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Physica C 437–438 (2006) 345–348
PHYSICA C
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Magnetic field induced suppression of vortex flow resistance in superconductors with periodic pinning centers

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Available online 3 February 2006

Abstract

We study vortex flow resistance (VFR) in films of Pb with holes as periodic pinning centers (PPCs) and of Nb with PPCs in the form of Ni dots, as function of temperature, dc current and constant applied magnetic field. The experimental resolution is better than 10^{-5} of the normal state resistance. At high temperatures near to T_c and high drive currents the resistance shows local minima both at matching fields and zero field. For lower temperatures, however, in a narrow temperature range before the vortex system becomes completely frozen, we observe suppression of the VFR with increasing magnetic field. In the Pb film with PPCs these phenomena show up as a clear zero field resistance excess, which is gradually suppressed by the applied magnetic field. We attribute this unusual feature in the magnetoresistance to thermally excited vortex–antivortex pairs. In the Nb superconducting film with PPCs we observe a gradual suppression of the VFR near integer matching fields up to $n = 3$ at the lowest accessible dc currents and relevant temperatures. This anomalous behaviour is followed by the observation of negligible VFL for higher fields ($H_3 < H < H_4$) and a strong enhancement of VFR for $H > H_4$. We tentatively explain this observation as due to the moving vortex glass.

Keywords: Superconductors with periodic pinning centers; Flux-flow resistance

1. Introduction

When vortices are created in a superconducting film by the applied external field perpendicular to the sample surface, and a transport dc current flows through the superconductor, they are subject to three main interactions, if we neglect thermal effects, namely: the repulsive vortex–vortex interaction $\mathbf{f}_V$, the attractive interaction from the pinning sites $\mathbf{f}_P$, and the Lorentz force $\mathbf{f}_L$ due to the transport current which tends to move the vortices perpendicularly to the current, giving rise to voltage (VFR) and dissipation.

For superconductors with periodic pinning centers (PPCs) the matching field H_n is defined as the field which produces a total flux through the sample equal to the flux of n flux quanta Φ_0 in each pinning center. Normally, the exact matching conditions reduce VFR (dissipation). The presence of interstitial vortices occurring for the applied magnetic fields in-between the matching fields ($H_n < H < H_{n+1}$) or for $H > H_1$ (if the pinning center is capable to pin only one flux quantum) enhances VFR. Application of the external magnetic field results in a monotonous enhancement of vortex flow resistance accompanied by smaller (as n increases) resistance dips at the matching conditions. Usually, the magnetoresistance curves are measured close enough to T_c in order to have sufficient resolution in resistivity. Here we report on high resolution magnetoresistance measurements in Nb/Ni and Pb films with PPCs in a wide dynamic range down to 10^{-6} of the normal resistance, which allows us to explore a much wider interval of vortex pinning energies by measuring VFR both

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0921-4534/$ - see front matter
doi:10.1016/j.physc.2005.12.073

at lower temperatures and with lower dc current densities than in previous experiments. We found that while very close to T_c and at high currents the VFR shows the previously reported features [1–3], it changed qualitatively further below the critical temperature and at low drive currents where vortex pinning is enhanced.

2. Experimental

The Nb/Ni structure has a 100 nm thick Nb film covering a rectangular array of Ni dots (unit cell of $0.5 \times 0.4\ \mu m^2$), each with a diameter of 200 nm, and 40 nm thick, with in-plane magnetization. The sample is a cross of $40 \times 40\ \mu m^2$ with four potential contacts in the cross corners. The Pb film, 40 nm thick, has a square array (unit cell of $2.67 \times 2.67\ \mu m^2$) of square microholes (antidots) of 1.5 μm side length. It is covered by a 20 nm thick film of Ge to protect it against oxidization. The sample is a strip 100 μm wide and the distance between contacts is 150 μm. More details on sample preparation are given in Refs. [2] and [4]. The dc magnetotransport and noise measurements were carried out in a JANIS cryostat with a temperature control stability of $\pm 10^{-4}$ K for many (up to 80) hours. The low frequency ($0.001 < f < 2\ Hz$) noise power spectrum was determined by the cross correlation technique.

