PHYSICAL REVIEW B, VOLUME 63, 054523

Electronic transport and possible vortex states at $T=0$ in highly disordered ultrathin films of a-Mo$_x$Si$_{1-x}$

Satoshi Okuma, Satoshi Shinozaki, and Makiko Morita
Research Center for Very Low Temperature System, Tokyo Institute of Technology, 2-12-1, Ohokayama, Meguro-ku, Tokyo 152-8551, Japan

(Received 4 August 2000; published 16 January 2001)

We present transport properties of highly disordered thin and thick films of amorphous Mo$_x$Si$_{1-x}$ at low temperatures. For thin films an anomalous peak and a subsequent decrease in the magnetoresistance (MR) have been observed on the insulating side ($B>B_C$) of the field-driven superconductor-insulator transition, while for thick films, or for thin films in parallel fields the MR is always monotonic and positive. In $B<B_C$ the metallic quantum-vortex-liquid phase is not evident, most likely absent. We interpret these results in terms of the two-dimensional quantum phase transition. Alternative interpretations of the data are also discussed.

DOI: 10.1103/PhysRevB.63.054523 PACS number(s): 74.25.Dw, 74.40.+k, 74.60.Ec

The superconductor-insulator (SI) transition in two dimensions (2D) continues to attract intense experimental[1–19] and theoretical[20–22] interest. Despite numerous effort, the basic picture of the SI transition has not been fully established. In some 2D superconductors a novel insulating phase indicative of the presence of the localized Cooper pairs has been observed just above the zero-field ($B=0$) (Refs. 7,12,17) and field-driven[4,7,15,16,19] SI transitions. Within a dirty boson model,[20] this unusual insulating phase has been interpreted as the Bose-glass insulator, where Cooper pairs are localized and vortices are Bose condensed. In the meanwhile, a distinct metallic phase at zero temperature ($T=0$) has been reported in other 2D systems in the field region just below the field-driven SI transition ($B<B_C$).[10,11] This result seems to be serious, since the picture of the SI transition might be questioned. Theoretically, the existence of the $T=0$ metallic phase is not compatible with the picture of the Bose-glass insulator which assumes the duality between Cooper pairs and vortices, while both phases originate from quantum vortex liquid. Experimentally, it is thus important to understand the 2D SI transition from the viewpoint of the vortex states at $T=0$.

In this paper we have made transport measurements for a series of 4-nm-thick films of amorphous (a)-Mo$_x$Si$_{1-x}$ (Refs. 14,15,23,24) near the zero-field and field-driven SI transitions down to $T\sim 0.04$ K. This system is identical to the one used in the previous studies,[15] where we observed an anomalous peak in the magnetoresistance (MR) $R(B)$ and a subsequent decrease in $R(B)$ with increasing B suggesting the presence of the localized Cooper pairs on the insulating side of the field-driven SI transition ($B>B_C$). Based on the results we proposed the possibility that the anomalous field region corresponds to the Bose-insulator phase. To prove this interpretation, however, detection of flux motion is essential. Thus, in this study we have carried out MR measurements in fields both perpendicular and parallel to the film surface. The thick (100, 300 nm) films have been also measured to study the effects of dimensionality.

The a-Mo$_x$Si$_{1-x}$ films used in this study were prepared by coevaporation of pure Mo and Si in the pressure better than 10^{-8} Torr. To obtain a series of samples with continuously changing x (along the length of a film) at a fixed thickness, we used gradient deposition technique.[14] The structure of the selected films was confirmed to be amorphous by means of transmission electron microscopy. The resistance R was measured by standard four-terminal dc and ac locking methods with a current $I\sim 10$ nA. For resistive films, we measured the current-voltage characteristics at ~ 0.05 K and checked Ohmic behavior at a measurement current. The field was applied both perpendicular B and parallel $B_\parallel$ to the film surface. In parallel fields, the current was also parallel to the field direction. The transport data for a series of 4-nm-thick films (films 1–10) has been presented in Ref. 15.

