Semiconductor-superconductor transition and magnetoresistance terraces in an ultrathin superconducting Pb nanobridge

Jian Wang[a)]
International Center for Quantum Materials, Peking University, Beijing 100871, China; Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China; and Department of Physics and The Center for Nanoscale Science, The Pennsylvania State University, University Park, Pennsylvania 16802-6300

Jin-Feng Jia
Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China and Department of Physics, Tsinghua University, Beijing 100084, China

Xu-Cun Ma, Quan-Tong Shen, Tie-Zhu Han, Ai-Zi Jin, Li Lu, and Chang-Zhi Gu
Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China

Ming-Liang Tian
Department of Physics and The Center for Nanoscale Science, The Pennsylvania State University, University Park, Pennsylvania 16802-6300

X. C. Xie
International Center for Quantum Materials, Peking University, Beijing 100871, China and Department of Physics, Oklahoma State University, Stillwater, Oklahoma 74078

Qi-Kun Xue[b)]
Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China and Department of Physics, Tsinghua University, Beijing 100084, China

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Using focused ion beam etching technique, the authors fabricated a 28 atomic monolayers thick, 500 nm wide, and 10 μm long Pb nanobridge from an atomically flat Pb thin film grown on Si by molecular beam epitaxy. Electric transport measurements show exotic resistance oscillations in the superconducting state far below its critical field H_C and cascading terraces near the superconducting transition region. Furthermore, the bridge shows an unusual semiconducting behavior above the superconducting transition temperature T_C. The results are in contrast to those observed in its counterpart of the two-dimensional thin film.
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I. INTRODUCTION

Two-dimensional (2D) superconductors refer to a filmlike superconducting material whose thickness is smaller than the Ginsburg–Landau superconducting phase coherence length (ξ).[1] Similarly, one-dimensional (1D) superconductors are wires whose the diameter is close to or smaller than the superconducting phase coherence length. In this regime, many intriguing physical phenomena, such as thermally activated phase slip,[2–4] quantum phase slip,[5,6] superconductor-insulator transition,[7] antiproximity effect,[8,9] magnetoresistance oscillations,[10–13] and quantum size effect driven oscillatory superconductivity,[14–16] have been observed. With rapid progress on electronic device miniaturization,[17–20] the applications of superconducting nanocircuits and the superconductivity in reduced dimensionality have attracted much attention in recent years.[21–26] The use of superconducting components will produce denser and more rapid chips since the resistance of interconnects is a major source of heat generation and charging time.[27,28] Therefore, superconducting nanodevices are predominately prepared or fabricated on semiconductor substrates. Along this line, an integration of the superconducting interconnecting nanocircuits with Si is of great interest.

Previously, we studied the superconductivity in a 28 atomic monolayers (ML) (~8 nm) single-crystal Pb bridge with a width of 285 nm and a length of 10 μm.[10] Since the superconducting coherence length in the Pb film of 28 ML thick is ~27 nm,[10] the 285 nm wide Pb nanobelt of the same thickness can be considered as a superconductor with dimensions between 2D and quasi-1D. In this work, we fabricated a 500 nm wide, 10 μm long, and 28 ML thick Pb bridge and measured the electrical transport property. This bridge, which is expected to be close to the 2D regime, showed an unusual semiconducting behavior above T_C and a series of cascading magnetoresistance terraces below T_C.

II. EXPERIMENT

High quality single-crystal Pb films were prepared on Si(111) substrates by standard molecular beam epitaxy in an ultrahigh vacuum low-temperature scanning tunneling microscopy (STM) system.[10] The base pressure of the system is

