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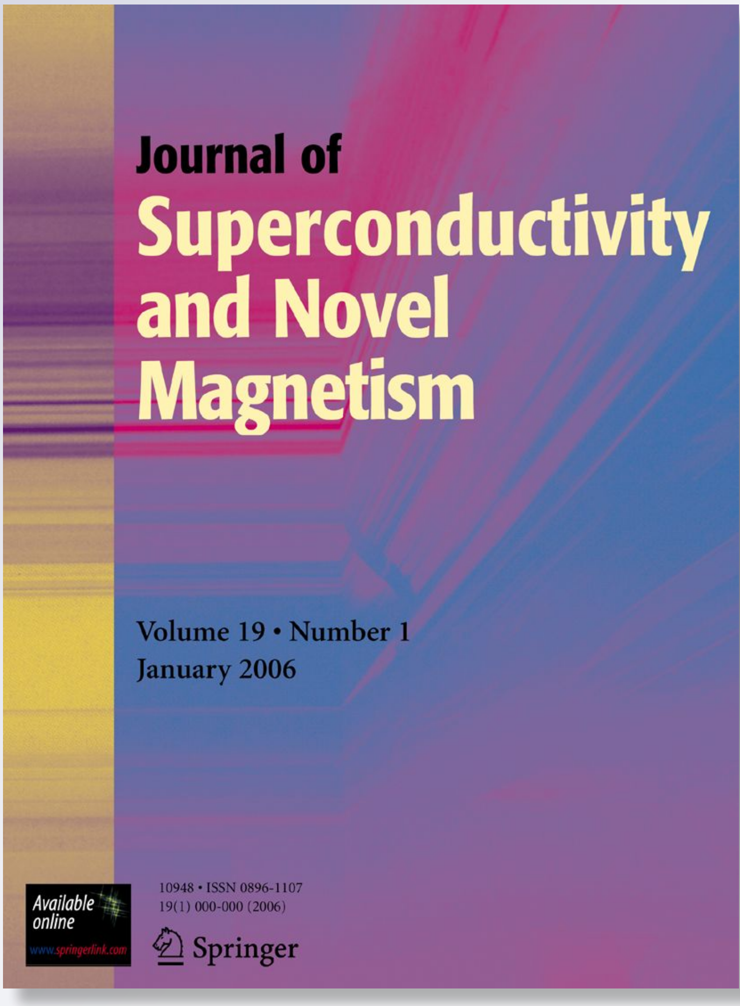

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ORIGINAL PAPER

Observation of Vortex Clustering in Nano-Size Superconducting Pb Island Structures by Low-Temperature Scanning Tunneling Microscopy/Spectroscopy

T. Tominaga · T. Sakamoto · T. Nishio · T. An · T. Eguchi · Y. Yoshida · Y. Hasegawa

Abstract Using low-temperature scanning tunneling microscopy/spectroscopy, we have studied superconductivity and vortex formation on Pb nano-size superconducting island structures by measuring the tunneling conductance at the bottom of the superconducting gap and making its spatial mapping. Peculiar clustering of vortices, which is not observed in large-scale superconductors, is observed in the nanosize superconductors.

Keywords Nanosize superconductor · Scanning tunneling microscopy · Tunneling spectroscopy · Vortex clustering

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1 Introduction

When the size of superconductors is comparable with or smaller than their coherence length, various properties of superconductivity, such as critical temperature or magnetic fields, changes from those of their bulk, depending on their dimensions. Recently, scanning tunneling microscopy/spectroscopy (STM/S) has been utilized to characterize individual nanosize Pb, Sn, or In superconductors [1–8] by directly measuring the superconducting gap on them in order to study their dependences on thickness, size, shape, temperature, applied magnetic field, etc. It has been revealed by the STM/S studies that smaller Pb superconductors have lower critical temperature [4, 7] until the Anderson's critical size, at which quantized energy level separation is comparable with the superconducting gap. Finite size effects were also observed by directly linking the gap with the size and shape of nanosize superconductors [7]. Thickness dependence of the critical temperature has also been studied [1, 5, 6, 9, 10] and in the case of Pb, superconductivity retains even at the ultimate 1 monolayer (ML) thickness [6].

