Coherent vortex motion in $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ nanobridges prepared by a substrate-etching technique

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Abstract

Nanobridges with widths down to 140 nm and lengths of about 250 nm were structured in a 25 nm $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ thin film, by means of a substrate-etching technique. At low temperatures, the current–voltage characteristics of these bridges show clear signs of periodic single-vortex motion. A quantitative comparison could be made with a vortex-flow model, which describes the forces acting on the vortices inside a hyperbolically shaped nanobridge, with dimensions much smaller than the thin film magnetic-penetration depth. It follows that the related viscous drag coefficient η is approximately 1.0×10^{-10} kg/ms and the penetration depth is approximately 4 μm . These values indicate that the transport properties are dominated by the weak-link behaviour of grain boundaries or twin boundaries in the thin film.

1. Introduction

To date, several successful techniques have been developed for preparing high- T_c Josephson devices [1–4]. In order to improve these high- T_c devices, high-resolution structuring techniques become important which do not degrade the superconducting properties of the films [5–8].

These techniques can also be applied for the preparation of “Dayem bridges” [9]. If their dimensions are less than a few times the coherence length, say of the order of 10 nm or less, they will show non-hysteretic high-speed Josephson behaviour [10]. Somewhat larger bridges, with dimensions which are still much smaller than the thin-film magnetic-penetration depth $\lambda_{\perp} \approx \lambda^2/d$, will also show Josephson-like behaviour (here λ is the magnetic-penetration depth and d is the film thickness). This is a result of the coherent (or periodic) motion of individual vortices

across the bridge [11,12]. By studying the dissipation processes in these bridges, clear information can be obtained about the mechanism of vortex motion in high- T_c material. This is a subject of ongoing interest [13–15].

In this article we report on the preparation and the current–voltage (I – V) characteristics of high- T_c $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ thin-film nanobridges, with widths down to 140 nm and lengths of about 250 nm. The bridges were prepared by etching steep trenches into the substrate, previous to the film deposition. The I – V characteristics of the smallest bridges show sharp steps and kinks which are clear signs of periodic vortex motion [11,12]. We will compare the I – V characteristics of these bridges with calculated I – V characteristics, derived from computer simulations of viscous vortex motion inside hyperbolically shaped bridges. The simulations make use of analytical expressions for the force on each vortex in those bridges [16]. It will be shown that there exists good agreement between these calculations and the mea-

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sured I – V characteristics of the smallest bridges at low temperatures.

2. Preparation

The preparation of high- T_c nanobridges is extremely difficult. At this moment there are still rather few reports on high- T_c thin films which are structured in a controllable way to dimensions well below 1 μm [6–8,17–24].

The conventional method for structuring YBCO thin films into small structures, i.e. by using some kind of etching or local damaging technique *after* the deposition of the superconducting film, tends to degrade the superconducting properties of the remaining structure, resulting in “dead layers” at the edges [19]. Only by applying this structuring technique with the utmost care, the degradation can be minimised, e.g. by using liquid-nitrogen cooling during the etching process [25].

To circumvent these problems, a few structuring processes have been developed where the substrate is structured into the desired pattern *before* the deposition and growth of the high- T_c film, e.g. by using an inhibition layer of Si or SiO_2 [26]. However, due to lateral diffusion of the inhibition material this method is not useful for the preparation of very small structures. An important improvement is made by vertical separation of the inhibition layer and the superconducting film [19,20].

We investigated a structuring method without inhibition layer, where very sharp substrate step edges are used to define the boundaries of the nanobridges (c.f. Ref. [27]).

First, a 300 nm niobium film is sputter deposited on a (100) SrTiO_3 substrate. On top of the niobium film, a resist mask with six nanobridges is prepared, using a trilayer electron beam lithography resist technique. This resist pattern is transferred into the niobium layer by reactive etching in a SF_6 plasma. After removal of the resist mask, the niobium pattern is transferred into the substrate by means of argon beam etching. This is the most critical part of the structuring process. We use a rotating sample holder and an argon beam under an angle of about 10° relative to the substrate normal, in order to obtain a very steep edge profile in the substrate and to avoid the build-

up of redeposited material along the edges of the niobium mask. With an acceleration voltage of 500 V, a beam current of 10 mA and beam diameter of approximately 2.5 cm, the measured etch rates of SrTiO_3 and Nb are 12 and 18 nm/min, respectively. Next, the niobium mask is removed in a SF_6 plasma, leaving almost perpendicular trenches in the substrate with sharp edges and depths of approximately 125 nm. To restore the surface quality of the substrate, we anneal the substrates at 1100°C for 6 h in flowing oxygen.