Figures 1(a) and 1(b) depict the MR for perpendicular field B above the critical field B_C for the thin (4-nm-thick) film 4 with $x=44$ at.% and thick (300-nm-thick) film with $x=54$ at.%, respectively. Here, B_C is defined as a field where $R(T)$ at low T is temperature independent. At $T\geqslant 0.3$ K the MR is always monotonic and positive for both films. However, for thin superconducting films an anomalous peak in the MR and a subsequent decrease in $R(B)$ with increasing B have been commonly observed below about 0.3 K irrespec-

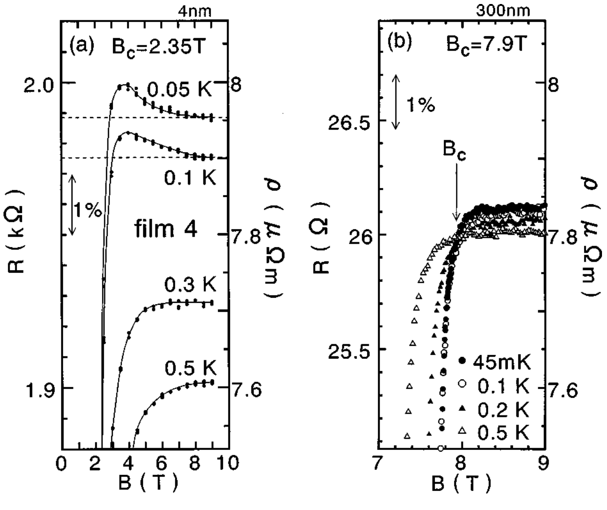

FIG. 1. High R regions of MR for (a) the 4-nm-thick film 4 and (b) 300-nm-thick film at different T. B_C is defined as a field where $R(T)$ at low T is temperature independent.

tive of disorder $\rho_n = 3.2–7.6\ \mu\Omega$ m, where ρ_n is the normal-state resistivity at 10 K. From this result, together with the finding that the MR is always positive for thin insulating films 5–10, the origin of the peak in the MR has been sought for the localized Cooper pairs present on the insulating side of the field-driven SI transition rather than the delocalization effect of unpaired electrons.[15] Since the peak in the MR is only visible at very low temperature, its origin has been attributed to quantum fluctuations (or the Bose-glass insulator). In contrast to thin films, the MR for the thick film is always monotonic and positive, and the anomalous peak in the MR is not observed down to the lowest temperature ($\sim$0.045 K). This cannot be attributed to the different strength of disorder between thick and thin films, since the degree of disorder $\rho_n = 7.8\ \mu\Omega$ m for the thick film is close to that $\rho_n = 7.2\ \mu\Omega$ m for the thin film. We have also found that the MR for the 100-nm-thick superconducting film with $\rho_n = 4.6\ \mu\Omega$ m ($x = 44$ at. %) is monotonic and positive at any T down to $\sim$0.04 K, while the peak in the MR is observed at $\sim$0.05 K for the 4-nm-thick film 1 ($x = 61$ at. %) with much less disorder ($\rho_n = 3.2\ \mu\Omega$ m).

These results indicate that the two dimensionality plays an important role in the appearance of the peak in the MR at $B > B_C$. Within the dirty-boson model of Fisher,[20] the field region where the resistance drop with B is observed corresponds to the Bose-glass insulator. To prove this interpretation, detection of the quantum-mechanically melted vortices in the "Bose-glass phase" is essential. Thus we have made MR measurements of film 4 for parallel field orientation. In parallel field $B_\parallel$ the contribution of MR from the motion of the field-induced vortices is negligible, as will be discussed in more detail below. If the peak in the MR was also observed in parallel fields, its origin would not be sought for flux motion.

