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Citation: Applied Physics Letters 82, 1081 (2003); doi: 10.1063/1.1554481
View online: http://dx.doi.org/10.1063/1.1554481
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Imaging of vortex configurations in thin films by scanning-tunneling microscopy

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(Received 22 October 2002; accepted 2 January 2003)

We report on imaging of vortices in thin superconducting films using surface passivation with an ultrathin Au layer. This allows investigation of surfaces that oxidize easily, as well as the mounting of samples in air. We studied vortex configurations in a material with weak vortex pinning ($a$-Mo$_{2.7}$Ge) and a strongly pinning material (NbN) at 4.2 K in magnetic fields up to 1.4 T. In $a$-Mo$_{2.7}$Ge, we observe a well-ordered hexagonal lattice, with local defects beginning to appear around 1.0 T. In NbN, the vortex lattice is fully disordered.

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[DOI: 10.1063/1.1554481]

Scanning tunneling microscopy (STM) is a useful technique for imaging vortex structures in superconductors. One of the principal advantages in comparison with other imaging tools, such as magneto-optics, Bitter decoration, or magnetic force microscopy, is that STM measures the electronic density of states instead of the magnetic flux density, thus requiring tools, such as magneto-optics, Bitter decoration, or magnetic force microscopy. The important point to realize is that the vortex positions as measured on the Au surface are still dictated by the pinning of the vortices in the NbN layer, since the pinning by the $a$-Mo$_{2.7}$Ge layer is much too weak to influence the vortex configuration.

The 50-nm-thick $a$-Mo$_{2.7}$Ge films were rf sputtered from a composite Mo/Ge target at room temperature in an Ar atmosphere on a Si substrate. Atomic force microscopy (AFM) on such a film showed a flat surface over the scan range of 0.5 $\mu$m within the resolution of our AFM measurement (0.4 nm). Next, we deposited the Au capping layer immediately after depositing the $a$-Mo$_{2.7}$Ge by first sputtering about 3-nm Au in Ar (100%) atmosphere to obtain a closed Au layer, followed by another 3 nm in Ar/95%/5% partial pressure) to obtain a flat Au surface consisting of small grains. Highest resolution is achieved having Au grains as small as possible, which is promoted by the O$_2$ addition. The 50-nm-thick NbN samples were reactively rf-sputtered at room temperature from a Nb target in an Ar/N$_2$ atmosphere (95%/5% partial pressure). This was followed by a 20-nm layer of $a$-Mo$_{2.7}$Ge and a Au layer as for the $a$-Mo$_{2.7}$Ge films. After sputtering, the samples were taken out of the vacuum and mounted on the scanner of the STM. During this procedure, which takes about half an hour, the samples were exposed to air.

Examples of the topography as measured by STM can be found in Refs. 9 and 10. The surface shows grains with a size of 10 nm and a maximum height variation of 1 nm over a scan length of 400 nm. The STM measurements were performed...
formed in the same setup as mentioned in Ref. 11, and the STM itself is directly immersed in the liquid helium; all data shown are acquired at 4.2 K.

The vortex imaging is done by acquiring full $I$–$V$ tunneling spectra simultaneously with the topography measurement (constant current mode): at each point, after stabilizing the tip height, the feedback is switched off and an $I$–$V$ curve is measured. From these $I$–$V$ curves, we evaluate the ratio of the zero-bias and high-bias (larger than the superconducting gap energy $\Delta$) slopes, providing information about the proximity-induced, local quasiparticle density of states, $N_r^\rho (E, r)$, where $E$ is the energy of the quasiparticles and $r$ is the position of the tip on the sample. On choosing a resolution of $128 \times 128$ points per image the acquisition time is about 1 h. For all vortex images shown, except otherwise mentioned, we applied some basic image processing to the acquisition data of measurements at 0.07, 0.3, and 1.0 T in Fig. 3.