a)Electronic mail: juw17@psu.edu
b)Electronic mail: qkxue@mail.tsinghua.edu.cn

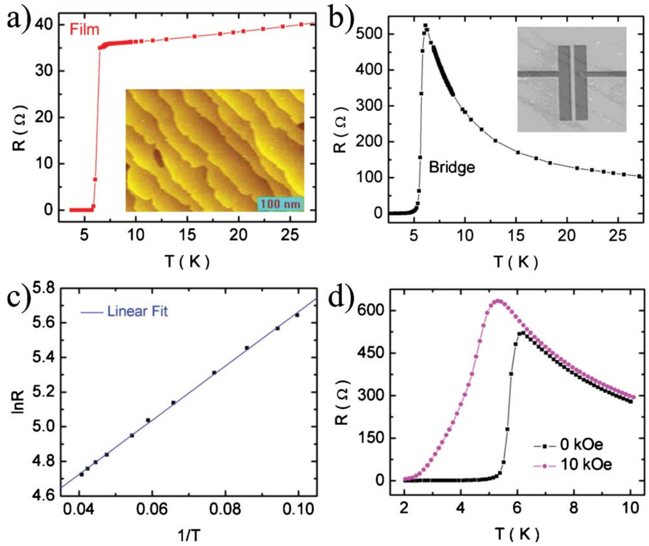

FIG. 1. (Color online) (a) Resistance vs temperature curve measured from a 28 ML Pb film. The inset is a scanning tunneling microscope image of the atomically flat Pb thin film. (b) Resistance vs temperature curve of a 28 ML thick, 500 nm wide, and 10 μm long Pb nanobridge. The inset is a scanning electron micrograph of the Pb nanobridge. The dark region on the two sides of the Pb bridge is the exposed Si substrate, which isolates two blocks of the Pb film. (c) $\ln R$ vs $1/T$ curve of the Pb nanobridge in the low-temperature regime from 9.5 to 28.6 K. The solid line is the linear fitting. (d) R-T curves of the Pb nanobridge at 0 and 10 kOe perpendicular fields for comparison.

better than 1.0×10^{-10} Torr. During the growth, the Si substrate was cooled down to 95 K by liquid nitrogen (LN_2) to achieve atomically smooth single-crystal Pb thin films, as reported elsewhere.[10,14] The inset of Fig. 1(a) shows a typical STM topographic image of the Pb film with a thickness of 28 ML prepared by this method, from which we can observe that the Pb film is atomically flat. To protect oxidation and contamination of the film in ambient condition for transport property measurement, 4 ML Au was deposited on the film before the sample was taken out from the ultrahigh vacuum chamber.[10,14] The transport measurements were carried out by using a standard four electrode method with a physical property measurement system. As shown in Fig. 1(a), the film exhibits a metallic behavior from 27 to 7 K (the resistance decreases linearly) and a superconducting transition at 6.3 K (onset T_C).

The Pb bridge was carved from this film by a commercial focused ion beam (FIB) etching and depositing system (FEI-DB235), as shown in the inset of Fig. 1(b). The dark region is the exposed Si surface and the gray straight structure is the Pb bridge. The etching current was set as low as 10 pA (the number of the etching ions is $6.24\times10^6/\mu\text{m}^2$ s) to minimize structure contamination by the Ga ions. As reported before,[10] four electrodes were connected to two parts of the film for transport measurement.

III. RESULTS AND DISCUSSION

Figure 1(b) shows the resistance versus temperature (R-T) curve of this bridge. Unexpectedly, the resistance of the bridge above T_C shows a semiconducting behavior. Figure

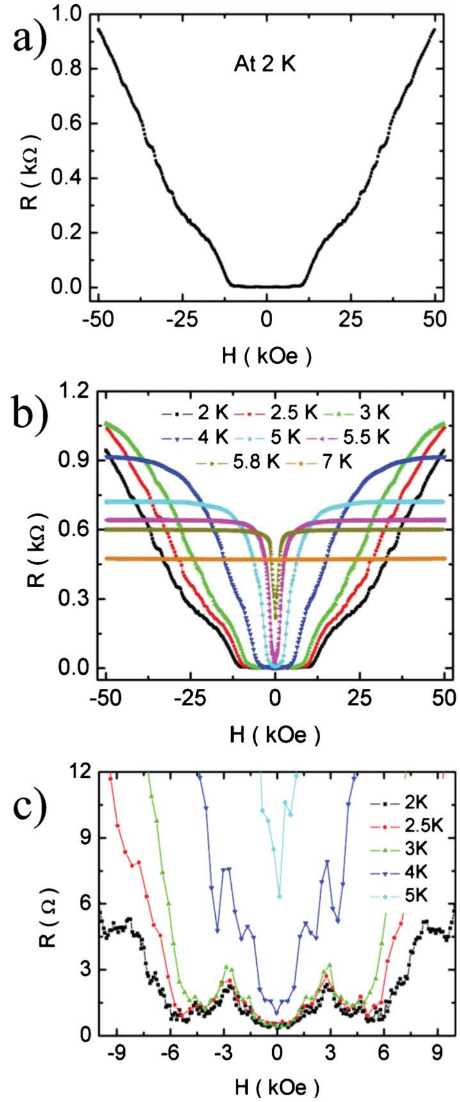

FIG. 2. (Color online) (a) Magnetoresistance of the Pb nanobridge with a magnetic field applied perpendicular to the film at 2 K. (b) R-H curves of the Pb nanobridge measured at different temperatures. (c) Close-up view of (b) in the low magnetic field regime at various temperatures for clarity.