Except for the enhanced field scale, R-$B_\parallel$ curves look similar to R-B curves; the critical field for the parallel orientation is $B_{\parallel C} = 5.7$ T, which is larger than $B_C = 2.35$ T for the perpendicular orientation.[25] However, the peak in the MR observed in perpendicular field is no longer visible in parallel field as shown in Fig. 2. This result looks consistent with the view that mobile vortices, as well as the localized Cooper pairs, are present in the insulating region where the resistance drop with increasing B is observed. Within this picture the absence of a peak in $R(B_\parallel)$ can be understood as follows: For perpendicular field, at B_C there is a Bose-glass insulator with localized Cooper pairs and mobile vortices. At some field that is higher, either at B_p or $B^*(0)$ defined later, the Bose insulator goes to a Fermi insulator. Below B_p or $B^*(0)$ but above B_C there is a nonvanishing order parameter amplitude. On the other hand, a parallel field couples to the amplitude of the order parameter, and does not primarily control phase fluctuations. Above $B_{\parallel C}$ there is no order parameter amplitude and thus no Bose-glass insulator that can be disrupted at higher fields. Thus R in this configuration would be a monotonic function of field.

We next focus on the field region lower than B_C for the thin superconducting films 1–4 and discuss the possibility of the metallic quantum-vortex-liquid (QVL) phase that has been claimed by other groups.[10,11] An Arrhenius-type resistance $R(T)$ is commonly observed in finite (perpendicular) fields $B < B_C$; i.e., $R(T,B) = R_0 \exp[-U(B)/T]$, where R_0 is a constant independent of T and weakly dependent on B except for $B \sim B_C$. The result for film 4 is typically shown in Fig. 3(a): $R(T)$ follows the above equation in $B = 0.1–1.7$ T below $B_C = 2.35$ T; however, in $B \geqslant 1.0$ T the slope of the straight line [i.e., activation energy $U(B)$] shows a discontinuous drop below about 0.1 K. Such a drop in the slope is no longer visible for the most conductive film 1, suggesting that disorder may play a role in the reduction of the activation energy at very low temperatures.

Shown in Fig. 3(c) is the activation energy $U(B)$ plotted against $\log B$. For $B \geqslant 1.0$ T we plot U's obtained from the

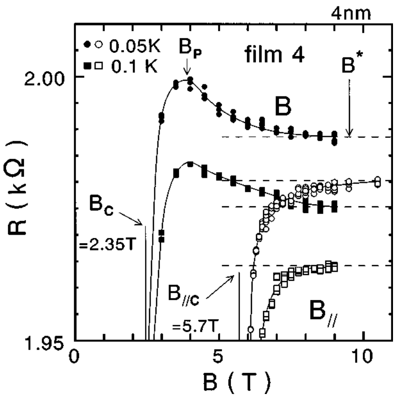

FIG. 2. High R regions of MR for film 4 at $T = 0.05$ and 0.1 K. The field is applied perpendicular B and parallel $B_\parallel$ to the film surface. B_p and B^* are characteristic fields at which the peak in $R(B)$ occurs and above which the decrease in $R(B)$ is no longer visible, respectively.

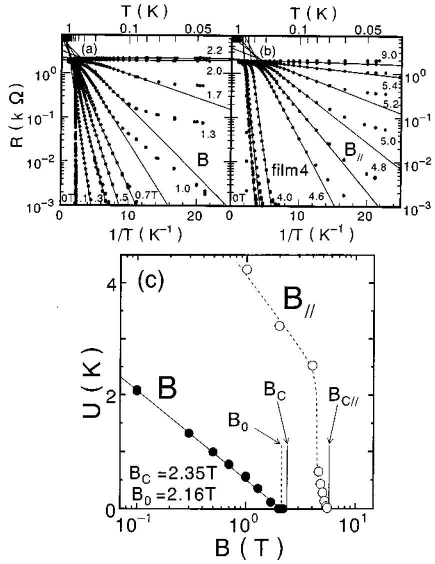

FIG. 3. Arrhenius plot of $R(T)$ for film 4 in various (a) perpendicular B and (b) parallel $B_\parallel$ fields. (c) Activation energies (●) derived from the slope of the straight lines in (a) plotted against $\log B$. The slope (○) of the straight lines in (b) is also plotted for comparison.