For a more quantitative analysis of the correlation of vortex positions, we generated two-dimensional (2D) maps of the autocorrelation function (with distances $r$ now scaled on $a_0$, the vortex–vortex distance defined from the peaks in the autocorrelation graphs), shown in Fig. 2. These maps directly yield an estimate for the VL correlation length $R_c$, in contrast to the often-presented 2D Fourier transforms [shown in the insert of Figs. 2(b) and 2(d)] where this information is in the width of the peaks. From the pictures, it is evident that in $a$-Mo$_2$Ge the VL has both high translational (bond length) and rotational (bond orientation) correlation, with a lower bound of $R_c \approx 6 a_0$ set by the limited amount of vortices. For NbN, we find $R_c \approx 1.5 a_0$ and almost no orientational correlation. The gray features that still can be seen in Fig. 2(c), the small variations of correlation above $2r/a_0$, and the nonuniformity of the ring in the Fourier transform in Fig. 2(d) are due to the limited amount of vortices on which to do these statistics.

Next, we consider the field dependence of the correlations. No qualitative changes were found in the VL structure of the NbN films up to 1.4 T, the highest magnetic field measured. In the whole field regime, we therefore essentially find $R_c \approx (1-2) a_0$. This confirms on a local scale the conclusion from pinning force measurements, that in the field regime below $b \approx 0.15$, grain boundary pinning is more important than the elastic interactions between vortices, leading to isolated vortex behavior. For $a$-Mo$_2$Ge, we show additional data of measurements at 0.07, 0.3, and 1.0 T in Fig. 3. In the lowest fields, we have the problem that the scan range, and therefore the total amount of vortices that can be imaged, is limited. However, inspection of Fig. 3(a) reveals several...
defects. For higher fields, up to 1.0 T, we always obtained images without any defects, although the lattice as a whole may show deformations, visible in the data at $B = 0.3$ T [Fig. 3(b)]. Since the fast-scan direction is horizontal, this deformation is a real property of the lattice rather than an artifact of the measurement. We also observe rotations of the VL after changing the magnetic field and measuring again at the same spot: panels (a) and (b) of Fig. 3 are subsequently measured on the same location on the film. We propose that these observations are due to the presence of large domains of different orientation that change in size and orientation after a field step. This emphasizes once more the collective nature of the forces in VLs of amorphous superconductors, due to the weak random nature of the pinning.

For the 1.0 T data, we used a convolution filter with a kernel of size $a_0^2$, since at these magnetic fields, the contrast becomes poor due to the overall suppression of the superconducting gap. Before measuring these images, we waited for 1.5 h to let the VL relax after the field was set to 1.0 T. Subsequently, we acquired 10 consecutive images on the same location of the film, each having an acquisition time of around 90 min. From this set of images, two subsequent images showed a lattice without defects, while all the others showed one or more defects on different locations in the lattice. Images without and with a defect are shown in Figs. 3(c) and 3(d). These apparently quite mobile defects indicate spontaneous nucleation of defects, which may be the first signal of the onset of melting at higher fields.

To summarize, we have developed a technique which makes imaging vortex configurations in superconducting thin films possible in magnetic fields that were not accessible before. We applied the technique to films of $\alpha$-Mo$_2$Ge and NbN, resulting in clear images of their vortex configurations. Measurements on $\alpha$-Mo$_2$Ge, a weak pinning material, show a triangular vortex lattice with defects appearing around 1.0 T. For NbN, a strong pinning material, the lattice is fully disordered. The technique can, in principle, be used to observe vortex configurations in any type-II superconductor on which Au can be grown in a smooth layer (possibly with the help of $\alpha$-Mo$_2$Ge). This opens a way to study the microscopic behavior of the vortices, for example, at phase transitions, and can produce information on artificially structured samples.

This work is part of the research program of the Stichting voor Fundamenteel Onderzoek der Materie (FOM), which is financially supported by the Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO). One of the authors (T.N.) acknowledges support from NWO and the Japanese Society for Promotion of Science (JSPS).

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7. R. Besseling (private communication).