Under magnetic fields, superconducting nanosize Pb thin films or islands have quantized magnetic fluxoids or vortices. Because of interactions between the vortices and the boundaries and among the vortices, nanosize superconducting islands exhibit various unique vortex configurations [8, 11–17], such as vortex clusters, giant vortex, and antivortex. In this paper, we report on our observation of vortices and their various configurations in nanosize Pb islands under magnetic fields using LT-STM.

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2 Experimental

Lead island structures studied in this experiment were formed on a highly doped Si substrate by depositing Pb at low temperature. Details of the sample preparation method are already reported elsewhere [2, 18]. As shown in the STM images presented in this paper, the surface of the islands are basically atomically flat and their height ranges from 7 to 9 ML (1 ML of Pb corresponds to the thickness of 0.284 nm) measured from a wetting layer covering the whole Si substrate. With an assumption of 1 ML wetting layer, the thickness of the Pb islands is 2.3–2.8 nm. Since all the island formation processes were performed in situ in ultrahigh vacuum conditions, the islands have no contamination or oxide layers. In ^{3}He-cooled LT-STM, electrochemically etched W tips were used to take tunneling spectra on the islands at 1.9 K to check their superconductivity. Since in the tunneling spectra the gap opens around the zero sample bias voltage (V) on superconducting area while the gap disappears on the normal area, we utilized the differential tunneling conductance (dI/dV) at $V = 0$ (zero bias conductance; ZBC) as a measure of superconductivity of an area below the probe and made ZBC mappings to observe its spatial distribution. At the vortices, superconductivity is locally broken and, therefore, they are visualized as a high ZBC region in the ZBC mappings [2, 3, 8, 19].

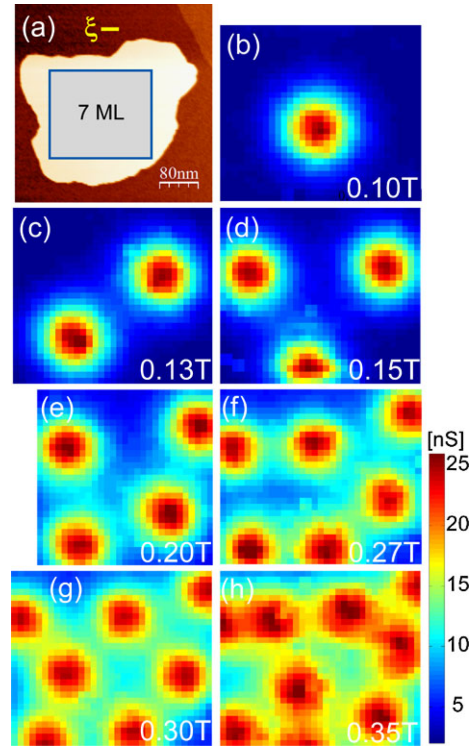

Fig. 1 (**a**) An STM image of a 7 ML thick Pb island. (**b**)–(**h**) ZBC mappings. (**b**)–(**h**) taken on the island under various magnetic fields applied in the direction perpendicular to the island surface. (**b**) 0.10 T, (**c**) 0.13 T, (**d**) 0.15 T, (**e**) 0.20 T, (**f**) 0.27 T, (**g**) 0.30 T, (**h**) 0.35 T

