Dissipation in an ultrathin superconducting single-crystal Pb nanobridge

Jian Wang,[1,2,a)] Xu-Cun Ma,[1] Yun Qi,[1] Shuai-Hua Ji,[1] Ying-Shuang Fu,[1] Li Lu,[1] Ai-Zi Jin,[1] Chang-Zhi Gu,[1] X. C. Xie,[1,3] Ming-Liang Tian,[2] Jin-Feng Jia,[1,4] and Qi-Kun Xue[1,4,b)]
[1]*Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China*
[2]*Department of Physics and the Center for Nanoscale Science, Pennsylvania State University, University Park, Pennsylvania 16802-6300, USA*
[3]*Department of Physics, Oklahoma State University, Stillwater, Oklahoma 74078, USA*
[4]*Department of Physics, Tsinghua University, Beijing 100084, China*

(Received 7 April 2009; accepted 29 June 2009; published online 3 August 2009)

The transport property of a superconducting Pb nanobridge, which is carved by focus ion beam technique from an atomically flat single-crystal Pb thin film grown on Si(111) substrate, is investigated. Below the superconducting transition temperature T_C, the nanobridge exhibits a series of sharp voltage steps as a function of current. The multiple voltage steps are interpreted as a consequence of spatially localized phase slip centers or hot-spot formation in the bridge. Just below the critical current, the voltages versus current curve shows a power-law behavior in the low temperature region, but Ohmic near the T_C. The thermally activated phase slip, quantum phase slip, and imhomogeneity in a one-dimensional superconducting system may contribute to the observed results. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3187908]

I. INTRODUCTION

When the thickness of a superconducting film or the diameter of a superconducting nanowire is reduced smaller than the Ginsburg-Landau phase coherence length (ξ) and the magnetic penetration depth (λ), the superconductivity of the film or nanowire exhibits quasi-two-dimensional (quasi-2D) or quasi-one-dimensional (quasi-1D) behaviors.[1–13] Compared to its bulk partner, the resistance of a 1D wire is no longer zero near or below the superconducting transition temperature. The nonzero dissipation has been attributed to thermally activated phase slip (TAPS) or quantum phase slip (QPS) process.[14–18] By applying an excitation current, the 1D wires can transform from superconducting state to normal state. One of the most striking features with this transition is the phase slip induced multiple steps in the voltage-current curve.[19–23] For quasi-2D crystalline films, oscillatory superconductivity modulated by quantum size effects was recently reported.[7–10,12] In addition, some interesting superconductivity behaviors related to the size confinement effect in nanobridges were also observed.[24,25]

Here, the nanobridges were made from the thin films with a thickness of up to ~10 nm. Their width is typically several hundred nanometers and is larger than the superconducting coherence length (~27 nm) of the Pb film.[25] In this work, the transport property of such nanobridge has been studied. The nanobridge we selected has a dimension of 30 atomic monolayers (ML) (thickness)$\times$350 nm(width) $\times$2 μm(length) and the effective diameter is 55 nm (equivalent cross section is about 55×55 nm^2), which is less than the superconducting coherent length of bulk Pb at 0 K, $\xi_0^{\text{bulk}}=90.5$ nm and the size confinement effect is expected. We found that the *V-I* curves obey a power law relation below the critical current, while above it multiple steps appear in approaching the normal state.

II. EXPERIMENT

Our experiments were conducted with an ultrahigh vacuum low-temperature scanning tunneling microscopy (STM) system integrated with a molecular beam epitaxy (MBE) chamber (Unisoku USM1300). The base pressure of the system is better than 1.0×10^{-10} Torr. Clean Si(111)-7 $\times$7 surfaces were prepared by standard high temperature flashing at 1200 °C for several seconds. As reported previously,[25,26] high quality single-crystal Pb films were grown on the clean Si (111) substrates in the MBE chamber. To obtain atomically flat Pb thin films over a macroscopic area, the Si substrates were cooled down to ~95 K by liquid nitrogen (LN_2). Pb with a purity of 99.999% was evaporated at a flux rate of 0.32 ML/min. A reflection high-energy electron diffraction (SPECS RHD-30) was used to monitor the growth and calibrate the deposition rates. All STM topography images were recorded at 80 K with a constant current of 100 pA.