data at $T>0.1$ K, since we have found that the decrease in the slope at $T<0.1$ K does not originate from flux motion, as will be shown below. Over the broad B the data points follow the functional form, $U(B)\propto\ln(B_0/B)$, predicted by the dislocation model.[26] A characteristic field B_0 at which $U(B)$ extrapolates to zero is 2.16 T, which is slightly lower than (or very close to) $B_C=2.35$ T. In parallel fields $B_\parallel$ seemingly activated behavior is also seen, such as shown in Fig. 3(b). However, plotting the slope as a function of $B_\parallel$ in Fig. 3(c), we find that it never obeys the $\ln B$ formula. This result confirms us that R in the presence of perpendicular field is indeed dominated by flux motion. It is important to note that the sudden decrease in the slope at $T<0.1$ K is also seen in parallel field, indicating that its origin is *not* related to flux motion.

The logarithmic field dependence of $U(B)$ as well as the activated resistance has been also reported in other thin film (2D) superconductors.[10,11] However, the reported values of B_0 are substantially smaller than the values of B_C; e.g., $B_0/B_C=0.64$ and 0.65–0.87 for a thin a-MoGe film[10] and thin Bi/Sb films,[11] respectively. From these results the existence of the metallic QVL regime ($B_C>B>B_0$) has been proposed in these systems. Although we cannot definitely exclude the possibility of the QVL regime from our data, the following facts suggest that such a regime is likely to be absent in our system: (1) B_0 is very close to B_C ($B_0/B_C>0.9$) even for the highly disordered films which lie in the vicinity of the zero-field SI transition. (2) The values of B_0/B_C are nearly independent of disorder over the broad range ($\rho_n=3.2$–$7.6\ \mu\Omega$ m). These results are in contrast to the results reported by other groups. Furthermore, (3) it is questionable whether we can claim the existence of the QVL phase based on the value of B_0 which has been determined from the linear extrapolation, such as shown in Fig. 3(c), when $B_0\approx B_C$.

In a-MoGe (Ref. 10) and a-NbGe (Ref. 13) films the temperature-independent resistance (the so-called ''flat tail'') has been observed at low temperatures over the broad B region below B_C. This result has been interpreted as evidence for quantum tunneling or quantum creep of *vortices*. We have not found the finite temperature-independent $R(T)$ from the measurements down to $T\sim0.04$ K for any field ($<B_C$) studied, while the tendency of $R(T)$ to flatten is visible (only) for highly disordered films, as seen in Fig. 3(a). We note that the deviation from the activated behavior occurs at lower temperatures in the presence of higher magnetic fields, which is in accord with the result for a-MoGe.[10] These results seem to suggest that the deviation of $R(T)$ observed in our system might have the same origin as the flat tail reported in other superconductors. However, this is not consistent with the present result described above that the deviation of $R(T)$ from the activated behavior does not originate from flux motion. The origin should be clarified in the future studies, while it is important to perform the transport measurements in parallel fields for other superconductors in which the flattening of the resistance is observed in perpendicular fields. This will offer further proof for the QVL phase.