3 Results and Discussion

Figure 1 shows an STM image (a) of a 7 ML thick Pb island and corresponding ZBC mappings (b)–(h) taken under various magnetic fields in rectangular areas, one of which for Figs. 1(b)–(d) is marked in the STM image. The coherence length ξ of Pb thin films with the same thickness, which was estimated from the critical magnetic field and temperature [10], is 34 nm at the measurement temperature, and the length is marked with a yellow line in the STM image. Under magnetic fields applied in the perpendicular direction to the island surface high ZBC regions appear in the ZBC mappings and the number of the high regions increases with the field. Obviously, they correspond to single vortices created by the magnetic field in a superconducting island. Calculated ZBC profile around a vortex located in a two-dimensional superconductor using the Eilenberger equation is compared with the experimental ones and found good agreements between them [2], and the coherence length obtained from the fitting was consistent with the one estimated for thin films. Repulsive interaction among the vortices tends to form a triangular lattice. Repulsive interactions between the vortices and peripheral of the island, however, make the lattice distorted near the periphery, as shown in Fig. 1(e); in the ZBC mapping, the lower-right vortex is pushed toward the center because of the repulsive interaction from the boundary nearby. Since the size of the island is quite large compared with the coherence length, the island can hold more than 10 vortices. In the ZBC mapping taken under rather high magnetic field (0.35 T), the mutual distances among vortices becomes close, and the high ZBC regions due to single vortices are significantly overlapped each other, implying tendency of the vortices to form clusters at the high field (Fig. 1(h)).

The behavior of vortices can also be investigated by measuring ZBC at specific sites on islands as a function of the applied magnetic field. Figure 2 shows the ZBC profile taken at the center (A) and periphery (B) of an island whose size is smaller than that studied in Fig. 1. With an increment of the magnetic field from zero, ZBC increases at the both sites, and the amount of the increase is larger at the peripheral site than the center. The higher ZBC at periphery indicates weaker superconductivity ($\sim$ lower order parameter) and can be explained with the supercurrent circulating the periphery. At 0.2 T, the ZBC at the center suddenly jumps up because of the penetration of a vortex, and the ZBC at the periphery steps down because of relaxation of the magnetic field and the supercurrent by the introduction of the vortex at the center. At 0.27 T (0.34 T), second (third) vortex penetrates into the island and the ZBC values at the two sites also

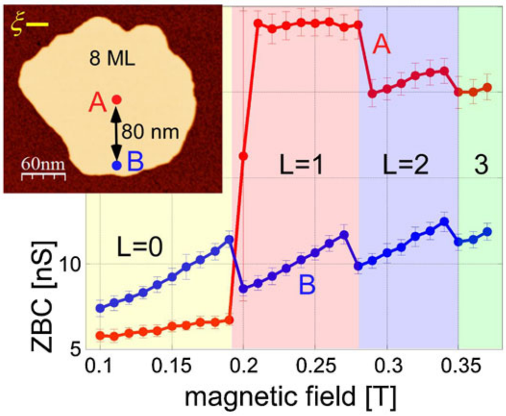

Fig. 2 Zero bias conductance (ZBC) measured at the center (A) and periphery (B) of a Pb island as a function of magnetic field applied in the perpendicular direction. The position of the measured sites is marked in the inserted STM image

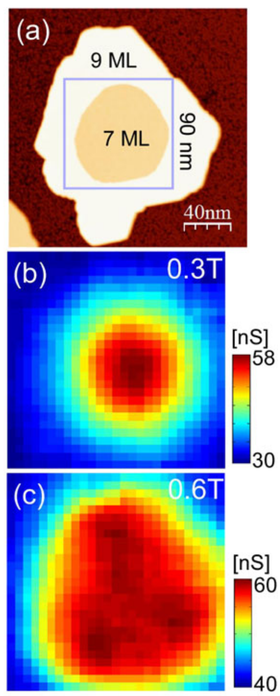

Fig. 3 STM image (**a**) and ZBC mappings ((**b**) 0.3 T, (**c**) 0.6 T) taken on a Pb island having a void structure inside

discretely change accordingly as the additional vortex penetrations induce shift in the position of the previously existing vortices. In this manner, by measuring ZBC and making its mappings under various magnetic fields, we can investigate and visualize behavior of vortices trapped in individual nanosize superconducting island structures.