1(c) shows corresponding $\ln R$ vs $1/T$ curve, and a linear relation (the blue line) was found from 28.6 to 9.5 K. The fitting was based on a formula of $R=R_0\exp(2\Delta/T)$ with $R_0=60.2\ \Omega$ and $2\Delta=15.7$ K (1.35 meV). This result indicates that the Pb bridge above T_C is a typical semiconductor with a band gap of 15.7 K (1.35 meV). To further understand this thermally activated semiconducting behavior, we measured the R-T curve of the same Si substrate by the standard four electrode method. It was found that the resistance of the Si substrate is on the order of 1 MΩ at 9.5 K. Therefore, the resistance of the Si substrate does not play a crucial role for this unusual semiconducting behavior. Figure 1(d) shows R-T plots of the Pb nanobridge at both 0 and 10 kOe magnetic fields perpendicular to the Pb film (the magnetic field was applied perpendicular to the Pb film in all data presented in this work). We can see that once the superconductivity is suppressed by the field, the normal state resistance follows the same semiconducting behavior.

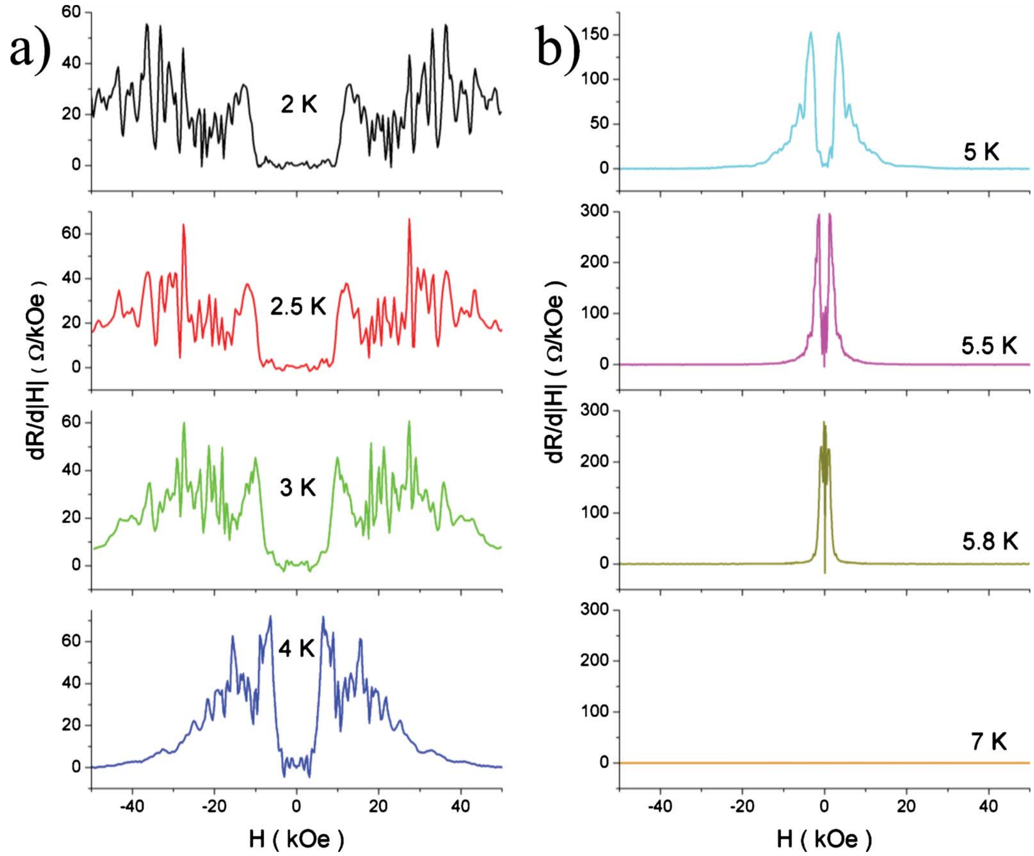

FIG. 3. (Color online) (a) $dR/d|H|$ curve of the Pb nanobridge at 2, 2.5, 3, and 4 K, respectively. The data are from the *R-H* curves. (b) $dR/d|H|$ curve of the Pb nanobridge measured at 5, 5.5, 5.8, and 7 K, respectively. The data are from the *R-H* curves.