In Fig. 4 we illustrate the field-disorder ($B-R_n$) phase diagram for the zero-field and field-driven SI transitions in 2D at zero temperature, which has been constructed based on the data for six thin films with different x; $x=61$, 54, 50, 44, 42, and 39 at. % (from left to right). Here, R_n is the normal-state sheet resistance at 10 K. We can see that the field region $B_C>B>B_0$ is too narrow to claim strongly the existence of the metallic QVL phase. Within the Fisher's model, B_C is interpreted as a phase boundary separating the vortex-glass phase[27] and Bose-insulator phase. The $T=0$ characteristic field B^* above which the decrease in MR is no longer visible is nearly identified with B_{C2}, where both the localized Cooper pairs and mobile vortices disappear. Plotted in Fig. 4 is $B^*(T)$ extracted from the MR data at $T=0.05$ K. We notice from Fig. 2 that B^* appears to be strongly temperature dependent in the limit of $T=0$. Upon cooling from 0.1 to 0.05 K, the amplitude of the peak in $R(B)$ becomes more pronounced (i.e., B^* shows a trend to decrease at $T\rightarrow0$), while the field B_p at which the peak occurs stays almost unchanged. Therefore $B^*(T)$ in the limit of $T=0$ is more likely to be close to B_p (or $B_{\parallel C}$) rather than $B^*(0.05\text{ K})$.

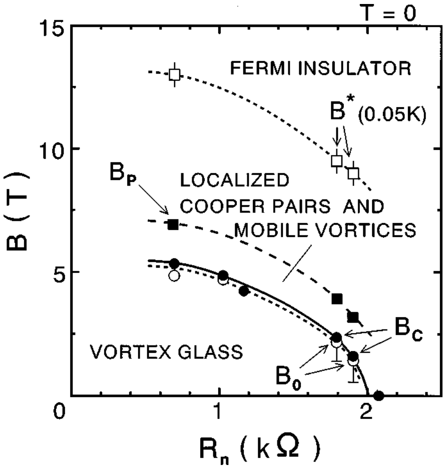

FIG. 4. B-R_n phase diagram for the zero-field and field-driven SI transitions in 2D at $T=0$. Within a dirty boson model B_C is interpreted as a phase boundary separating the vortex-glass and Bose-insulator phases. $B^*(T\rightarrow0)$ around which both the localized Cooper pairs and mobile vortices disappear is considered to be close to B_p rather than $B^*(0.05\text{ K})$.

An anomalous peak in the perpendicular MR has been also observed in granular films,[2,5] whose origin is related to destruction of local superconductivity within each grain. In contrast to our films, however, for granular films the peak is clearly visible even in insulating films. We have not obtained particular evidence of granular structure for our films.[15] We note, however, that pure Mo is a superconductor with a transition temperature T_C about 0.9 K, while clusters of Mo in a sample could have different T_C. If there exist such clusters with low T_C which cannot be detected within our experimental resolutions, they may affect the transport at low temperatures, leading to other interpretations of the data. The different behaviors of MR between thin and thick films could be attributed to structural differences rather than to dimensionality.

There are alternative explanations for MR, which could be associated with the morphology of the films, or derived from intrinsic effects. In the model of Ghosal, Randeria, and Trivedi,[22] which addresses the formation of superconducting clusters in a homogeneous system near the SI transition, a perpendicular field could uncouple the clusters. As a result, global superconductivity would disappear and the transport would be dominated by single particle excitations. The resistance would be high because of the energy gap in the excitation spectrum of the quasiparticles in the clusters. At some high field B_p or B^*, the superconductivity (energy gap) within the clusters would be destroyed, resulting in a decrease in $R(B)$. This behavior is similar to what has been observed in granular films or Josephson junction arrays. On the other hand, with the parallel field, decoupling of superconducting clusters does not occur and the onset of resistance corresponds to the full destruction of the superconductivity at $B_{\parallel C}$. This picture looks consistent with the observations of MR presented here, although we have not observed nonlinearities in the I-V characteristics in the regime where the peak in $R(B)$ occurs, within the current range studied.

In summary, we have presented transport properties of highly disordered a-Mo$_x$Si$_{1-x}$ films. For thin films an anomalous peak in the MR and a subsequent decrease in $R(B)$ with increasing B have been observed on the insulating side ($B > B_C$) of the field-driven SI transition, while for thicker films, or for thin films in parallel fields the MR is always monotonic and positive. In $B < B_C$ the metallic quantum-vortex-liquid phase is not evident, most likely absent. We interpret these results in terms of the 2D quantum phase transition. Alternative interpretations based on the idea of the formation of superconducting clusters near the SI transition have been also discussed.