On the annealed substrate a smooth thin $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ film with a thickness $d=25$ nm is deposited by means of laser ablation. Standard deposition parameters were used. These parameters were optimised for the growth of epitaxial films with thicknesses between 60 and 200 nm, yielding reproducibly critical temperatures above 87 K [28]. After film deposition, silver contacts are evaporated and contact leads are defined by conventional photolithography and argon plasma etching, at a pressure of 4 Pa and a plasma bias voltage of 600 V. For these conditions, the etching rate of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ is approximately 9 nm/min. In order to minimise the temperature increase during etching and thereby the deterioration of the superconducting properties of the nanobridges, the substrate is glued onto the water cooled cathode (10°C) with a low vapour-pressure heat-conducting paste. For the same reason, we used a pulsed plasma (5 s on, 10 s off).

3. Measurements

Using the technique described above, nanobridges were prepared, which are defined by the gap between two trenches etched in the substrate. The widths w of the nanobridges range from 140 to 740 nm, and their length l is approximately 250 nm. Fig. 1(a) shows an optical micrograph of the central part of the sample, with one common electrode and six nanobridges around it. One of the nanobridges is shown in detail in Fig. 1(b). It can be seen that the edges of the trenches are very sharp, and the $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ film is “broken” at the edges. To estimate the “leakage” resistance over the edges of the trench, the structure also includes two “open bridges”.

Fig. 2 shows the resistance of the six bridge struc-

Fig. 1. (a) An optical micrograph showing the six nanobridges grouped around a common electrode. The widths of the bridges are, respectively, (1) 740 nm, (2) 440 nm, (3) 300 nm, (4) 140 nm, and (5, 6) 0 nm. (b) SEM micrograph of one of the nanobridges ($w \approx 300$ nm, $l \approx 250$ nm). (—) = 250 nm.

Fig. 2. The temperature dependence of the resistance in four nanobridges, with different widths and two “open” structures as described in the text.

tures on one substrate as a function of the temperature. In order to shield external fields during measurements the samples were mounted inside a copper and a μ metal (Cryoperm) can. The two open bridges show semiconducting behaviour, with a resistance at 100 K which is three orders of magnitude higher than the resistance of the four nanobridges. Taking the actual geometry of the structure into account, we estimate a negligible “leakage” conductance over the edge of the trench, between 10^{-8} and $10^{-7} \Omega^{-1}$ per $1 \mu\text{m}$ of the edge.

A systematic decrease of the transition temperature T_c of the nanobridges is observed for decreasing widths w . The $T_c \approx 46$ K of the widest bridge ($w = 740$ nm) is approximately equal to the T_c of an unstructured $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ film of the same thickness (i.e. $d = 25$ nm). The transition temperature is rather low, probably because the film deposition parameters were not optimised for the growth of thin films with a thickness of only 25 nm [29]. To be sure to have no Josephson coupling across the edges (like in step-edge junctions [27]), we did not use thicker films to obtain higher T_c 's.

In spite of the lower T_c of the bridges with the smallest widths (the T_c of the smallest bridge ($w = 140$ nm) is ≈ 20 K), we conclude that it is possible to define nanobridges in thin $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ films by means of a substrate-etching technique.

Fig. 3 shows the I - V characteristics of the nanobridges at 4.2 K. The simulated curves plotted in the same figure will be discussed in Section 5. A sharp

Fig. 3. The I - V characteristics of four nanobridges at 4.2 K, and simulated I - V characteristics with parameters as listed in Table 1. The simulated characteristics are shifted in the vertical direction in order to avoid overlap with the measurements. The bridge dimensions are $l = 250$ nm, and (a) $w = 740$ nm, (b) $w = 440$ nm, (c) $w = 300$ nm and (d) $w = 140$ nm.

step from the zero voltage to the dissipative state, and one or two kinks are observed in the I - V curves of the two smallest bridges ($w = 140$ and 300 nm). The step is more rounded for the bridge with $w = 440$ nm and is not visible in the I - V curve of the widest bridge with $w = 740$ nm.