From the measured magnetoresistances we obtain $H_1 = 103$ Oe for the Nb structure and $H_1 = 3.0$ Oe for the Pb one, both in excellent agreement with the values calculated from the artificial arrays dimensions. It may be noted that both structures attain high superconducting critical temperatures, which is a proof of the high quality of the measured samples.

3. Results and discussion on Nb film with PPCs

In Fig. 1 we represent the magnetoresistance $R(H)$, with R the resistance and H the applied field, at two selected temperatures, for the sake of clarity, close to T_c. We have

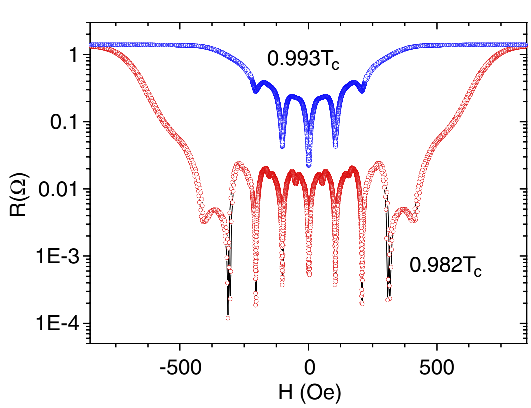

Fig. 1. Logarithm of magnetoresistance as function of perpendicular applied magnetic field of Nb film with array of magnetic Ni dots. Two temperatures have been selected, close to T_c and further below, to show different pinning regimes (see text).

measured T_c with a 10 μV criterion, and it ranges from 8.680 K with $I = 10$ μA to 8589 with $I = 5$ mA. Note the logarithmic scale for the resistance to appreciate its variation of several orders of magnitude. In both cases, the well-known oscillations of $R(H)$ when crossing the first three matching fields are observed.

Therefore, at the first three matching fields most of the vortices make up a vortex lattice pinned inside the antidots, with the corresponding reduction of resistance. We may quantify this reduction, for example for the first matching field, by the ratio $R(H_1)/R_{max1}$, where R_{max1} stands for the maximum resistance between $H = 0$ and H_1. This ratio varies from 0.17 in the upper curve to 0.02 in the lower one, at a lower temperature.

But there are striking differences between the behaviour as function of the field of both curves. Let us call the upper curve ($T = 0.993\ T_c$) in weak pinning regime and the lower curve ($T = 0.982\ T_c$) in strong pinning regime, in order to discuss these features. First of all we note that in the weak pinning regime, the integer matching field resistances $R(H_1)$ and $R(H_2)$ are higher than $R(H = 0)$, and their values increase with increasing field, an observation which had been reported before [2]. However, in the strong pinning regime the situation is reversed: dissipation gradually decreases at integer matching fields and is highest at H zero field.

Second, in the weak pinning regime, the average magnetoresistance between integer matching fields up to H_2 gradually increases with increasing field, also as previously reported. For higher fields, $R(H)$ increases steadily until reaching the normal state resistance. H_3 may be identified by a gentle change of slope in the corresponding R values.

The situation is different in the strong pinning regime: a pronounced minimum in $R(H)$ appears at H_4 and a significant reduction of magnetoresistance occurs between H_3 and H_4, in comparison with the regions between lower matching fields, i.e. we find a field region where dissipation decreases with increasing field. On further increase of the field, the magnetoresistivity increases steeply to the normal resistance value showing H_5 as a change of slope.

These complete field scans have been performed with several dc current drives of 500 μA, 1 mA (25 kA/cm^2), 2 mA and 5 mA, and at 6–8 temperatures with each dc drive. The strong pinning regime shows up for a given drive current in a very narrow temperature range before the vortex lattice becomes completely frozen and at low dc drives ($I \leqslant 2$ mA). It is suppressed with $I = 5$ mA.

These counterintuitive features that characterize this strong pinning regime have been confirmed by critical current measurements (with a 10 μV criterion) in the strong pinning regime at $T/T_c = 0.977$ (see Fig. 2).

It may be stressed that both strong pinning features commented above appear usually together, which points out to a common or complementary origin.

It is not easy to interpret this rich phenomenology. Strong pinning of integer quanta in the dots could favour the stability of this structure via vortex–vortex interactions.

