Impact of Surface Conditions on the Superconductivity of Si(111)-($\sqrt{7} \times \sqrt{3}$)-In*

Shunsuke Yoshizawa
International Center for Materials Nanoarchitectonics, National Institute for Materials Science, 1-1 Namiki, Tsukuba 305-0044, Japan

Howon Kim
Institute for Solid State Physics, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8581, Japan

Takuto Kawakami
International Center for Materials Nanoarchitectonics, National Institute for Materials Science, 1-1 Namiki, Tsukuba 305-0044, Japan

Yuki Nagai
CCSE, Japan Atomic Energy Agency, Kashiwa, Chiba 277-8587, Japan

Tonomobu Nakayama and Xiao Hu
International Center for Materials Nanoarchitectonics, National Institute for Materials Science, 1-1 Namiki, Tsukuba 305-0044, Japan

Yukio Hasegawa
Institute for Solid State Physics, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8581, Japan

Takashi Uchihashi
International Center for Materials Nanoarchitectonics, National Institute for Materials Science, 1-1 Namiki, Tsukuba 305-0044, Japan

*Received 29 December 2014; Accepted 23 March 2015; Published 11 April 2015

We performed low-temperature scanning tunneling microscopy and spectroscopy on Si(111)-($\sqrt{7} \times \sqrt{3}$)-In in magnetic fields. Superconducting vortices were observed by mapping zero-bias conductance in an area consisting of flat terraces separated by atomic steps. While vortices in the terrace regions have an isotropic shape with a normal-state core, those at the atomic steps have anisotropic shapes and the superconductivity is only weakly suppressed in the cores. These properties are understood as a crossover from a normal vortex to a Josephson vortex. We conclude that the atomic steps work as Josephson junctions limiting the density of supercurrents. [DOI: 10.1380/ejssnt.2015.151]

Keywords: Scanning tunneling microscopy; Scanning tunneling spectroscopy; Superconducting surfaces; Indium; Silicon

I. INTRODUCTION

The recent discovery of superconductivity in surface reconstructions induced by metal adatoms on silicon has offered a new opportunity to study two-dimensional superconductivity in atomically thin films [1–5]. Shortly after the first observation of superconducting energy gap by means of scanning tunneling spectroscopy (STS) [1], in situ electrical transport measurements have demonstrated that supercurrents can travel over macroscopic distances in those surface systems [2–4]. The finding of the macroscopic supercurrents was unexpected, because the surfaces always have atomic steps that may decouple metallic films grown on the terraces [6, 7]. The temperature dependence of the critical current suggests that the supercurrents flow across the atomic steps with the help of the Josephson effect [2]. There was, however, no direct information about how the atomic steps disturb the flow of supercurrents.

Here, we present results of STS on the Si(111)-(\(\sqrt{7} \times \sqrt{3}\))-In superconductor with a critical temperature of 3 K [1, 8]. After applying magnetic fields to the sample, vortex cores were observed in a region consisting of flat terraces separated by a few atomic steps. While vortices in the terrace regions have an isotropic shape with a normal-state core, those at the atomic steps have anisotropic shapes and the core was still superconducting. We conclude that a crossover from a normal vortex to a Josephson vortex has been directly observed. Our results indicate that the atomic steps work as Josephson junctions and allow supercurrents to flow with a limited rate. Detailed results, discussions and theoretical calculations are presented elsewhere [9, 10].

II. EXPERIMENTAL

Experiments were performed using a low-temperature scanning tunneling microscope (STM) equipped with ultra-high-vacuum chambers for sample preparation. Si(111) substrates were flashed and annealed several times to prepare a clean surface with the 7 \times 7 reconstruction. Indium was deposited onto the surface at room tempera-

* This paper was presented at the 7th International Symposium on Surface Science, Shimane Prefectural Convention Center (Kunihiki Messe), Matsue, Japan, November 24, 2014.