We would like to acknowledge useful conversations with V. F. Gantmakher, G. E. Tsydynzhapov, M. V. Feigel'man, N. Nishida, and R. Ikeda. This work was supported by a Grant-in-Aid for Scientific Research (B) from the Ministry of Education, Science, Sports, and Culture.

---

[1] D. B. Haviland, Y. Liu, and A. M. Goldman, Phys. Rev. Lett. **62**, 2180 (1989).

[2] S. Kobayashi, Physica B **152**, 2236 (1988).

[3] A. F. Hebard and M. A. Paalanen, Phys. Rev. Lett. **65**, 927 (1990).

[4] M. A. Paalanen, A. F. Hebard, and R. R. Ruel, Phys. Rev. Lett. **69**, 1604 (1992).

[5] K. M. Beauchamp *et al.*, Physica B **194-196**, 2321 (1994); T. Wang *et al.*, Phys. Rev. B **47**, 11 619 (1993).

[6] J. M. Valles, Jr. *et al.*, Physica B **197**, 522 (1994).

[7] S. Okuma and N. Kokubo, Phys. Rev. B **51**, 15 415 (1995); **56**, 410 (1997).

[8] A. M. Goldman and Y. Liu, Physica D **83**, 163 (1995).

[9] A. Yazdani and A. Kapitulnik, Phys. Rev. Lett. **74**, 3037 (1995).

[10] D. Ephron *et al.*, Phys. Rev. Lett. **76**, 1529 (1996).

[11] J. A. Chervenak and J. M. Valles, Jr., Phys. Rev. B **54**, R15 649 (1996).

[12] G. Martinez-Arizala *et al.*, Phys. Rev. Lett. **78**, 1130 (1997).

[13] P. H. Kes, M. H. Theunissen, and B. Becker, Physica C **282-287**, 331 (1997).

[14] S. Okuma, T. Terashima, and N. Kokubo, Solid State Commun. **106**, 529 (1998).

[15] S. Okuma, T. Terashima, and N. Kokubo, Phys. Rev. B **58**, 2816 (1998).

[16] V. F. Gantmakher *et al.*, JETP Lett. **68**, 363 (1998).

[17] N. Marković *et al.*, Phys. Rev. Lett. **81**, 701 (1998).

[18] N. Marković, C. Christiansen, and A. M. Goldman, Phys. Rev. Lett. **81**, 5217 (1998).

[19] V. F. Gantmakher *et al.*, Ann. Phys. (Leipzig) **8**, SI73 (1999).

[20] M. P. A. Fisher, Phys. Rev. Lett. **65**, 923 (1990).

[21] R. Ikeda, Int. J. Mod. Phys. B **10**, 601 (1996).

[22] A. Ghosal, M. Randeria, and N. Trivedi, Phys. Rev. Lett. **81**, 3940 (1998).

[23] S. Okuma, S. Shinozaki, and M. Morita, in *Proceedings of the 12th International Symposium on Superconductivity, Morioka, 1999*, editted by T. Yamashita and K. Tanabe (Springer-Verlag, Tokyo, 2000), p. 398.

[24] S. Okuma and N. Kokubo, Phys. Rev. B **61**, 671 (2000).

[25] This is in contrast to the result for the 100-nm-thick film, in which the MR is only weakly dependent on field direction.

[26] M. V. Feigel'man, V. B. Geshkenbein, and A. I. Larkin, Physica C **167**, 177 (1990).

[27] For thick a-Mo$_x$Si$_{1-x}$ films [S. Okuma and M. Arai, J. Phys. Soc. Jpn. **69**, 2747 (2000)], as well as thick In films [S. Okuma and N. Kokubo, Phys. Rev. B **56**, 14 138 (1997)], convincing evidence of the second-order transition is obtained from the ac complex resistivity measurements.