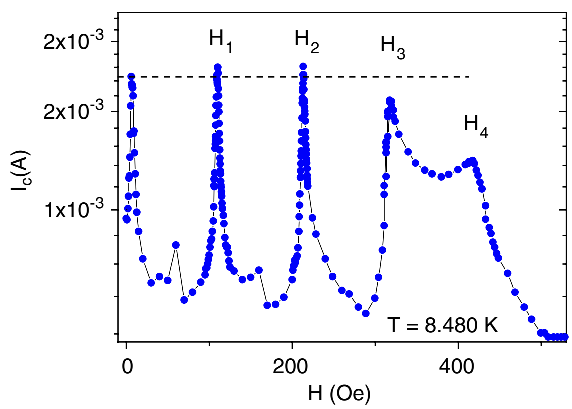

Fig. 2. Logarithm of critical current I_c as function of applied field of the Nb nanostructured sample at a temperature which shows the strong pinning regime (see text). Note that I_c is higher at H_1 and H_2 than at zero field, its enhancement between H_3 and H_4, relative to the regions between lower matching fields, and the structure at $H_{1/2}$ and $H_{3/2}$.

One possibility is the formation of vortex–antivortex pairs (which are easier detected close to the matching fields due to the smaller vortex flow resistance) gradually annihilated when an external magnetic field interacts with them. A somewhat similar mechanism could work in the Pb structure with square PPCs. It would certainly be interesting to look for the possible role of the rectangular symmetry of the Nb/Ni structure by studying a sample with a square symmetry. Another possible scenario involves the influence of the magnetic field on the perpendicular component of the magnetization of the Ni dots. Initially, for low magnetic fields, the Ni dots magnetization is aligned in the plane and the enhanced vortex pinning is mainly due to the Nb film shape periodic modulation and/or the edge stray fields. Applying a perpendicular magnetic field, the reversibly induced perpendicular component of the magnetization on the Ni dots might enhance the pinning. The second model implies that each single Ni dot pins up to three flux quanta. For higher magnetic fields ($H > H_3$), the field enhanced pinning mechanism could be influenced by the appearance of interstitial vortices.

Indeed, our experimental finding of an enhanced critical current (i.e. reduced flux-flow resistance) for the interval $H_4 > H > H_3$ in comparison with $H_{n+1} > H > H_n$ ($n =$ 0,1,2) could be interpreted by involving moving interstitial vortices. It has been theoretically predicted in a simpler system by numerical simulations [5] the formation of different vortex matter phases, including a highly ordered glass of interstitial vortices moving with a high viscosity.

4. Pb films with PPCs

In Fig. 3a we represent the magnetoresistance $R(H)$ of a nanostructured sample of Pb film with antidots at three different selected temperatures, and a drive current of 1 mA. It may be seen that in the upper curve ($T = 7.138$ K), very close to T_c, $H = 0$, H_1 and H_2 are easily identified by the corresponding minima in the magnetoresistance. Besides, some structure is seen near $\pm H_{1/2}$, and near $\pm H_{1/4}$. When lowering the temperature to 7.136 K (just 2 mK), the latter features develop into visible minima.

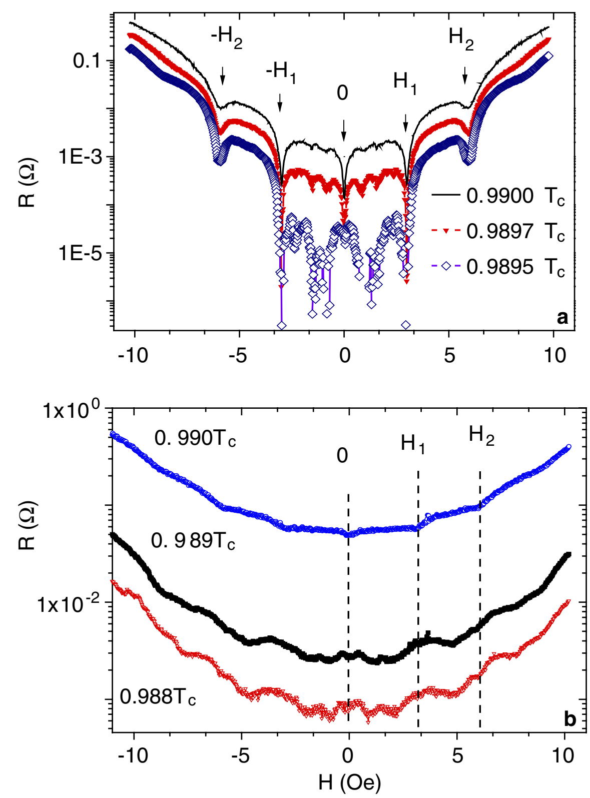

Fig. 3. Logarithm of magnetoresistance as function of perpendicular applied magnetic field of two Pb films with arrays of antidots: (a) N1, and (b) N2, at different temperatures close to T_c.

