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Controlling flux flow dissipation by changing flux pinning in superconducting films

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We study the flux flow state in superconducting materials characterized by rather strong intrinsic pinning, such as Nb, NbN, and nanostructured Al thin films, in which we drag the superconducting dissipative state into the normal state by current biasing. We modify the vortex pinning strength either by ion irradiation, by tuning the measuring temperature or by including artificial pinning centers. We measure critical flux flow voltages for all materials and the same effect is observed: switching to low flux flow dissipations at low fields for an intermediate pinning regime. This mechanism offers a way to additionally promote the stability of the superconducting state. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.4718309]

In view of applications of type II superconducting materials, it is a common ambition to search for strong pinning materials with the aim of increasing the superconducting critical current \(I_c\), which sets the onset of a dissipative regime identified with the flux flow state between the fully superconducting state and the normal state. In several applications, some features of the flux flow such as the shape of the \(I-V\) characteristic or the current value at which the switching to the normal state takes place become of fundamental importance. To improve the performance of superconducting materials in magnets, current-leads and fault current limiters, it is crucial to ensure current stability and low dissipation in a wide range of bias current larger than the critical current \(I_0 > I_c\). Furthermore, superconducting single-photon detectors operating in self-field are current biased close to \(I_c\) but their efficiency is strictly related to the transition to the normal state of the superconducting wire.

The low dissipative state above \(I_c\), limited by a threshold current \(I'\), above which an abrupt voltage jump to the normal state occurs. In the absence of self-heating effects and according to the Larkin and Ovchinnikov (LO) theory, this jump corresponds to an instability of the moving vortices which occurs at a vortex critical velocity \(v^*\), due to the quasiparticle runaway from the vortex core. Hence, the instability point defined by the threshold current \(I'\) and by the critical voltage \(V^*\) sets the upper limit of the low dissipative state. Vortex pinning can play a non trivial role in this current-driven transition. However, despite a wide experimental and theoretical investigation existing on vortex matter, the relation between pinning and instability point \((I', V^*)\) remains unclear.

In this letter, we provide experimental evidence that an intermediate pinning regime can sustain a low dissipative flux flow state at high currents and at low fields. Remarkably, we show that maximum pinning does not always correspond to highest stability of the superconducting state. Namely, for some applications it is recommended to reach high critical currents \(I_c\) and low critical flux flow voltages \(V^*\). Focusing on the magnetic field dependence of the critical vortex velocity, we identify a particular non-conventional behavior as a signature of an intermediate pinning regime in which the critical flux flow voltages reach the lowest values. Current-voltage characteristics have been measured in different superconducting strips of Nb and NbN [which are among the low temperature superconductors (LTSs) often used in the above mentioned applications] as well as in Al with an artificial pinning structure.

We perform a flux flow instability analysis based on the measurements of the critical flux flow voltages \(V^*\) as a function of the external magnetic field at several temperatures. We then derive the average critical vortex velocity \(v^*\) from instability voltages \(V^* = v^*BL\) \((B\) is the magnetic field, \(L\) is the strip length) in the \(I-V\) curves. The details about the geometry of the measured samples are given in Table I. A pulsed-current technique has been used in order to ensure negligible heating effects.

Table I. Summary of the geometry of Nb and NbN samples \((w\) is the strip width, \(t\) is the film thickness, and \(L\) is the distance between the voltage leads).