Using these methods, we have tried to observe various unconventional phenomena unique to nanosize superconductors, such as clustering of vortices, giant vortex, antivortex, etc. A Pb island shown in the STM image of Fig. 3(a) has a void structure (7 ML) whose thickness is thinner than the outer area (9 ML) by 2 ML. Because of reduced condensation energy, a vortex formed in the island can be pinned

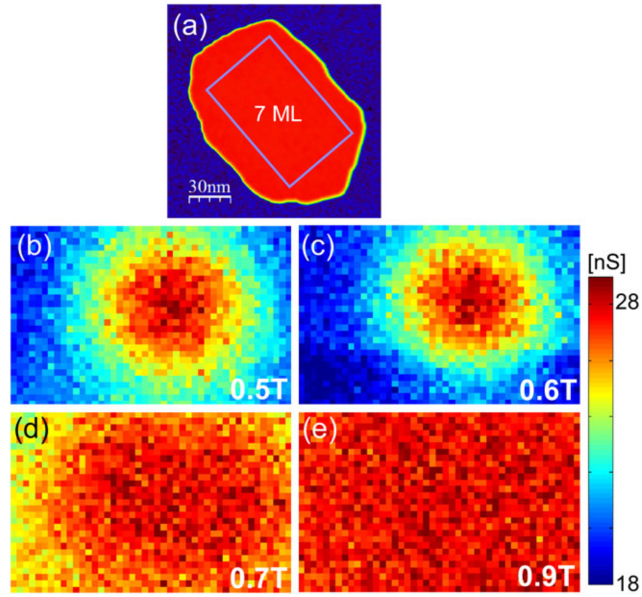

Fig. 4 STM image (**a**) and ZBC mappings (**b**)–(**e**) taken on a Pb island. Magnetic field applied on the sample is (**b**) 0.5 T, (**c**) 0.6 T, (**d**) 0.7 T, and (**e**) 0.9 T

in the void [10], as shown in the ZBC image taken at 0.3 T (Fig. 3(b)) where a single vortex is trapped there. With an increment of the magnetic field, more vortices are trapped in the thinner area, but because of limited area, they form a cluster. In the ZBC mapping shown in Fig. 3(c), which was taken at 0.6 T, triangular-shaped high ZBC area is observed in the void. As the area has three separated peaks, we can safely assign it to a cluster of three vortices. The pinning induced clustering was reported by Grigorieva et al. [17], who observed the phenomenon using the Bitter method at pinning centers which was formed by ion sputtering on Nb superconducting disks. Using STM/STS, detailed size and shape of the pinning sites can be clearly characterized and its correlation with the clustering can be revealed as a function of magnetic field.

Similar vortex clustering was also observed on flat islands whose example is presented in Fig. 4. Figure 4(a) is an STM image and (b)–(e) are ZBC patterns taken in the marked rectangular area under various magnetic fields. After the introduction of a vortex by the applied magnetic field ((b), 0.5 T), the size of the vortex shrinks a little with the magnetic field ((c), 0.6 T) presumably because of the enhanced supercurrent circulating around the periphery of the island. At 0.7 T (d), the shape of the high ZBC area changes into an oval one, implying a significant transition from a single vortex. It is most probably due to cluster formation of two vortices although separated peaks are not clearly observed in this case. It might be a giant vortex which has been theoretically predicted by Deo et al. [12], experimentally detected by Kanda et al. [13], and recently visualized with STM/STS by Cren et al. [8]. Obviously, further experimental and theoretical studies are needed to clarify the identity of the oval high ZBC area. By further increasing magnetic fields, ZBC reaches the conductance almost same as that outside the superconducting gap, indicating complete breakdown of superconductivity of the whole island.

4 Conclusions

In summary, by measuring the tunneling conductance at the bottom of the superconducting gap and making its spatial mapping using LT-STM/STS, we have studied superconductivity and vortex formation on Pb nanosize superconducting island structures. Peculiar clustering of vortices, which is not observed in conventional large-scale superconductors, is observed in the nanosize superconductors.

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