Figure 1(a) shows a typical STM topographic image of a Pb film with a thickness of 30 ML. The steps seen on the image are all one atomic ML high. A bridge was carved from the film by a commercial focused ion beam etching and depositing system (FEI-DB235), as schematically shown in Fig. 1(b). The etching current was set less than 10 pA to minimize contamination and structure damage by the Ga ions. Four indium electrodes with Au wires of 25 μm in diameter were made and connected to the surface of the two parts of the film for transport measurements [see Fig. 1(b)].

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

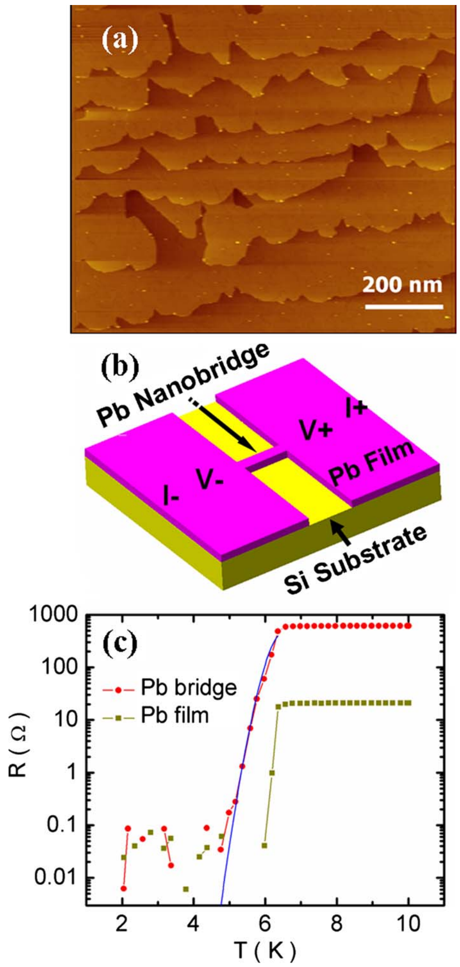

FIG. 1. (Color online) (a) A scanning tunneling microscope image of the 30 ML single-crystal Pb thin film grown on the Si(111)-7×7 substrate. (b) The schematic for transport measurement across a Pb nanobridge. (c) Resistance of the Pb nanobridge as a function of temperature measured from the Pb bridge and the Pb film. The solid blue curve is a fitting of TAPS resistance dependence near T_C (Ref. 27). The fitting parameters γ_1 and γ_2 are 0.14 and 288.24, respectively.

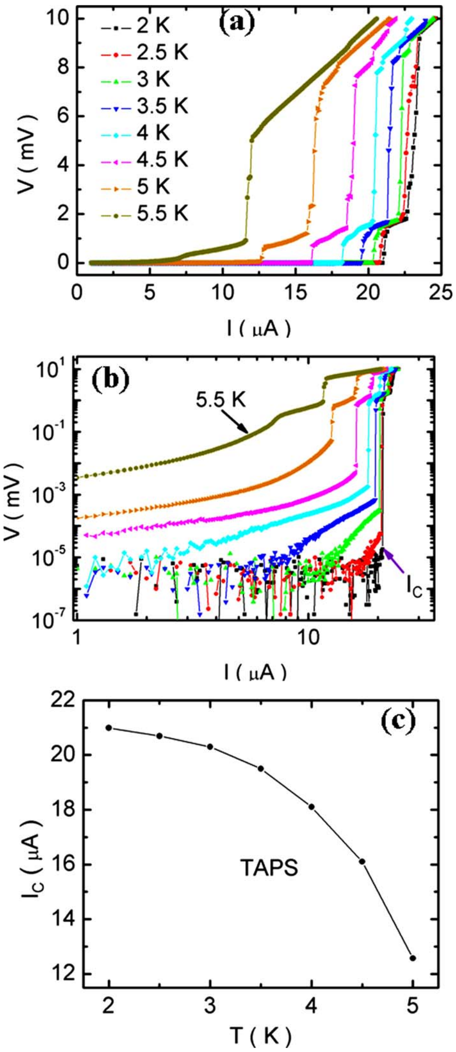

FIG. 2. (Color online) (a) Voltage vs current curves of the Pb nanobridge measured at different temperatures in linear scale. (b) Log V vs log I curves at different temperatures showing details in low current regime. (c) I_C vs T plot.

