sqrt{3} \times \sqrt{3}$ spots appeared in RHEED patterns (figure 1(d, e)). The sharp $\sqrt{3} \times \sqrt{3}$ spots were observed after the tin deposition to any of the Si(111) surfaces corresponding to figure 1(a-c). Figure 1(d) is the RHEED pattern of Si(111)-($\sqrt{3} \times \sqrt{3}$)-Sn formed on the Si(111)-7×7 surface like figure

1(a), and figure 1(e) is the pattern of one formed on the Si(111)-$\sqrt{3} \times \sqrt{3}$-B surface like figure 1(c). We succeeded in making the Si(111)-($\sqrt{3} \times \sqrt{3}$)-Sn structure regardless to the amount of boron segregation at the Si(111) surface.

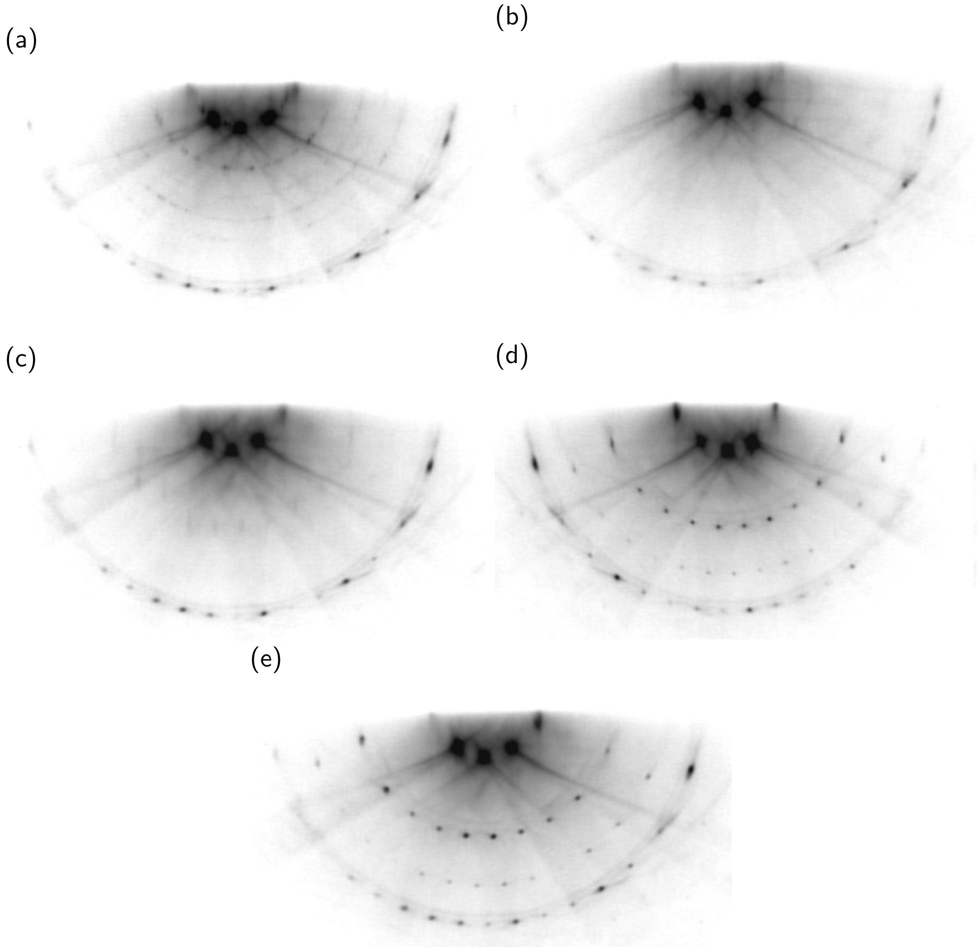

Figure1 (a) RHEED pattern of Si(111)-7 × 7 surface obtained by flashing the SOI substrate. (b, c) After heating up the substrate to around 1250 °C several times, the dopant boron segregated to the surface and the 7 × 7 spots disappeared (b). By continuing the same operation further, the $\sqrt{3} \times \sqrt{3}$-B structure was formed (c). (d) Si(111)-($\sqrt{3} \times \sqrt{3}$)-Sn was obtained by depositing 1/3 ML of tin onto Si(111)-7 × 7 surface with keeping the substrate temperature at approximately 600 °C. (e) As well as (d), Si(111)-($\sqrt{3} \times \sqrt{3}$)-Sn was formed by deposition of tin on the boron segregated surface like (b) and (c). This RHEED pattern was obtained by depositing on the surface like (c). The direction of incident electron beam was $\langle\bar{1}10\rangle$.