In Section 5 we will show that the appearance of the sharp steps and the distinct kinks in the I - V curves of the smallest bridges, is in good agreement with a model which describes (coherent) viscous vortex motion across superconducting thin-film nanobridges with w and $l \ll \lambda_\perp$ [11,12,16]. In the next section, this model and related computer simulations will be discussed.

4. Model simulations

Expressions for the forces $F = F_x + iF_y$ (complex notation, $\sqrt{-1} \equiv i$) acting on the vortices inside hyperbolically shaped bridges, with dimensions $d \ll w$, l and $\xi \ll w$, $l \ll \lambda_\perp$ (cf. Fig. 4) were derived by

Fig. 4. Schematic drawing of a hyperbolic bridge.

Rogalla in Ref. [16]. The derivation is analogous to the calculations by Aslamazov and Larkin [12] which apply to the forces in extremely short bridges (i.e. hyperbolic bridges with angle $\beta = \pi/2$). By means of Youkowski conformal transformations, the hyperbolic bridge structure can be mapped onto an infinite strip and a halfplane. The resulting expression for the force on a vortex with index j is

$$F_j(z_j) = E_0 \frac{\pi}{\beta} (a^2 - z_j^2)^{-1/2} \times \left[q_j \frac{I}{I_0} + \frac{\beta}{\pi} \frac{\bar{z}_j}{(a^2 - z_j^2)^{1/2}} + \frac{1}{2} \tan \frac{\pi(\pi/2 - \Theta_j)}{2\beta} + i \sum_{k=1, k \neq j}^n q_j q_k \left(\frac{\bar{w}_j^{\pi/2\beta}}{\bar{w}_j^{\pi/2\beta} - \bar{w}_k^{\pi/2\beta}} - \frac{\bar{w}_j^{\pi/2\beta}}{\bar{w}_j^{\pi/2\beta} + (w_k e^{-i\pi})^{\pi/2\beta}} \right) \right], \quad (1)$$

where $z_k = x_k + iy_k$ and $z_j = x_j + iy_j$ are the positions of the vortices with indices k and j and orientations q_k and $q_j = \pm 1$. $z = \pm a$ are the positions of the two foci of the hyperbolas which make the perimeters of the bridge. Furthermore,

$$w_{j,k} \equiv z_{j,k}/a + \sqrt{z_{j,k}^2/a^2 - 1}, \quad \Theta_j \equiv \arg(w_j) \in [0, \pi], \\ \arg(\sqrt{z_{j,k}^2/a^2 - 1}) \in [0, \pi],$$

and $E_0 \equiv \Phi_0^2 d / 4\pi\mu_0\lambda^2$, $I_0 \equiv \Phi_0 d / 2\mu_0\lambda^2$ ($\Phi_0 = h/2e$ is the elementary flux quantum).

The first term in this expression accounts for the Lorentz force due to the interaction with the transport current, the second and third term describe the edge pinning force, whereas the summation describes the interaction with the other vortices. It can be verified that for $\beta = \pi/2$, $y = 0$ and vortex positions close to the edges, this expression becomes equal to the

expression in Ref. [12], describing the force near the edges in an infinitely short bridge.

In analogy with the discussion in Refs. [12] and [16] we assume viscous vortex motion, i.e. $dz_j/dt = F_j/\eta d$ with F_j as given in Eq. (1). Here η is the viscous-drag coefficient.

The current density is the highest at the line $y = 0$. Therefore, we restrict the simulations to the case where the vortices nucleate near the edges at positions $z = x$, with $x = -w/2 + \delta_l$ or $x = w/2 - \delta_r$, and subsequently, move along the x -axis. This is a reasonable restriction for small currents. At higher currents, when the distance between the vortices decreases, the vortices may start moving across the bridge along more than one path ($y \neq 0$). The nucleation distances δ_l and δ_r from, respectively, the left and right boundary of the bridge, are assumed to be constant and of the same order of magnitude as the coherence length [12,16].

