STM imaging of vortex structures in NbN thin films

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Abstract

We report on imaging of the vortex structure in NbN thin films by using low-temperature scanning tunnelling microscopy and spectroscopy at 4.2 K in magnetic fields up to 1.2 T. In order to avoid oxidation while retaining a smooth surface, a very thin film of Au ($\sim$ 4 nm) was deposited immediately after sputtering of the NbN thin film ($\sim$ 60 nm). The topography shows that the average grain size of the NbN thin film is 35 nm and the roughness of NbN/Au film surface is below 0.7 nm. From the spectroscopic measurements, vortices show a disordered structure in the whole field region measured, indicating the strong pinning effects in the NbN thin films.

Key words: scanning tunnelling microscopy and spectroscopy; vortex structure; NbN thin films

1. Introduction

Low-temperature scanning tunnelling microscopy and spectroscopy (LT-STM/STS) provide topographic and spectroscopic information with nano-scale resolution. For studies in superconductors, LT-STM/STS is a unique technique to image vortices by mapping the local density of states (LDOS) in a magnetic field as a function of the STM tip position on the sample surface. The LT-STM/STS method can be used in high fields and has much potential for the identification of the vortex structure, dynamics, and the pinning mechanism. However, experiments of vortex imaging by LT-STM/STS have mainly been performed in single crystalline samples with a clean and stable surface which can be prepared by a cleaving method. In thin film superconductors, the first LT-STM/STS observation of vortices was performed in NbC_xN_{1-x} films [1]; however, the resolution of the vortex core strongly depends on the position on the surface. Recently, a clear vortex lattice has been reported in amorphous (a)- Mo_3Ge thin films using a thin protecting Au layer on the surface [2]. In this study, we have performed LT-STM/STS measurements on NbN and NbN/Au thin films and observed disordered vortex structures in NbN/Au thin films.

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2. Experimental

The NbN thin films ($\sim$ 60 nm) were deposited onto Si (100) substrates by rf-sputtering from a Nb target in Ar and N_2 gas atmosphere. In order to avoid oxidation and to obtain smooth surfaces for vortex imaging, a very thin film of Au ($\sim$ 4 nm) was deposited immediately after deposition of the NbN thin film. The superconducting transition temperature T_c was 10.6 K. The LT-STM/STS measurements were performed by using a home built LT-STM [2,3] which can be operated at 4.2 K in magnetic fields up to 2.2 T.

3. Results and Discussion

Figures 1(a) and 1(b) show topographic images (130×350 nm^2) for NbN and NbN/Au thin films,

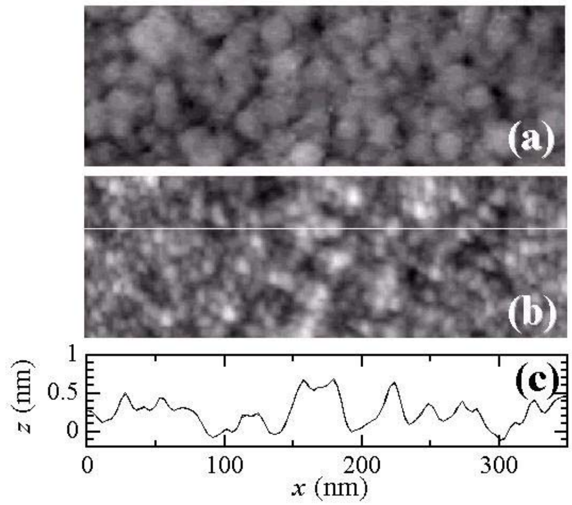

Fig. 1. STM topographic images (130×350 nm^2) of (a) NbN and (b) NbN/Au thin films at 4.2 K. (c) The line profile of the topography along the white line shown in (b).

respectively, under the typical tunnelling condition of a tunnelling current $I = 10 - 13$ pA and a tip(PtRh)-sample bias $V = 1.2 - 2.0$ mV. Generally, it is known that NbN films are inhomogeneous and usually possess grain structures with amorphous grain boundaries, voids, and columnar morphology [4,5]. The average grain size in our NbN thin film is $\sim$ 35 nm with a range of $\pm$15 nm. For NbN/Au thin films, on the other hand, very fine grains of Au are observed as shown in Fig. 1(b). The grain size of the Au surface is about $5 - 10$ nm. Figure 1(c) shows a line profile of the topography along the white line in Fig 1 (b), and a roughness of NbN/Au thin film is below 0.7 nm; the value mainly results from the structure of the NbN layer. These results for both NbN and NbN/Au thin films are consistent with the surface morphology measured by atomic force microscopy (AFM).

The spatial dependence of the I-V characteristics has been measured simultaneously with the topographic data. The differential tunnelling conductance dI/dV, which is proportional to the LDOS, provides the spectroscopic information and shows that the proximity induced superconductivity is uniform on the Au surface of the NbN/Au thin film in zero field. Figure 2 shows a spectroscopic image (352×352 nm^2) for the NbN/Au thin film measured at 4.2 K and 0.45 T after zero field cooling. The gray scale is defined by the ratio of the $dI/dV(V)$ values at zero bias ($V = 0$) and high bias larger than the energy gap ($V > \Delta$). The bright spots indicate the vortex core position. The vortices form disordered structures which strongly deviate from the hexagonal lattice which is reported in the weak pinning materials such as a-MoGe films [2] and $NbSe_2$ crystals [3]. The disordered vortex structures due to the strong pinning effect are observed in the whole measured field region ($0.1 - 1.2$ T). The average vortex distance in Fig. 2 is about 67 nm, which is smaller than the distance $a_0 = 72.9$ nm expected from the applied field. The difference can be explained by the overestimation of moving vortices in the short time scale as compared with the typical time of the measurement ($\sim$ 90 min/image).

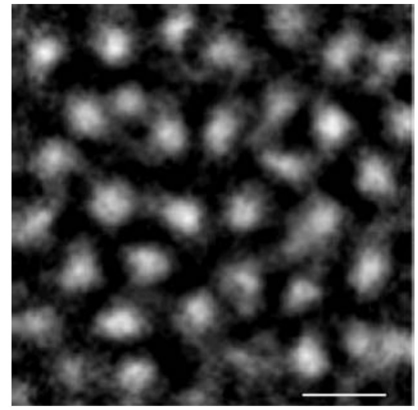

Fig. 2. Spectroscopic image (352×352 nm^2) of the vortex structure for NbN/Au thin film at 4.2 K and 0.45 T. The simultaneously measured topography in the upper region is shown in Fig. 1(b). The average vortex distance ($a_0 = 72.9$ nm) estimated from the applied field is shown by the scale.

For NbN thin films without Au layer, no clear vortex image can be extracted directly from the I-V data. However, vortex structures become visible after subtracting the zero field data, indicating apparently inhomogeneous superconductivity in zero field. The reason is not clear yet, but a partial oxidation at the NbN surface and/or the distribution of the superconducting gap may be the possible origin. These results also show that the Au protection is very useful to obtain uniform superconducting surface for vortex imaging.

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