III. RESULTS AND DISCUSSION

Figure 1(c) shows resistance versus temperature (R-T) curves of the Pb bridge (30 ML×350 nm×2 μm) and the 30 ML thick Pb film. Both the bridge and film exhibit superconducting transition and zero residual resistance (defined as a resistance smaller than the instrumental resolution of +/−0.1 Ω). It is worth noting that the transition region of the bridge (4.76–6.36 K) is much wider than that of the film. In quasi-1D superconducting nanowires, the broadening of the transition near T_C has been reported and interpreted as a consequence of a TAPS process.[21] For the Pb nanobridge, we were able to fit the data well [the solid blue curve in Fig. 1(c)] by using the formula[27] of the TAPS model, which indicates quasi-1D superconductivity in the bridge.

The voltage-current (V-I) characteristics were measured at different temperatures. The result is shown in Fig. 2(a). Several steps are observed during the transition to the normal state. The multiple stepped V-I characteristic is a common feature in the electrical transport property of quasi-1D superconducting systems[20,21] and was interpreted as a result of spatially localized phase slip centers (PSCs) due to the local defects or imperfections in the nanowires. When the excitation current exceeds the local critical current of a specific PSC, a step in voltage is created.

Nevertheless, normally the phase slip formation is valid very close to T_C but our measurement temperature is apparent lower than T_C. Another possible origin for the observed voltage steps is the current-induced nonequilibrium process in the Pb bridge since the shape of V-I dependencies can be determined by hot-spot formation at lower temperatures in quasi-1D superconductors.[28]

Figure 2(b) shows the V-I curves in Fig. 2(a) in log-log scale. Just below the critical current (I_C), a small finite resistance is noted, which is different from the zero resistance state below I_C in bulk or 2D film. The most interesting feature is that the curves below the I_C exhibit a power-law behavior, $V \sim I^{\alpha}$ when the temperature is below 4.0 K. The value of the current at the initial point of the voltage jump in the V-I curve is defined as a critical current I_C [see Fig. 2(b)]. However, the power α is temperature dependent, which is 12, 8, and 4 for T=2.5, 3.0, and 3.5 K, respectively. The power-law relationship is consistent with the QPS model in the low current limit at the temperatures far below T_C in a superconducting nanowire.[29] Recently, quantum fluctuations in ultranarrow superconducting Al nanowires have been reported and a QPS model was suggested to fit the *V-I* characteristic at $I<I_C$.[30] In the high-current limit, $V\sim I^{2\gamma-1}$, where the dimensionless conductance $\gamma=R_Q/R_{qp}$ is related to the effective "quasiparticle" resistance R_{qp} and quantum resistance $R_Q=h/(4e^2)=6.47$ kΩ, being associated with dissipation provided by the quasiparticle channel. R_{qp} can be considered as a fitting parameter and should be of the order of the normal-state resistance. According to the above relations, at $T=2.5$, 3.0, and 3.5 K, we are able to fit the *V-I* data below I_C with the parameter R_{qp} at 995 Ω, 1.4 kΩ, and 2.6 kΩ, respectively, which are same order of the normal-state resistance of the Pb bridge at 8 K (612 Ω).

Although we can use the QPS mechanism to explain the power law *V-I* plots below I_C and T_C, we have to note that the QPS induced broadening of the low-*T* part of the *R-T* dependence was not observed [see Fig. 1(c)]. Maybe the QPS induced *R-T* behavior is within the instrumental resolution of +/−0.1 Ω or some other mechanisms are crucial for the observed *V-I* phenomena.

At higher temperatures (4.5, 5, and 5.5 K), the power law phenomenon decays and the bridge becomes Ohmic in the low current regime ($I<3$ μA). The result is similar to the property of 20 nm Sn nanowires reported by Tian *et al.*,[21] which was interpreted by the TAPS model close to T_C. On the other hand, close to I_C (above 3 μA) the *V-I* curves deviate from the Ohmic behavior. Currently, we do not have a good explanation for this. Figure 2(c) shows a plot of I_C as a function of temperature. When the excitation currents are smaller than I_C, the dissipations are governed by TAPS process,[21] which is confirmed by the TAPS induced transition broadening near T_C [Fig. 1(c)].

The *V-I* curves measured in different magnetic fields at 4.3 K are shown in Figs. 3(a) and 3(b). The magnetic field was applied perpendicularly to the film surface. In the low current regime, voltage steps and finite resistance were seen and the *V-I* characteristic also obeys a power law. The difference here is that with increasing magnetic field the power α increases first and then decreases: 1.3 at zero field, 1.9 at 1 kOe, 1.3 at 2 kOe, and 1.2 at 3 kOe. We hope this phenomenon will inspire further theoretical and experimental effort.