In order to generalise the results we change over to dimensionless expressions. We define

$$\tilde{I} \equiv \frac{I}{I_0}, \quad \tilde{x} \equiv \frac{x}{w}, \quad \text{and} \quad \tilde{t} \equiv \frac{t}{t_0}, \quad (2)$$

where

$$t_0 = \frac{w^2 \eta d}{E_0}. \quad (3)$$

By substituting these expressions, together with an expression for the distance a between the foci of the hyperbolic boundaries and the centre of the bridge, i.e. $a = w/2 \sin \beta$, the equation of motion for the vortices becomes

$$\frac{d\tilde{x}}{d\tilde{t}} = \frac{\pi}{\beta} \frac{1}{\sqrt{(2\sin \beta)^{-2} - \tilde{x}_j^2}} \times \left[q_j \tilde{I} + \frac{\beta}{\pi} \frac{\tilde{x}_j}{\sqrt{(2\sin \beta)^{-2} - \tilde{x}_j^2}} + \frac{1}{2} \tan \frac{\pi(\pi/2 - \Theta_j)}{2\beta} + q_j q_k \sum_{k=1, k \neq j}^n \left(\frac{\Re_j(\mathcal{I}_j - \mathcal{I}_k) - \Im_j(\Re_j + \Re_k)}{(\Re_j - \Re_k)^2 + (\mathcal{I}_j - \mathcal{I}_k)^2} - \frac{\Re_j(\mathcal{I}_j + \mathcal{I}_k) - \Im_j(\Re_j + \Re_k)}{(\Re_j + \Re_k)^2 + (\mathcal{I}_j + \mathcal{I}_k)^2} \right) \right], \quad (4)$$

where

$$\Theta_j = \arctan(\sqrt{(2\sin \beta)^{-2} - \tilde{x}_j^2} / \tilde{x}_j) \in [0, \pi],$$

$\mathcal{R}_j = \cos(\pi\Theta_j/2\beta)$ and $\mathcal{J}_j = -\sin(\pi\Theta_j/2\beta)$. Furthermore $\mathcal{R}_k = \cos(\pi\Theta_k/2\beta)$ and $\mathcal{J}_k = -\sin(\pi\Theta_k/2\beta)$ with

$$\Theta_k = \arctan(\sqrt{(2\sin\beta)^{-2} - \tilde{X}_k^2}/X_k) \in [0, \pi];$$

$\mathcal{R}'_k = \cos(\pi\Theta'_k/2\beta)$ and $\mathcal{J}'_k = +\sin(\pi\Theta'_k/2\beta)$ with $\Theta'_k = \Theta_k - \pi$.

In Figs. 5(a) and (b), the simulated vortex motion is shown for two different transport currents in a symmetric bridge with $\beta = \pi/2$ and $\delta_1 = \delta_r = \delta = 0.02w$. The vortex motion is periodic and symmetric in $x=0$. Vortices with opposite signs appear in pairs at the edges of the bridge. In the centre of the bridge

they annihilate. Between two successive annihilations, the phase of the superconducting wave function between the banks of the bridge is shifted by an amount 2π . As a result, the average voltage over the bridge can be calculated as $V = \Phi_0/\tau$, where τ is the period of the vortex motion. Fig. 5(c) shows the resulting I - V characteristics. Also shown are I - V characteristics for three other ratios δ/w (with $\delta = \delta_1 = \delta_r$). The voltage is scaled with a factor $t_0\sqrt{\delta/w}/\Phi_0$.

In the limit $I \ll I_c$ (cf. Fig. 5(a)) (sufficiently low current) there is no more than one pair present inside the bridge. Here I_c is the current at which the Lorentz force equals the edge pinning force, and vortices start to move across the bridge. The entrance of the next pair is hindered by the presence of the previous pair. Only when the latter pair is annihilated, a new vortex pair can enter the bridge. With increasing transport current, the crossing of different vortex pairs begins to overlap in time (Fig. 5(b)). At currents, where the moment of vortex nucleation coincides with the annihilation of a vortex pair, i.e. at currents where the time-average number of vortex pairs inside the bridge equals an integer number, an additional term appears in the summation in Eq. (4). These positions show up as characteristic kinks in the I - V curves (Fig. 5(c)). We note that the successive kinks do not appear at equally spaced voltage positions, as calculated by Aslamazov and Larkin [12]. It can be verified that only for unrealistically small ratios δ/w , i.e. less than about 0.0005, the successive kinks are approximately equally spaced. By substituting the coherence length (a typical estimate for $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ $\xi \approx 2.5$ nm), we obtain $w > 5$ μm . This value is in conflict with the condition $w \ll \lambda_\perp$, which holds for the derivation of Eq. (1) and its equivalent in Ref. [12].

