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Voltage noise measurement of the vortex mean free path in superconducting granular tin films

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We present the results of simultaneous current-voltage and voltage noise measurements on granular tin films in the region of the superconducting transition. Interpretation of the results in terms of a phase-slip shot noise demonstrates that vortex motion is uniform only over some characteristic length. This effective mean free path increases as the temperature is lowered and is probably dominated by vortex-antivortex recombination.

Granular superconductors, with their high sheet resistances, large penetration depth, and two-dimensional nature, have become a fashionable material for studies of the Kosterlitz-Thouless vortex-antivortex unbinding transition.[1,2] Within the past two years experimental results have been reported[3,4] which tend to support the theoretical predictions. Typical current-voltage or resistance-temperature characteristics measure only the average rate of some elementary process (e.g., vortex motion across a film). Noise measurements, however, are sensitive to the size of the elementary events. Our previous experiments,[5] which monitored voltage noise and average voltage at constant current while the sample temperature was changed, were interpreted in terms of a phase-slip shot noise due to the motion of free vortices consistent with theory. In this Communication, we present simultaneous current-voltage and voltage-noise measurements on granular tin films at constant temperature. Interpretation of the results demonstrates that the motion of an individual vortex is uniform over some characteristic length that is in general less than the sample width. This effective mean free path increases as the temperature is lowered.

The samples were prepared by evaporating tin in an oxygen atmosphere (4×10^{-4} Torr) at a rate of approximately 10 Å/sec onto glass substrates at room temperature. This technique was first used by Abeles *et al.*[6] to produce fine-grained films of soft metals without resorting to cryogenically cooled substrates. The deposition produced 400–700-Å-thick films in which the tin tended to coalesce into hillocks with an average width of 1500 Å. The sheet resistances $R_\square$ ranged from 10 to 300 $\Omega/\square$, giving a $T=0$ coherence length of about 2250 Å. Although these tin films are morphologically different from the granular aluminum films previously studied,[3–5] they still retain a two-dimensional nature since the film thickness is less than the coherence length. After deposition the substrates were cut into smaller sections and the film was scribed into a standard sample size (50–140 μm wide and 1020–1060 μm long) to minimize variations of $R_\square$ across the sample and to provide separate current and voltage leads.

Contacts to the film were made using individually shielded, twisted pair leads which were secured to the films by means of small clamps. In order to minimize Joule heating, the samples were placed directly in liquid helium inside a double mumetal shielded cryostat which had an ambient field of less than 1.7×10^{-4} Oe. The bath temperature was stabilized by regulation of the He vapor pressure to about 0.5 mm Hg in the region of the superconducting transition (≈ 3.8 K). The temperature was monitored using a carbon resistance thermometer as well as the vapor pressure. In addition to current and voltage connections one pair of sample leads was connected to a special low-noise field-effect transistor preamplifier. This preamplifier, in combination with a PAR 124A lock-in amplifier operating as a bandpass filter and ac voltmeter, allowed estimation of the voltage-noise spectral density $S_V(f)$ in the frequency range of 10 to 100 kHz. The current in the sample was slowly varied and the dc voltage V_{dc}, as well as $S_V(f)$, was digitally recorded and averaged. All measurements were made inside an rf shielded environment to minimize external noise and interference.

A typical series of data for a 12.4-$\Omega/\square$ sample is shown in Fig. 1. Figure 1(a) shows a family of voltage-noise spectral density curves at 100 kHz, S_V(100 kHz), as a function of bias current I at various temperatures while Fig. 1(b) gives the corresponding V_{dc}-I characteristics. Data were recorded below and in the vicinity of T_c, the temperature at which the low bias dc resistance approached zero. At higher temperatures, S_V(100 kHz) shows a broad peak in the region of the strong nonlinearity of the V_{dc}-I characteristic. As T is lowered, the peak narrows and shifts to higher I while subsidiary maxima appear. At temperatures below those shown in Fig. 1 hysteresis appears in the V_{dc}-I characteristic. As previously reported,[5] the noise was independent of fre-