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Superconductor</th>
<th>(w) [(\mu)m]</th>
<th>(t) [nm]</th>
<th>(L) [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1</td>
<td>Bare Nb</td>
<td>100</td>
<td>135</td>
<td>2</td>
</tr>
<tr>
<td>N1i</td>
<td>Irradiated Nb</td>
<td>100</td>
<td>135</td>
<td>2</td>
</tr>
<tr>
<td>N2</td>
<td>Bare Nb</td>
<td>50</td>
<td>150</td>
<td>2</td>
</tr>
<tr>
<td>NNA</td>
<td>NbN</td>
<td>20</td>
<td>100</td>
<td>2</td>
</tr>
<tr>
<td>NNb</td>
<td>NbN</td>
<td>50</td>
<td>100</td>
<td>2</td>
</tr>
</tbody>
</table>

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based on the Bezuglyi-Shklovskij model has been carried out. Following this model, heating mechanisms become significant well above a threshold field \( B_T = (0.374e\hbar\tau) / (k_BT_N) \) (where \( e \) is the electron charge, \( \tau \) is the time of quasi-particle energy relaxation, \( k_B \) is the Boltzmann constant, \( \sigma_N \) is the normal conductivity and \( t \) is the film thickness). In our experimental data, we estimate \( B_T^{NB} \approx 240 \text{ mT} \) and \( B_T^{NN} \approx 100 \text{ mT} \). As a consequence, in the entire investigated magnetic field range \( B < B_T \) and therefore we can neglect the heating effects.

**Niobium.** Starting from Nb samples, we explore the effect of introducing a random distribution of pinning centers by irradiation with Ar\(^{++} \) ions of 600 keV with a dose of \( 4 \times 10^{10} \text{ cm}^{-2} \). In the bare Nb, softening of the pinning strength is obtained by increasing the measurement temperature. In Fig. 1(a), we show the magnetic field dependence of the critical velocity \( v^* \) at 4.2 K measured on a bare Nb strip (full circles) and on the same sample irradiated with Ar\(^{++} \) ions (open symbols). As already reported for Nb samples, this low-field behavior can be attributed to a vortex channel-like motion induced by inhomogeneously distributed intrinsic pinning centers. On the contrary, the effect of increasing the random pinning centers introduced by irradiation seems to smear out such a channeling effect, leading to a more homogeneous sample in which the usual power-law decreasing dependence of \( v^*(B) \) is observed. In Fig. 1(a), we also show the effect of changing the temperature for the irradiated sample, which results in a smooth power law decrease of \( v^*(B) \) as the temperature is gradually increased. In Fig. 1(b), we show the experimental \( v^*(B) \) curve for another bare Nb sample at 4.2 K (blue full circles) and the same data at a higher temperature \( T = 8.2 \text{ K} \) (red open circles). The comparison of the \( v^*(B) \) data in Figs. 1(a) and 1(b) reveals an unexpected behavior: the non-conventional low field dependence of \( v^* \) (see blue and black full circles) can be reversed in the usual monotonic decrease with increasing field by increasing disorder (see red open square) or by increasing the temperature (see red open circles). In these two modes higher critical velocities, i.e., higher instability voltages, have been found, leading to higher levels of power dissipation.

**Niobium nitrate.** To confirm these observations we investigated a different material, namely, NbN, which is commonly known as a stronger pinning superconductor. In Figs. 2(a) and 2(b), the evaluated \( v^*(B) \) at different temperatures are reported for sample NNA and sample NNB, respectively. We observe that by increasing the measurement temperature in order to weaken the effectiveness of pinning, we have succeeded in reversing the \( v^*(B) \) behavior from decreasing to increasing monotonically with the magnetic field. In Figs. 2(c) and 2(d), the differential resistance \( \frac{dV}{dI} \) as a function of the bias current for different magnetic fields (at \( T = 14.5 \text{ K} \) and \( T = 15.5 \text{ K} \), respectively) is also shown for sample NNB. The \( \frac{dV}{dI} \) data at these two temperatures show two different behaviors. At \( T = 14.5 \text{ K} \), the presence of a peak in the differential resistance \( \frac{dV}{dI} \) can clearly be seen, in contrast with the monotonic behavior of \( \frac{dV}{dI} \) at \( T = 15.5 \text{ K} \). This behavior is related to the change of pinning strength with the temperature variation. Since the peaked differential resistance can be associated to the presence of a...
current-driven dynamic transition from a disordered to an ordered moving vortex lattice, namely dynamic ordering (see Ref. 21 and references therein), it is expected that in the dynamic phase diagram of a moderately strong pinning superconductor a more stable motion of the vortex lattice can be observed.21 This is indeed the case for NbN samples, thus, whenever temperature is increased an intermediate pinning regime is achieved and low dissipative states are established with lower vortex critical velocities, as shown in Fig. 2.