Fig. 5(c) shows that the height V_0 of the voltage steps is given by $V_0 \approx 5.7(\Phi_0/t_0)\sqrt{w/\delta}$. Furthermore, it can be verified that $I_c \approx \frac{1}{2}I_0\sqrt{w/\delta}$. Apart from small correction factors, of 1.1 and $1/\sqrt{2}$, respectively, these expressions are equivalent with the relations derived by Aslamazov and Larkin [12]. As indicated with the thin straight lines, the slope dV/dI at currents close to I_c can be approximated with V_0/I_0 . It follows that near I_c the slope can be estimated according to

$$\frac{dV}{dI} \sim 0.9 \frac{\Phi_0^2}{\eta d w^2} \sqrt{\frac{w}{d}}. \quad (5)$$

Fig. 5. (a), (b) The vortex positions as a function of time for two different transport currents in a hyperbolic bridge with $\beta = \pi/2$ and $\delta/w = 0.02$. (a) $I/I_0 = 3.5$ and (b) $I/I_0 = 5$. (c) Resulting I - V characteristics for four different ratios δ/w . The voltage is multiplied with a factor $(t_0/\Phi_0)[\delta/w]^{1/2}$.

Table 1

Parameters used for the simulated I - V characteristics in Fig. 3 and resulting estimations for the effective penetration depth λ and the viscous-drag coefficient η

Fig. 3	w (nm)	β (rad)	δ_l (nm)	δ_r (nm)	t_0 (ps)	I_0 (μ A)	λ (μ m)	η (10^{-10} kg/ms)
(a)	740	$\pi/2$	2.5	3	40	82	0.44	0.96
(b)	440	$\pi/2$	4.5	4	14	82	0.44	0.95
(c)	300	$\pi/3$	7	12	89	11	1.2	1.7
(d)	140	$\pi/3$	4.2	12	125	1	4.0	1.0

Fig. 6. (a), (b) The positions of the vortices as a function of time, in a hyperbolic bridge with $\beta=\pi/2$, $\delta_r/w=0.075$ and $\delta_l/w=0.015$, at a current (a) $I/I_0=2$, and (b) $I/I_0=3.5$. (c) Resulting I - V characteristic. The voltage is multiplied with a factor $(t_0/\Phi_0)[\delta_l/w]^{1/2}$.

In general, real bridges will never be perfectly symmetric, since the superconductor may be degraded over a larger distance at the edge than at the other edge. To introduce some asymmetry in the simulations, we investigated the effect of different values for the nucleation distances δ_l and δ_r at both sides of the bridge. Fig. 6 shows the simulated vortex motion in a bridge with $\beta=\pi/2$, $\delta_r/w=0.075$ and $\delta_l/w=0.015$, at two different transport currents. As expected, vortices start moving first from the edge where δ is largest, i.e. from the edge with the smallest pinning. When these vortices approach the other side of the bridge, vortices with opposite signs start moving from that side as a result of their mutual attraction. The resulting time-average voltage over the bridge, which is shown in Fig. 6(d), is again $V=\Phi_0/\tau$, where τ is the period of the vortex motion.

5. Discussion of the measurements

In Fig. 3 we plotted the I - V characteristics of four nanobridges at 4.2 K, and four I - V curves obtained from simulations as described in the previous section. The parameters of the simulations are listed in Table 1. The two smallest bridges were approximated as hyperbolic bridges with $\beta=\pi/3$ rather than $\pi/2$, to account for the larger ratio between the length and the width. The other parameters are only adjusted to yield a rough agreement with the measurements. It can be seen that the calculated and measured I - V curve in Fig. 3(d) ($w=140$ nm) are very similar. The agreement between simulation and measurement becomes worse if the width increases (Figs. 3(c), (b), and (a), respectively). The step from the zero-voltage state to the dissipative state is more rounded and the typical kinks are not present in the characteristics