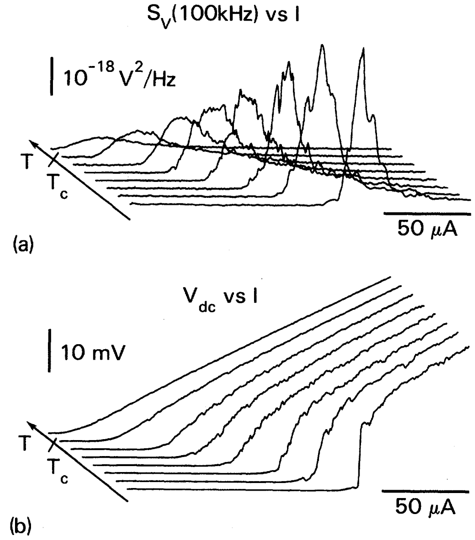

FIG. 1. (a) $S_V(f)$ vs I for a 12.4-Ω/□ film at the temperatures 3.826, 3.832, 3.835, 3.841, 3.844, 3.848, 3.855, and 3.862 K. (b) V_{dc} vs I at the same temperatures.

quency over the range studied and inversely proportional to sample width.

From Fig. 1 it can be seen that as I increases S_V first starts to increase when V_{dc} appears. This approximate proportionality between S_V and V_{dc} is seen more accurately in Fig. 2, which shows a logarithmic plot of S_V(100 kHz) vs V_{dc} for the same sample as Fig. 1 at different temperatures. For small V_{dc}, $S_V \propto V_{dc}$ (solid line) with a constant of proportionality that increases as T decreases. As V_{dc} increases, S_V eventually reaches a maximum and finally decreases at large V_{dc}.

This observance of $S_V(f)$ proportional to V_{dc} and independent of f is expected[5] from a phase-slip shot-noise mechanism. In the usual current-dependent

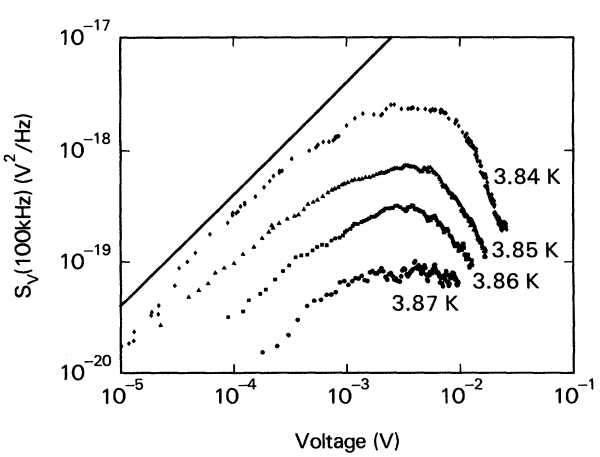

FIG. 2. S_V(100 kHz) vs V_{dc} for the 12.4-Ω/□ film shown in Fig. 1.

shot noise,[7] independent carriers with charge e that arrive randomly at an average rate r produce a dc current $I_{dc}=er$ and current noise $S_I(f)=2eI_{dc}$ independent of frequency f. At large I_{dc} motion of the individual carriers becomes correlated and S_I is drastically reduced.[7] In a superconductor, any vortex motion (of even a small distance) produces a change in the phase difference θ between the ends of the sample[2] and, consequently, in the voltage across the sample.[8] If the vortex motion consists of independent random phase slips of magnitude $\Delta\theta$ at an average rate r then the Josephson relation[9] gives

$$V_{dc}=\frac{\phi_0}{2\pi}\frac{d\theta}{dt}=\frac{\phi_0\Delta\theta}{2\pi}r \ ,$$

where the ϕ_0 is the flux quantum. In this case, $\phi_0\Delta\theta/2\pi$ plays the role of the charge e in the usual current shot noise. Consequently, the voltage noise becomes

$$S_V(f)=2\frac{\phi_0\Delta\theta}{2\pi}V_{dc} \qquad (1)$$

for $f\lesssim\tau^{-1}$, where τ is the characteristic time duration of $\Delta\theta$. The application of a current causes vortex motion perpendicular to the current flow, and a total phase slip of 2π occurs when a vortex completely crosses the width w of the sample.