R vs *H* scan at 2 K is displayed in Fig. 2(a). Above 10.4 kOe the resistance increases rapidly with *H*, accompanied by a series of terraces up to 50 kOe. These terraces in *R* are almost symmetric in both positive and negative fields. Above 50 kOe, the resistance does not reach a constant value, indicating the field does not drive the bridge completely to the normal state at this field. In contrast, at 2.0 K, the 28 ML Pb film shows zero resistance below 9.3 kOe and fully reaches the normal state at 16.6 kOe.[10] The *R-H* plots for the Pb nanobridge at different temperatures are shown in Fig. 2(b). With increasing temperature, the constant normal state resistance is seen from 4 to 7 K and its value decreases correspondingly. This is consistent with the semiconducting behavior above T_C [see Fig. 1(d)]. Figure 2(c) shows a close-up of the *R-H* curves in the low field region. The magnetoresistance exhibits oscillations in the superconducting state and the shape of the oscillations is similar to the behavior observed in 200 nm wide granular Sn wires near the superconductor-insulator transition.[11] However, our bridge is single crystal, and especially, its resistance is much smaller than that of the granular Sn wires, where the normal state resistance is on the order or larger than the quantum resistance, $R_Q = h/4e^2 = 6.5\ \text{k}\Omega$.

The magnetoresistance terraces shown in Fig. 2(b) are better viewed in the $dR/d|H| - H$ plots (see Fig. 3). At $T = 5.8$, 5.5, and 5 K, the $dR/d|H| - H$ curves show field-symmetric broad peaks. The broad peaks evolve outward and become broader with decreasing temperature. Below 4 K, strong oscillations are seen, which are overlapped with the symmetric broad peaks. The oscillations do not show well-defined periodicity. To ascertain that they originate from the size-confined Pb nanobridge, we performed similar measurement on the Pb films. In this case, no oscillation was observed.[10]

Nonmetallic conductivity behaviors have been reported in weak localization metals,[29,30] which exhibit localization of conduction electrons by interference of constructive interference of backscattered electrons. The applied magnetic field can destroy the weak localization and induce negative magnetoresistance. However, we did not see negative magnetoresistance in this semiconducting Pb nanobridge. A semiconductor-superconductor transition was ever observed in granular Al–Ge specimens.[31,32] This system is semiconducting in the normal state and undergoes a superconducting transition in low temperature, which is explained by the interplay between the Josephson coupling energy and the Coulomb charging energy. However, our Pb bridge is not granular and the normal resistance above T_C (around 500 Ω) is much smaller than that of the granular Al–Ge ($\sim 2.2 \times 10^5\ \Omega$). Furthermore, below T_C, the Pb bridge shows zero resistance while the Al–Ge exhibits large residual resistance.

We do not yet have a satisfactory explanation of the observed semiconducting effect above T_C. A very speculative explanation is that the bridge might not be fully protected by the Au layer and thus oxidized and degraded, because the Pb bridge was exposed in air at room temperature for a certain time (a few days) before cooling down to helium temperature for measurement. Another possible reason is that the bridge was damaged by the Ga ion irradiation during the FIB process. It should be noted that the gallium ions used in the FIB process are not responsible for the observed superconductivity since the FIB deposited Pt strip containing the Ga ions is not superconducting.[33]

As for the intriguing oscillations in the differential magnetoresistance (magnetoresistance terraces), we appeal to the analogy of oscillations in the supercurrent of superconductor-normal metal-superconductor (S-N-S) junctions in the bridge, which in the presence of a magnetic field is given by $I_S \propto \sin(\Delta\phi - (2e/h)HS)$,[34,35] where HS is the magnetic flux through the bridge, and $\Delta\phi$ is the difference in the phases of the superconducting order parameters. In a simple picture, because we use a constant current mode in the measurements, the oscillations in the supercurrent are "compensated" by oscillations in the normal current. Since the possible S-N-S junctions are not homogenous in the Pb bridge, the observed oscillations are not good periodic.

Another possible qualitative explanation for the differential magnetoresistance oscillations is thermally activated phase slips. Due to the oxidation or defects some superconducting phase slip centers[36] may be produced in the Pb nanobridge. When a magnetic field is applied and the bridge is driven to normal state, a sequence of magnetoresistance terraces can be induced by a series of corresponding phase slip events. Further experiments on the size dependence will be helpful to understand the origin of the observed phenomena.

IV. CONCLUSION

Semiconductor-superconductor transition and magnetoresistance terraces are observed in an ultrathin Pb nanobridge. Although some observations are not well understood at the moment, the intriguing behaviors indicate that some new devices based on superconductor nanostructures may be developed by using well-established Si microelectronics technology.