A further decrease of temperature of 2 mK gives rise to an excess dissipation at $H = 0$, in comparison with the field region between $H = 0$ and $\pm H_1$. The rest of the features commented above in the intermediate regime are more visible, and the minima at $\pm H_{3/4}$ are now clearly identified. At this temperature we are also able to observe a change in the slope of $R(H)$ in the proximity of $\pm H_3$. Also with this material the outstanding symmetry of the resistivity under field inversion is a guarantee of the intrinsic characters of all these features.

Most unusual is the excess resistivity in a narrow field range around zero applied field. This feature may be attributed to the presence of thermally excited vortex–antivortex pairs. The external magnetic field is expected to destroy these pairs inducing localized vortices with zero VFR. The existence of these pairs at zero field has been proposed experimentally [6,7] and theoretically [8,9] in nanostructured superconductors, though in structures quite different from the one reported here.

On the other hand, the developing of minima at low temperatures at rational fields multiples of 1/4 may be related to the four-fold symmetry of the array of antidots, as suggested by simulations [5]. These complete field scans have been performed at six or eight temperatures with each

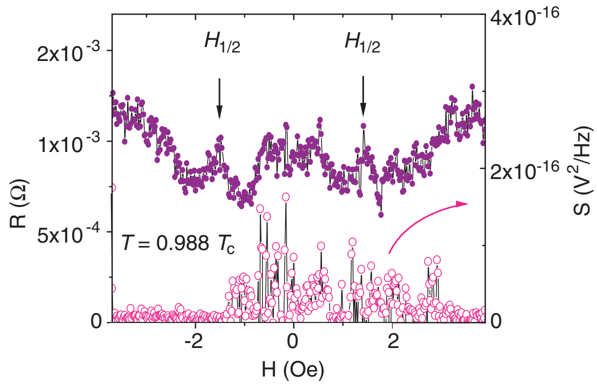

Fig. 4. Magnetoresistance (left scale) and noise power (@1 Hz) measured simultaneously close to T_c and at small fields in the Pb film with PPCs N2.

of dc current drives of 200 μA, 500 μA and 1 mA (25 kA/cm^2). The features commented above are well reproduced in all cases.

Moreover, the experiments have been reproduced with a similar sample (Fig. 3b), and though in this case pinning at integer matching fields was very reduced, the excess dissipation at zero field and lower temperature was clearly established. Additionally, shallow minima at $\pm H_{3/2}$ and $\pm H_{5/2}$ were observed.

Preliminary noise power measurements in the Pb with PPCs sample N2 (see Fig. 4) have shown that at the lowest temperatures of these experiments, noise power at 1 Hz which is very low (2×10^{-18} V^2/Hz) for low fields is enhanced about one order of magnitude for $|H| < H_{1/2}$. This could be further support the role of vortex–antivortex pairs in the proximity of zero field [10].

5. Conclusions

Thanks to a very good temperature stability (10^{-4} K for many hours) and very small steps in the applied field (between 0.02 Oe and 0.1 Oe), we have observed new features of the vortex flow resistance in the strong pinning regime in superconducting films with PPCs. In Nb with PPCs we observe a depression of magnetoresistivity at low matching fields, relative to the zero field resistivity, and a suppression of VFR for $H_3 < H < H_4$, followed by a steep enhancement of VFR at higher fields. In Pb with PPCs we observe at the lowest relevant temperatures an enhancement of resistivity at zero field and first matching field. These findings, which are qualitatively different from those reported in Ref. [6] with VFR transformed by increasing the drive current or Lorentz force are briefly discussed in the context of existing proposals.

Acknowledgements

We thank F. Peeters and D. Milosevic for fruitful discussions and R. Guerrero for assistance with measurements. This work was supported by the Grants MAT-2003-02600 from the Spanish MEC and GR/MAT/0252/2004 from CM. V.V. Pryadun thanks the ESF-VORTEX Program for support.

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