Though the MBE technique was used for fabrication of the samples, it does not automatically guarantee homogeneity of the Pb nanobridges. There might be some parasitic contributions degrading the quality of the samples. Even in the best case of structurally perfect superconducting nanostructures, there exists a well-known effect: variation of the local T_C with size.[31] Here, the utilized geometry of a relatively short nanobridge between much wider contacts [see Fig. 1(b)] is particularly sensitive to that phenomenon. If that is the case, the superconducting order parameter can vary along the wire disabling an adequate interpretation of the data using idealized models derived for uniform systems.[32] Imhomogeneous superconductivity in the Pb nanobridges may be crucial for our experimental observations.

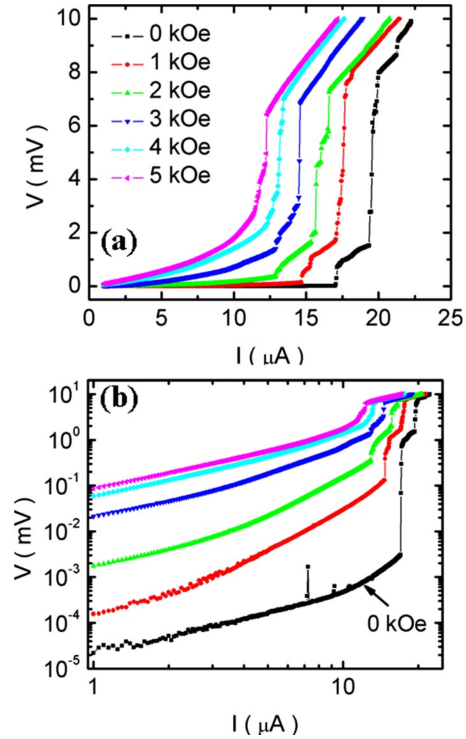

FIG. 3. (Color online) (a) Voltage vs current curves of the Pb nanobridge measured at different magnetic fields in linear scale. (b) Log *V* vs log *I* curves at different magnetic fields showing details in low current regime.

IV. CONCLUSION

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. Therefore, superconducting nanodevices are predominately prepared or fabricated on semiconductor substrates. Along this line, integration of the superconducting interconnecting nanocircuits with Si is of great interest. We report the transport property of single-crystal Pb nanobridges on Si wafers. Interesting physical properties such as sharp voltage steps and power-law *V-I* behavior were observed. Although some behaviors are not well understood at the moment, the results suggest that the single-crystal Pb nanobridges not only provide a domain for research on low dimensional superconductivity, but also offer an opportunity for integrating superconducting circuits in silicon chips.

ACKNOWLEDGMENTS

We thank Dr. Quantong Shen, Dr. Tiezhu Han, Dr. Peng Jiang, Dr. Lili Wang, and Shaokui Su for the help in sample preparation and transport measurement. This work was financially supported by the National Science Foundation and Ministry of Science and Technology of China and the Penn State MRSEC under NSF Grant No. DMR-0820404.

[1] A. V. Herzog, P. Xiong, F. Sharifi, and R. C. Dynes, Phys. Rev. Lett. **76**, 668 (1996).
[2] M. Tian, N. Kumar, S. Xu, J. Wang, J. S. Kurtz, and M. H. W. Chan, Phys. Rev. Lett. **95**, 076802 (2005).
[3] K. Y. Arutyunov, D. S. Golubev, and A. D. Zaikin, Phys. Rep. **464**, 1 (2008).
[4] M. Zgirski, K.-P. Riikonen, V. Touboltsev, and K. Arutyunov, Nano Lett.