5 Electrical transport measurement

We conducted the electrical transport measurements of the Si(111)-($\sqrt{3} \times \sqrt{3}$)-Sn sample which is prepared by depositing tin on the Si(111)-(7 × 7) surface like figure 1(a). The temperature dependence of its resistivity is shown in figure 2. The resistivity was 1.3 $\Omega/\Box$ and it was alomost constant at the

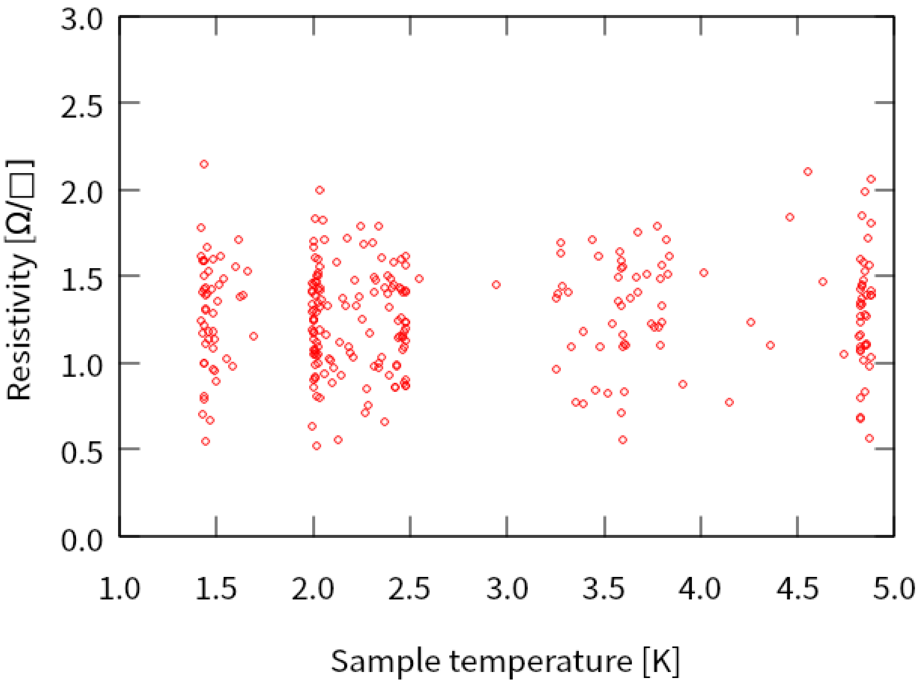

Figure2 The temperature dependence of the resistivity of Si(111)-($\sqrt{3} \times \sqrt{3}$)-Sn. The tin atomic layer is formed on the Si(111)-(7×7) surface. The resistivity shows almost constant value, approximately 1.3 Ω/□ at the temperature from 1.4 K to 5.0 K.

temperature from 1.4 K to 5.0 K. Considering the resolution of the circuit, if superconductivity emerges, the measured resistivity will be in the order of 0.1 Ω/□. According to this result, it is thought that the sample did not show superconductivity.

If tin is deposited on the substrate to whose surface the dopant segregates like figure 1(b, c), more holes will be doped to the tin layer and it can be expected that the sample shows superconductivity. Due to the machine trouble, however, we could not measure such samples during the self-directed joint research.

6 Conclusion

We succeeded in forming Si(111)-($\sqrt{3} \times \sqrt{3}$)-Sn surface superstructure on SOI substrate by depositing 1/3 ML of tin. It was comfirmed that the superstructure can be formed regardless of the amount of boron segregation.

The sample without boron segregation did not show the superconductivity down to 1.4 K. By using SOI substrates, the normal resistivity reached to 1.3 Ω/□, which is high enough to detect the superconducting transition by electrical transport measurements.

Considering the result of STS measurement [4], the superconducting transition is strongly expected on the samples using substrates with the segregation of boron. During this self-directed joint research, we could not measure such a sample due to the machine trouble. After recovery, we will prepare the sample of Si(111)-($\sqrt{3} \times \sqrt{3}$)-Sn superstructure on boron segregated surface and do the electrical transport measurements aiming to observe the superconductivity.

7 Acknowledgement

We would like to thank our advisors, Professor Shuji Hasegawa of the Department of Physics, The University of Tokyo, and Professor Canhua Liu of School of Physics and Astronomy, Shanghai Jiao Tong University, for their great support and guidance in this research, and thank Assistant Professor Ryota Akiyama of Hasegawa Laboratory for his guidance and cooperation. Finally, we appreciate Professor Yoshinobu Nakamura for the approval of our proposal, and MERIT program for giving an opportunity to conduct this self-directed joint research.

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