of the wide bridges ($w \approx 740$ nm and 440 nm). This is probably due to the fact that the flux pinning by distributed pinning sites inside the bridge becomes more important relative to the edge pinning. The flux pinning tends to randomise the vortex motion, thereby destroying the periodicity. This results in more rounded I – V characteristics. Moreover, the ratio between the characteristic interaction range $\lambda_{\perp}$ of the vortices and the width of the bridge decreases, resulting in a weaker interaction between the vortices, for a given number of vortices inside the bridge. The same holds for nanobridges prepared in thicker $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ films which show no clear voltage step ($d \approx 85$ – 100 nm [22,24]). In these bridges d is larger and λ is smaller due to the better film quality, resulting in a smaller interaction range $\lambda_{\perp} \sim \lambda^2/d$.

Thus, we believe that the viscous-flow model as described in the previous section provides a more or less adequate description of the vortex motion across the smallest bridge (Fig. 3(d)). It follows that the average vortex velocity $\bar{v}$ and the nucleation frequency ν can be estimated directly from the height of the voltage step V_0 at the critical current I_c . For currents close to I_c there is always just one vortex or vortex pair present inside the bridge (Figs. 5(a) and 6(a)). Therefore, $V_0 = \Phi_0 \nu \approx \Phi_0 \bar{v} / fw'$, where $f \sim 0.5$ is a geometrical factor which accounts for the fact that opposite vortices annihilate each other somewhere in the middle of the bridge, and $w' = w - \delta_l - \delta_r \sim w$. With $V_0 = 0.10$ mV and $w' \approx 1.2 \times 10^{-7}$ m, this results in $\nu \approx 5 \times 10^{10}$ Hz and $\bar{v} \approx 3 \times 10^3$ m/s.

From the parameters t_0 and I_0 of the simulated I – V characteristics, we can obtain order of magnitude estimations for the viscosity η and the penetration depth λ . These estimations only have limited significance for the two widest bridges where the correspondence between measurement and simulation is very poor (i.e. Figs. 3(a) and (b)). Substituting the widths w , and an estimated effective thickness $d = 20$ nm (instead of 25 nm to account for a presumably somewhat deteriorated top and interface layer) yields values as listed in the last two columns of Table 1.

According to this table the effective penetration depth increases for decreasing widths of the bridges. This is in agreement with the lower T_c and higher resistivity (Fig. 2) observed for the smallest bridges. The value $\lambda \sim 0.44$ μm is in reasonable agreement with values of λ reported in the literature if we take into

account the low T_c of the film material [30]. The rather large λ obtained for the smallest bridge suggests that the vortices are (almost) Josephson vortices [10]. Similar values were reported and discussed by Halbritter, and attributed to the intragrain weak-link behaviour in epitaxial thin films, caused by e.g. twin boundaries [31].

For all four simulations we find approximately the same viscous drag coefficient, i.e. $\eta \sim 1 \times 10^{-10}$ kg/ms. Similar estimations for η can be obtained by making use of Eq. (5). Thus, substitution of the approximate slope $dV/dI \approx 100(670)$ Ω of the I – V curves in respectively Figs. 3(c) and (d), together with $w = 300(140)$ nm, $d = 20$ nm and $\delta \sim \xi \sim 2.5$ nm, yields $\eta \approx 2.2(1.1) \times 10^{-10}$ kg/ms. This is almost the same value as we determined earlier, from the steps in the I – dV/dI characteristics of a small bridge in a (105) oriented $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ film [23]. These steps could be attributed to the activation of additional paths, along which vortices could cross the bridge.

The viscous-drag coefficient η can be compared with the standard Bardeen–Stephen approximation [32]

$$\eta = \frac{\Phi_0^2}{2\pi\xi^2\rho_n}, \quad (6)$$

where ρ_n is the normal-state resistivity. By substituting typical values $\xi \sim 2.5$ nm and $\rho_n \sim 100$ $\mu\Omega$ cm, we obtain $\eta \sim 1 \times 10^{-7}$ kg/ms, which is about a factor 500 larger than the experimentally determined values listed in Table 1.