5, 1029 (2005).
[5]A. Johansson, G. Sambandamurthy, D. Shahar, N. Jacobson, and R. Tenne, Phys. Rev. Lett. **95**, 116805 (2005).
[6]F. Altomare, A. M. Chang, M. R. Melloch, Y. Hong, and C. W. Tu, Phys. Rev. Lett. **97**, 017001 (2006).
[7]Y. Guo, Y. F. Zhang, X. Y. Bao, T. Z. Han, Z. Tang, L. X. Zhang, W. G. Zhu, E. G. Wang, Q. Niu, Z. Q. Qiu, J. F. Jia, Z. X. Zhao, and Q. K. Xue, Science **306**, 1915 (2004).
[8]T.-C. Chiang, Science **306**, 1900 (2004).
[9]Y. F. Zhang, J. F. Jia, T. Z. Han, Z. Tang, Q. T. Shen, Y. Guo, Z. Q. Qiu, and Q. K. Xue, Phys. Rev. Lett. **95**, 096802 (2005).
[10]X. Y. Bao, Y. F. Zhang, Y. P. Wang, J. F. Jia, Q. K. Xue, X. C. Xie, and Z. X. Zhao, Phys. Rev. Lett. **95**, 247005 (2005).
[11]M. M. Ozer, J. R. Thompson, and H. H. Weitering, Nat. Phys. **2**, 173 (2006).
[12]D. Eom, S. Qin, M.-Y. Chou, and C. K. Shih, Phys. Rev. Lett. **96**, 027005 (2006).
[13]J. Wang, X. C. Ma, Y. Qi, Y. S. Fu, S. H. Ji, L. Lu, J. F. Jia, and Q. K. Xue, Appl. Phys. Lett. **90**, 113109 (2007).
[14]W. A. Little, Phys. Rev. **156**, 396 (1967).
[15]J. E. Lukens, R. J. Warburton, and W. W. Webb, Phys. Rev. Lett. **25**, 1180 (1970).
[16]N. Giordano, Phys. Rev. Lett. **61**, 2137 (1988).
[17]C. N. Lau, N. Markovic, M. Bockrath, A. Bezryadin, and M. Tinkham, Phys. Rev. Lett. **87**, 217003 (2001).
[18]A. Rogachev, A. T. Bollinger, and A. Bezryadin, Phys. Rev. Lett. **94**, 017004 (2005).
[19]D. Y. Vodolazov, F. M. Peeters, L. Piraux, S. Matefi-Tempfli, and S. Michotte, Phys. Rev. Lett. **91**, 157001 (2003).
[20]A. Rogachev and A. Bezryadin, Appl. Phys. Lett. **83**, 512 (2003).
[21]M. Tian, J. Wang, J. S. Kurtz, Y. Liu, and M. H. W. Chan, Phys. Rev. B **71**, 104521 (2005).
[22]M. Tian, J. Wang, N. Kumar, T. Han, Y. Kobayashi, Y. Liu, T. E. Mallouk, and M. H. W. Chan, Nano Lett. **6**, 2773 (2006).
[23]A. Falk, M. M. Deshmukh, A. L. Prieto, J. J. Urban, A. Jonas, and H. Park, Phys. Rev. B **75**, 020501(R) (2007).
[24]M. Hermele, G. Refael, M. P. A. Fisher, and P. M. Goldbart, Nat. Phys. **1**, 117 (2005).
[25]J. Wang, X. C. Ma, L. Lu, A. Z. Jin, C. Z. Gu, X. C. Xie, J. F. Jia, X. Chen, and Q. K. Xue, Appl. Phys. Lett. **92**, 233119 (2008).
[26]J. Wang, X. C. Ma, Y. Qi, Y. S. Fu, S. H. Ji, L. Lu, X. C. Xie, J. F. Jia, X. Chen, and Q. K. Xue, Nanotechnology **19**, 475708 (2008).
[27]Following Ref. 21, we use $R_{\mathrm{TAPS}}=\gamma_1\pi\hbar^2\Omega_{\mathrm{TAPS}}/(2e^2k_BT)e^{-\gamma_2\Delta F/k_BT}$. γ_1 and γ_2 are the fitting parameters.
[28]R. Tidecks, *Current-Induced Nonequilibrium Phenomena in Quasi-One-Dimensional Superconductors* (Springer, New York, 1990).
[29]A. D. Zaikin, D. S. Golubev, A. van Otterlo, and G. T. Zimanyi, Phys. Rev. Lett. **78**, 1552 (1997).
[30]M. Zgirski, K.-P. Riikonen, V. Touboltsev, and K. Yu. Arutyunov, Phys. Rev. B **77**, 054508 (2008).
[31]A. A. Shanenko, M. D. Croitoru, M. Zgirski, F. M. Peeters, and K. Arutyunov, Phys. Rev. B **74**, 052502 (2006).
[32]M. Zgirski and K. Yu. Arutyunov, Phys. Rev. B **75**, 172509 (2007).