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[1] W. J. Skocpol and M. Tinkham, Rep. Prog. Phys. **38**, 1049 (1975).
[2] A. Rogachev, A. T. Bollinger, and A. Bezryadin, Phys. Rev. Lett. **94**, 017004 (2005).
[3] J. E. Lukens, R. J. Warburton, and W. W. Webb, Phys. Rev. Lett. **25**, 1180 (1970).
[4] W. A. Little, Phys. Rev. **156**, 396 (1967).
[5] C. N. Lau, N. Markovic, M. Bockrath, A. Bezryadin, and M. Tinkham, Phys. Rev. Lett. **87**, 217003 (2001).
[6] N. Giordano, Phys. Rev. Lett. **61**, 2137 (1988).
[7] F. Sharifi, A. V. Herzog, and R. C. Dynes, Phys. Rev. Lett. **71**, 428 (1993).
[8] M. L. Tian, N. Kumar, S. Y. Xu, J. G. Wang, J. S. Kurtz, and M. H. W. Chan, Phys. Rev. Lett. **95**, 076802 (2005).
[9] M. L. Tian, N. Kumar, J. G. Wang, S. Y. Xu, and M. H. W. Chan, Phys. Rev. B **74**, 014515 (2006).
[10] J. Wang *et al.*, Appl. Phys. Lett. **92**, 233119 (2008).
[11] A. V. Herzog, P. Xiong, and R. C. Dynes, Phys. Rev. B **58**, 14199 (1998).
[12] A. Johansson, G. Sambandamurthy, D. Shahar, N. Jacobson, and R. Tenne, Phys. Rev. Lett. **95**, 116805 (2005).
[13] U. Patel *et al.*, Appl. Phys. Lett. **91**, 162508 (2007).
[14] Y. Guo *et al.*, Science **306**, 1915 (2004).
[15] T. C. Chiang, Science **306**, 1900 (2004).
[16] D. Eom, S. Qin, M.-Y. Chou, and C. K. Shih, Phys. Rev. Lett. **96**, 027005 (2006).
[17] Y. Makhlin, G. Schon, and A. Shnirman, Nature (London) **431**, 138 (2004).
[18] J. L. O'Brien, G. J. Pryde, A. G. White, T. C. Ralph, and D. Branning, Nature (London) **426**, 264 (2003).
[19] P. K. Day, H. G. LeDuc, B. A. Mazin, A. Vayonakis, and J. Zmuidzinas, Nature (London) **425**, 817 (2003).
[20] G. Wendin and V. S. Shumeiko, Science **292**, 231 (2001).
[21] M. Berciu, T. G. Rappoport, and B. Janko, Nature (London) **435**, 71 (2005).
[22] D. A. Ricci, T. Miller, and T.-C. Chiang, Phys. Rev. Lett. **95**, 266101 (2005).
[23] J. Eroms, D. Weiss, J. De Boeck, G. Borghs, and U. Zulicke, Phys. Rev. Lett. **95**, 107001 (2005).
[24] C. Castellana, F. Giazotto, M. Governale, F. Taddei, and F. Beltram, Appl. Phys. Lett. **88**, 052502 (2006).
[25] F. Giazotto, P. Pingue, and F. Beltram, Mod. Phys. Lett. B **17**, 955 (2003).
[26] K. Y. Arutyunov, D. S. Golubev, and A. D. Zaikin, Phys. Rep. **464**, 1 (2008).
[27] J. Wang *et al.*, Nanotechnology **19**, 475708 (2008).
[28] M. Zgirski, K. P. Riikonen, V. Touboltsev, and K. Arutyunov, Nano Lett. **5**, 1029 (2005).
[29] G. Bergmann, Phys. Rep. **107**, 1 (1984).
[30] M. Henzler, T. Luer, and J. Heitmann, Phys. Rev. B **59**, 2383 (1999).
[31] Y. Shapira and G. Deutscher, Phys. Rev. B **27**, 4463 (1983).
[32] I. S. Beloborodov, A. V. Lopatin, V. M. Vinokur, and K. B. Efetov, Rev. Mod. Phys. **79**, 469 (2007).
[33] F. Hernandez-Ramirez *et al.*, Phys. Rev. B **76**, 085429 (2007).
[34] A. A. Abriskosov, *Fundamentals of the Theory of Metals* (North-Holland, Amsterdam, 1988).
[35] J. Wang, C. Shi, M. Tian, Q. Zhang, N. Kumar, J. K. Jain, T. E. Mallouk, and M. H. W. Chan, Phys. Rev. Lett. **102**, 247003 (2009).
[36] A. Falk, M. M. Deshmukh, A. L. Prieto, J. J. Urban, A. Jonas, and H. Park, Phys. Rev. B **75**, 020501(R) (2007).