The large deviation might be a result of the possible intragrain or intergrain weak-link behaviour of the $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ films [31]. Evidence for the weak-link behaviour of the bridges is provided by the very small magnitude of the magnetic self-field B near the observed critical current of the bridges. With $B \sim \mu_0 I_c / 2d$ and $I_c \sim 2$ μA we find $B \sim 1$ G which is well below the intrinsic $B_{c1} \sim 0.1$ T of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$. Following the approach of Sonin and Tagantsev [33] where a high- T_c superconductor with numerous weak links is treated as a Josephson medium, the effective viscous-drag coefficient related to the motion of “hyper-vortices” is given by

$$\eta = \frac{\Phi_0^2}{\rho_n s^2}. \quad (7)$$

Here s is the grain size. The normal-state resistivity

ρ_n can be estimated from Fig. 3. For the smallest bridge with $w \approx 140$ nm, $d \sim 20$ nm, $l \sim 250$ nm and $R_n \approx 10^3 \Omega$, it follows that $\rho_n \sim R_n w d / l \sim 1.1$ m Ω cm. Substituting this value, together with $\eta \approx 1.0 \times 10^{-10}$ kg/ms as listed in Table 1 (d), in Eq. (7) yields $s \sim 60$ nm. This is comparable with the average diameter $s \sim 100$ nm of the “hilly” surface structures seen in Fig. 1 (b), which may be related to the often observed spiral growth due to screw dislocations [34]. As we mentioned before, the weak-link behaviour can also be responsible for the large value of the observed penetration depth.

An estimation can be obtained for the boundary resistivity R_{bn} , according to $R_{bn} \sim R_n w d / N$ where $N \sim 5$ is the estimated number of weak-link boundaries across the smallest bridge ($w \approx 140$ nm). We find $R_{bn} \sim 10^{-8} \Omega \text{ cm}^2$ which is comparable with the magnitude of the intragrain twin-boundary resistivity reported in Ref. [31].

In the simulations we neglected the mass of the vortices. This can only be justified if the relaxation rate $\nu_0 = \eta / m$, where m is the vortex mass, is considerably higher than the frequency of the vortex motion. Following Suhl [35] the mass is given by $m \approx 3 \Phi_0^2 / 8 \pi \mu_0 v_F^2 \lambda^2$, where v_F is the Fermi velocity. Substitution of $v_F \sim 10^5$ m/s and $\lambda \sim 1$ μ m, yields $m \sim 4 \times 10^{-23}$ kg/m. Hence, $\nu_0 \sim 3 \times 10^{12}$ Hz, which is well above the typical vortex frequency $\nu \sim 5 \times 10^{10}$ Hz, as determined above.

6. Conclusion

In conclusion, we showed that nanoscale bridges can be prepared in very thin $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ films with a substrate-etching technique. Good insulating properties over the edges of prepared structures were observed.

The I - V characteristics of the smallest bridges ($w \approx 140$ nm and $w \approx 300$ nm), show characteristic steps and kinks. At 4.2 K they are in agreement with simulations, based on a model which describes viscous-vortex motion across hyperbolic nanobridges. The I - V characteristics of the two widest bridges ($w \approx 440$ nm and $w \approx 740$ nm) are more rounded, probably due to pinning of the vortices at random pinning sites inside the bridge, and due to a weaker interaction between the vortices (i.e. a smaller ratio

$\lambda_{\perp} / w$). From a comparison between the simulations and the measured I - V characteristics of the smallest bridge, a viscous-drag parameter of approximately 1.0×10^{-10} kg/ms can be obtained. This value is two orders of magnitude smaller than estimations based on the standard Bardeen–Stephen expression. A consistent explanation for the deviation is found if the transport properties are dominated by the weak-link behaviour of intergrain or intragrain boundaries. This interpretation is also in agreement with the large value obtained for the penetration depth λ (i.e. $\lambda \sim 4$ μ m for the smallest bridge). A typical distance between the boundaries of approximately 60 nm, and a boundary resistivity R_{bn} of the order $10^{-8} \Omega \text{ cm}^2$ were estimated.

We would like to emphasize that the investigated film was epitaxially grown, but with reduced T_c . For such films the transport properties are often dominated by weak-link behaviour of twin boundaries or grain boundaries. The obtained characteristic “grain” size of about 60 nm suggests that the boundaries correspond to interfaces between screw dislocations.

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