† Corresponding author: YOSHIZAWA.Shunsuke@nims.go.jp
We characterize the sample by observing vortices on a flat terrace region. Figure 1(b) shows a ZBC image taken in a magnetic field of 0.04 T. Two high-ZBC regions in the image are vortex cores created by the penetration of magnetic flux. In Fig. 1(c), the tunneling spectrum measured away from the vortex cores (P) exhibits a superconducting energy gap with two coherence peaks at the gap edges. By contrast, the tunneling spectrum at the center of one of the vortex core (Q) is nearly flat, reflecting the complete suppression of superconductivity in the core. The spectrum does not show a quasiparticle bound-state peak typical of vortex cores in clean-limit superconductors [11–16]. This suggest that our sample is in the dirty limit in the sense that the coherence length $\xi$ is limited by the electron mean free path. Hereafter, we use ZBC normalized by the coherence peak height to increase signal-to-noise ratio in vortex core images.

To explore the role of atomic steps in the superconducting state of Si(111)-($\sqrt{7} \times \sqrt{3}$)-In, we observed vortices in a larger field of view shown in Fig. 2(a). The region consists of three terraces separated by two atomic steps $S_1$ and $S_2$ each with the single atomic height of 0.31 nm. We applied a magnetic field of 0.08 T to the sample and measured ZBC. Figure 2(b) shows the obtained ZBC image displaying many high ZBC spots corresponding to vortex cores. When we decreased the magnetic field to 0.04 T, the number of vortex cores decreased accordingly [Fig. 2(c)]. After the magnetic field was reduced to zero, vortices disappeared from the terrace regions [Fig. 2(d)]. Two bright features A and B were still present at the atomic steps. They are vortex cores trapped at atomic steps rather than regions where superconductivity had been intrinsically weakened, because at higher fields the steps rather than regions where superconductivity had been intrinsically weakened, because at higher fields the steps rather than regions where superconductivity had been intrinsically weakened.

We found that the vortex cores A and B in the atomic step differ from C in the terrace in the following two respects. First, while the shape of the vortex core C is isotropic, those of A and B are elongated along the step. The full widths at half maximum (FWHMs) measured along and across the step are 213 and 103 nm for vor-
FIG. 3. (a) Schematic illustration of a normal vortex in a uniform superconductor. The green circle represents the shape of the core. The dark color inside the core region indicates the suppression of superconductivity. The phase \( \varphi \) of the order parameter varies by \( 2\pi \) around the vortex. (b) Schematic plot of \( |\Psi|/|\Psi_0| \) across the normal vortex. Here, the amplitude of the order parameter \( |\Psi| \) is normalized by the value \( |\Psi_0| \) in the absence of the supercurrents and magnetic fields. (c) Schematic illustration of a Josephson vortex penetrating a straight Josephson junction drawn as a dotted line. The \( 2\pi \) phase evolution includes phase shifts \( \Delta \varphi \) at the junctions. (d) Schematic plot of \( |\Psi|/|\Psi_0| \) across the Josephson vortex.

text A. The latter is approximately the same as the FWHM of 94 ± 5 nm for C. The vortex core B is largely spread over the step S2 and the intensity appears to be fluctuating. Second, the ZBC in the vortex cores A and B is smaller than the value in C. In other words, the superconductivity survives in A and B, while it is strongly suppressed in C. As explained below, these two properties of vortex cores in the atomic steps are the consequence of crossover from a normal vortex to a Josephson vortex.