Aluminum. In the case of the Al thin film, we estimate a threshold field $B^2_{\text{Al}} \approx 20 \text{ mT}$, thus self-heating can be neglected. By comparing the critical vortex velocity $v^*$ in the same sample with a different magnetic pinning underneath (see Fig. 3), we notice that a non monotonous dependence of $v^*$ is again observed by changing the magnetic state of the pinning centers (see Fig. 4). Here, a different magnetic state corresponds to a different pinning strength of the magnetic pinning centers.22 In particular, it has already been established that when switching the micromagnets from the as-grown to the magnetic vortex state and then to the onion state, their pinning strength results further increased.13 As shown in Fig. 4, the critical vortex velocity values are strongly enhanced in the onion state at low fields, whereas at larger external fields, the same decreasing behavior is achieved for both the as-grown and the vortex state. In the intermediate pinning regime, i.e., the vortex state, the unusual non-monotonic low field dependence is clearly observed.

The general picture that can be drawn from these experimental findings is that, although it is always true that stronger pinning has the direct consequence of increasing $J_c$ in static conditions, for $J > J_c$, the stability of the flux flow state can be improved by weakening the pinning to an effectively intermediate regime. Therefore from the point of view of those applications requiring low dissipative states, it is favorable to gain a more stable and less dissipative superconducting state with low critical voltages $V^*$. As a consequence, a compromise should be found between the critical current $I_c$ and the instability current $I'$. In other words, the strongest pinning is not always the best choice, contrary to what is commonly accepted. Flux flow dissipations decrease if the pinning can be controlled/held in a moderately strong regime. This is an important fact in the quest for stronger pinning materials,23 particularly for those applications in which the stability of the superconducting state is strictly demanded.

We therefore promote a viewpoint in which one can follow the changing of flux pinning from weak to strong and vice versa, by looking at the magnetic field dependence of the critical vortex velocity $v^*(B)$, as illustrated in Fig. 5. In the horizontal frame, there are three panels which show the magnetic field dependence of the critical vortex velocity as a function of the magnetic field. Depending on the investigated material, the change of pinning can be realized in different ways: (i) by changing the temperature (see the horizontal temperature arrow); (ii) by changing the material; (iii) by changing the pinning strength in the same material (see the horizontal pinning arrow). The result is a rather straightforward control of how to get the lower flux flow dissipations by changing flux pinning. For example, we identify the bare Nb superconducting films with an intermediate intrinsic pinning, so that disorder moves towards left, while temperature moves towards right (see Fig. 5). For either NbN or irradiated Nb films, we start from the left (strong) panel and increasing the temperature the intermediate pinning regime can be reached. Finally, in the tunable pinning Al films we recover all the three cases, thus from either left (onion state) or right (as-grown) the intermediate (vortex state) pinning regime can be achieved.

In conclusion, we have studied the influence of pinning on flux flow dissipations in strong pinning superconductors Nb and NbN, as well as in artificially structured Al. By changing the intrinsic pinning, we are able to identify the improved stability conditions in which the low dissipative superconducting state can be maintained for $J > J_c$. Either by increasing the temperature in the strongest pinning NbN or by irradiating moderately strong pinning Nb samples, we...
managed to modify the flux pinning from strong to weak, and we found that the lowest dissipative states are achievable only in the intermediate pinning regime. We reach the same conclusion by changing the artificial pinning in a structured Al sample. This overall study clearly provides a way of extending the stability of the superconducting state just above $J_c$, which may be of significant interest to technological applications.

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