The solid line in Fig. 2 shows the prediction of Eq. (1) for $\Delta\theta=2\pi$, the result expected for a single flux quantum moving without interruption entirely across the sample width. Early work on flux flow noise in type-I superconductors[10] was interpreted in terms of Eq. (1) with $\Delta\theta \gg 2\pi$ (corresponding to the motion of flux bundles, each with many quanta, completely across the sample). We find, however, at low V_{dc}, that $\Delta\theta \ll 2\pi$ but increases toward 2π as T is lowered. Since the unit of flux cannot be smaller than ϕ_0, $\Delta\theta$ can be less than 2π only if the elementary motion corresponds to uninterrupted flow across a distance less than the sample width. Independent vortices undergoing uniform motion over some characteristic distance $l<w$ result in phase slips $\Delta\theta\approx 2\pi l/w$ and a voltage noise

$$S_V(f)=2\phi_0\frac{l}{w}V_{dc} \ . \qquad (2)$$

Thus the constant of proportionality between S_V and V_{dc} is a measure of the effective mean free path for uniform vortex motion independent of the actual density of free vortices. The decrease in S_V at large V_{dc} is probably due to correlated motion of neighboring vortices (in analogy with the current shot noise discussed above) or the breakdown of the independent vortex model at sufficiently large densities and flow rates.

The temperature dependence of the effective vortex mean free path l is illustrated in Fig. 3 for samples with varying $R_\square$ and temperatures T_c at which

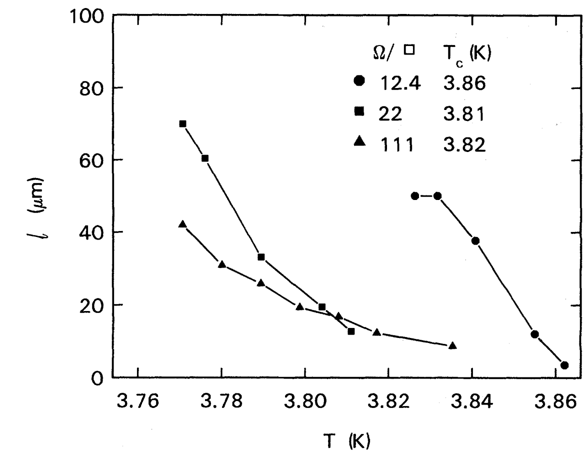

FIG. 3. Effective mean free path l for several low-$R_{\square}$ tin films as a function of temperature.

the low bias dc resistance vanished. At each T, Eq. (2) was used to estimate l at low V_{dc}. Preamplifier background noise limited our sensitivity to l of order 1 μm for our standard sample size. The low-T, high-l limit for each sample results from the onset of hysteresis in the film's I-V_{dc} characteristics. For the 12.4- and 22-$\Omega/\square$ samples the onset of hysteresis occurs when the vortices have traveled almost the full sample width (65 and 70 μm, respectively). In the 111-$\Omega/\square$ sample, hysteresis sets in when the vortices travel only about $w/3$. The physical mechanism for this hysteresis, which does not appear to be due to Joule heating, is not understood in these films.[11]

Figure 3 demonstrates that the effective mean free path for uniform motion increases rapidly as T is lowered until $l \approx w$ or hysteresis occurs. Either random trapping or vortex-antivortex recombination could cause the limited mean free path indicated by the data. However, the strong T dependence suggests that l is a measure of the average distance traveled by a free vortex before annihilation, with the scarcity of free vortices at low T giving a large l. Although our original noise measurements[5] on aluminum films suggested a temperature-independent l that increased with I, those results are consistent with the ones presented here. The early measurements were performed at constant I. V_{dc} and S_V were varied by changing T in the vicinity of the resistive transition. At each I, S_V was proportional to V_{dc} only over a small ΔT near the onset of resistance. At larger I this onset occurred at lower T (large l) and the curves at different I effectively probed different T.

In conclusion, we have shown that voltage-noise measurements near the superconducting transition can be interpreted in terms of a phase-slip shot noise arising from the motion of individual vortices over a characteristic length $l(T) < w$. A quantitative analysis demonstrates that l increases as T is lowered until hysteresis appears in the V_{dc}-I characteristic and suggests that l is a measure of the effective mean free path for uniform vortex motion before recombination.

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