Let us begin with a brief description of the vortex core in a uniformly superconducting region [17]. Figure 3(a) shows a schematic picture of a vortex in a superconducting region. The superconducting state is represented by a complex order parameter \( \Psi(r) = |\Psi(r)| \exp[i\varphi(r)] \). Suppose a magnetic field is applied and a vortex is present at \( r = 0 \). Supercurrents circulate around it and the phase of the order parameter, \( \varphi \), varies by \( 2\pi \). With approaching the vortex center, the supercurrent density \( J_s \) increases and reaches the critical current \( J_0 \) at \( |r| = \xi \), where \( \xi \) is the coherence length. As a result, as shown in Fig. 3(b), the amplitude of the order parameter, \( |\Psi| \), is strongly suppressed in the vortex core region \( (|r| < \xi) \) and it falls to zero at \( |r| = 0 \). The situation changes when a Josephson junction line is present and the vortex penetrates it, as illustrated in Fig. 3(c). The phase evolution around the vortex includes phase shifts \( \Delta \varphi \) at the junctions. The supercurrent density \( J_s \) at the junctions follows the relation:

\[
J_s = J_c \sin \left[ \Delta \varphi - \frac{2\pi}{\Phi_0} \int A(s) \cdot ds \right],
\]

where \( J_c \) is the critical current of the junction, \( \Phi_0 = 2e/h \) is the magnetic flux quantum, \( \int A(s) \cdot ds \) is the integral of the vector potential across the junction. This means that the maximum density of supercurrents crossing the junction is limited to \( J_c \), which is smaller than \( J_0 \) of the superconducting region. Consequently, the vortex in the junction acquires two properties different from normal vortices. First, the circulating supercurrents around the vortex is strongly deformed and the shape of the vortex core is elongated along the junction by a factor of \( (J_c/J_0)^{-1} \). Second, as displayed in Fig. 3(d), the amplitude of the order parameter at the vortex center is nonzero and is given approximately by \( 1 - (J_c/J_0)^2 \) \( |\Psi_0| \), where \( |\Psi_0| \) is the value of \( |\Psi| \) in the absence of supercurrents and magnetic fields. These two properties are what we observed for the vortex cores at the atomic steps.

As described above, the behavior of a vortex in a Josephson junction is determined by the ratio \( J_c/J_0 \). This ratio is a measure of the coupling strength between two superconducting regions. In our sample, the coupling strength depends on the local atomic-scale structures at the steps. Figures 2(e) and 2(f) show magnified STM images at the steps S1 and S2, respectively. We found narrow grooves along the lower side of each step. The presence of the grooves indicates that the In film did not grow up to the atomic steps and that the electrical coupling between the terraces were weakened. Since the groove is more obvious at the step S2 than at S1, the coupling between terraces and thus the ratio \( J_c/J_0 \) is smaller at S2 than at S1. This explains why ZBC in vortex B at the step S2 is smaller than that in vortex A at the step S1.

The value of \( J_c/J_0 \) can be estimated from the anisotropy of vortex core images. For vortex A, the ratio of FWHM across the step to that along the step is 0.48. This suggests that the critical current across the step \( S_1 \) is reduced by about half compared with the critical current in the superconducting terrace region. Since the vortex B has a weaker intensity than vortex A, the step S2 should have smaller \( J_c/J_0 \) than \( S_1 \).

To compare the theoretical prediction with the experimental results more directly, we performed numerical calculations [10]. The Bogoliubov-de Gennes equations were self-consistently solved on a two-dimensional tight-binding model. An atomic step was modeled as a straight line with one atomic spacing where the hopping integral \( t_s \) was decreased from the constant hopping integral \( t \) for the other parts. The pair potential and the quasiparticle density of states at the Fermi energy were calculated as functions \( t_s/t \). We found that the spatial distribution of zero-energy density of states, corresponding to ZBC in the experiment, in a vortex core is elongated along the step and its intensity decreases with decreasing \( t_s/t \). The numerical results agree well with the experimental observations and strongly support our conclusion.

**IV. CONCLUSION**

In conclusion, we observed superconducting vortices on the surface of Si(111)-(√7×√3)-In by using STM and STS. Vortex cores located in the terraces were found to have a round shape and superconductivity was destroyed there. In contrast, those penetrating atomic steps exhibit...
Anisotropic shapes elongated along the steps, and superconductivity was only weakly suppressed there. These results can be understood as a crossover behavior from a normal vortex core to a Josephson vortex core, demonstrating that the atomic steps work as Josephson junctions that allow supercurrents to travel with a limited rate.

ACKNOWLEDGMENTS

This work was financially supported by JSPS under KAKENHI Grants No. 25247053, No. 25286055, No. 25400385, No. 24340079 and by World Premier International Research Center (WPI) Initiative on Materials Nanoarchitectonics, MEXT, Japan. The calculations were performed using the supercomputing system PRIMERGY BX900 at the Japan Atomic Energy Agency.

[1] T. Zhang, P. Cheng, W. J. Li, Y. J. Sun, G. Wang, X. G. Zhu, K. He, L. Wang, X. Ma, X. Chen, Y. Wang, Y. Liu, H. Q. Lin, J. F. Jia, and Q. K. Xue, Nat. Phys. 6, 104 (2010).
[2] T. Uchihashi, P. Mishra, M. Aono, and T. Nakayama, Phys. Rev. Lett. 107, 207001 (2011).
[3] T. Uchihashi, P. Mishra and T. Nakayama, Nanoscale Res. Lett. 8, 167 (2013).
[4] M. Yamada, T. Hirahara, and S. Hasegawa, Phys. Rev. Lett. 110, 237001 (2013).
[5] C. Brun, T. Cren, V. Cherkez, F. Debontridder, S. Pons, D. Fokin, M. C. Tringides, S. Bozhko, L. B. Ioffe, B. L. Altshuler, and D. Roditchev, Nat. Phys. 10, 444 (2014).
[6] T. Uchihashi and U. Ramsperger, Appl. Phys. Lett. 80, 4169 (2002).
[7] I. Matsuda, M. Ueno, T. Hirahara, R. Hobara, H. Morikawa, C. Liu, and S. Hasegawa, Phys. Rev. Lett. 93, 236801 (2004).
[8] S. Yoshizawa and T. Uchihashi, J. Phys. Soc. Jpn. 83, 065001 (2014).
[9] S. Yoshizawa, H. Kim, T. Kawakami, Y. Nagai, T. Nakayama, X. Hu, Y. Hasegawa, and T. Uchihashi, Phys. Rev. Lett. 113, 247004 (2014).
[10] T. Kawakami, Y. Nagai, S. Yoshizawa, H. Kim, Y. Hasegawa, T. Nakayama, T. Uchihashi, X. Hu, J. Phys.: Conf. Ser. 568, 022022 (2014).
[11] H. F. Hess, R. B. Robinson, R. C. Dynes, J. M. Valles, Jr., and J. V. Waszczak, Phys. Rev. Lett. 62, 214 (1989).
[12] Ch. Renner, A. D. Kent, Ph. Niedermann, O. Fischer, and F. Lévy, Phys. Rev. Lett. 67, 1650 (1991).
[13] H. Nishimori, K. Uchiyama, S. Kaneko, A. Tokura, H. Takeya, K. Hirata, and N. Nishida, J. Phys. Soc. Jpn. 73, 3247 (2004).
[14] I. Guillamón, H. Suderow, S. Vieira, L. Cario, P. Diener, and P. Rodière, Phys. Rev. Lett. 101, 166407 (2008).
[15] S. Kaneko, K. Matsuba, M. Hafiz, K. Yamasaki, E. Kakizaki, N. Nishida, H. Takeya, K. Hirata, T. Kawakami, T. Mizushima, and K. Machida, J. Phys. Soc. Jpn. 81, 063701 (2012).
[16] T. Hanaguri, K. Kitagawa, K. Matsubayashi, Y. Mazaki, Y. Uwatoko, and H. Takagi, Phys. Rev. B 85, 241405 (2012).
[17] M. Tinkham, Introduction to Superconductivity, 2nd ed. (Dover Publications, Inc., New York, 2004).
[18] G. Blatter, M. V. Feigel’man, V. B. Geshkenbein, A. I. Larkin, and V. M. Vinokur, Rev. Mod. Phys. 66, 1125 (1994).