Evidence for nonlocal electrodynamics in planar Josephson junctions

A. A. Boris,1 A. Rydh,1 T. Golod,1 H. Motzkau,1 A. M. Klushin,2 and V. M. Krasnov1

1Department of Physics, Stockholm University, AlbaNova University Center, SE-106 91 Stockholm, Sweden
2Institute of Physics of Microstructures, 603950 Nizhni Novgorod, Russia

(Dated: May 6, 2013)

We study temperature dependence of the critical current modulation \( I_c(H) \) for two types of planar Josephson junctions: a low-\( T_c \), Nb/CuNi/Nb and a high-\( T_c \), YBa\(_2\)Cu\(_3\)O\(_{7-\delta}\) bicrystal grain-boundary junction. At low \( T \) both junctions exhibit a conventional behavior, described by the local sine-Gordon equation. However, at elevated \( T \) the behavior becomes qualitatively different: the \( I_c(H) \) modulation field \( \Delta H \) becomes almost \( T \)-independent and neither \( \Delta H \) nor the critical field for penetration of Josephson vortices vanish at \( T_c \). Such an unusual behavior is in good agreement with theoretical predictions for junctions with nonlocal electrodynamics. We extract absolute values of the London penetration depth \( \lambda \) from our data and show that a crossover from local to nonlocal electrodynamics occurs with increasing \( T \) when \( \lambda(T) \) becomes larger than the electrode thickness.

PACS numbers: 74.50.+r 74.45.+c 74.72.Gh 85.25.Cp

Josephson junctions are usually formed by a barrier sandwiched between two superconducting electrodes, as sketched in Fig. 1(a). Such overlap-type junctions have a local electrodynamics, described by a differential sine-Gordon equation \([1]\). The locality is caused by the smallness of the London penetration depth \( \lambda \), at which the magnetic field is screened in the electrodes, in comparison with the Josephson penetration depth, \( \lambda_J \), at which the field is varied along the junction, \( \lambda_J \gg \lambda \). In this case the field is locked inside the junction. Its distribution is quasi-one-dimensional and depends only on local, instantaneous values of the Josephson phase difference.

However, if the effective penetration depth becomes larger than \( \lambda_J \), the magnetic field is no longer locked in the junction. The field distribution becomes two-dimensional and is determined by a nonlocal integro-differential equation involving phases in the whole junction \([2]\).

It has been suggested that nonlocal electrodynamics can be realized in planar junctions formed at the edge between two superconducting films with the thickness of \( d < \lambda \) \([2,7]\). Incomplete screening by thin films leads to increase of the effective penetration depth. For \( d \ll \lambda \) it is equal to the Pearl length \( \Lambda = 2\lambda^2/d \gg \lambda \). Furthermore, unlike in the case of overlap junctions, the field should be applied perpendicular to the films. This leads to appearance of a large demagnetization factor (flux focusing) \([3,4,8]\) and causes spreading of stray magnetic fields at the surface of superconducting electrodes to a distance of the order of the junction width \( w \gg \lambda \), as sketched in Fig. 1(b). In recent years several types of planar junctions have been studied, including high-\( T_c \) grain boundary junctions \([9,12]\) and proximity-coupled junctions via semiconducting heterostructures \([13,14]\), ferromagnets \([14,16]\), normal metals \([17,18]\) or graphene \([19]\). The effect of flux focusing has been established in previous works \([3,8,9]\), but the role of nonlocality remains to be clarified.

Theoretically it has been predicted that properties of nonlocal and local junctions should be significantly different \([4,7]\). The difference is summarized in Table I. For example, in local junctions the Josephson critical current \( I_c \) as a function of applied magnetic field \( H \) exhibits periodic-in-field Fraunhofer modulation with a period \( \Delta H \approx \Phi_0/2\lambda \), where \( \Phi_0 \) is the flux quantum. The \( T \)-dependence of \( \Delta H \) is determined by \( \lambda(T) \). Close to \( T_c \), \( \lambda(T) \) diverges and \( \Delta H \) vanishes as \( (T_c - T)^{1/2} \). On the other hand, for nonlocal junctions the \( I_c(H) \) is not perfectly periodic in field and \( \Delta H \) is determined by spreading of stray fields, which depends solely on the geometry \( w \) and should be \( T \)-independent. Therefore, analysis of the \( T \)-dependence of \( I_c(H) \) close to \( T_c \) should provide a clear distinction between the local and nonlocal models.

In this work we experimentally study the temperature dependence of the \( I_c(H) \) modulation for two types of planar thin film junctions: a low-\( T_c \) Nb/CuNi/Nb and a high-\( T_c \) YBa\(_2\)Cu\(_3\)O\(_{7-\delta}\) (YBCO) bicrystal grain-boundary junction. We observe that at low \( T \) junctions can be described by local electrodynamics. However, at elevated \( T \) both junctions exhibit a qualitatively different behavior, consistent with occurrence of the nonlocal electrodynamics. We show that a temperature driven crossover from local to nonlocal electrodynamics, occurs when \( \lambda(T) \) becomes larger than electrode thickness.

Figures 1(c) and (d) represent images of studied junction. The YBCO grain-boundary junction was fabricated on a symmetrical bicrystal yttria-stabilized zirconia substrates ([001] tilt) with a misorientation angle of 24°. To prevent interface reactions, 40 nm thick CeO buffer layer was deposited prior to depositing the YBCO films. The YBCO film with the thickness \( d \sim 300 \text{ nm} \) and \( T_c = 86.5 \text{ K} \) was grown epitaxially by reactive high-oxygen-pressure metal co-evaporation using a rotating substrate holder at Ceraco Ceramic Coating company \([20]\). The substrate temperature was 665°C and the deposition rate \( \sim 0.4 \text{ nm/s} \). Subsequently, a \( w \approx 6 \mu \text{m} \) wide junction was patterned by photolithography and cryogenic Ar\(^+\)-ion etching. Details of bicrystal junction fabrication can be found in Refs. \([21,22]\). A low-\( T_c \) Nb/CuNi/Nb planar junction \((T_c = 8.3 \text{ K}) \) was made by focused ion beam (FIB) etching of a narrow (\( \sim 20 \text{ nm} \)) groove through a Nb/CuNi (70/50 nm) bilayer film. The films were deposited at room temperature on oxidized Si substrates by dc-magnetron sputtering at a base pressure \( \sim 10^{-8} \text{ Torr} \) and processing Ar pressure 5 mTorr. The
Cu57Ni43 film was deposited by co-sputtering from Cu and Ni targets with controlled Ni and Cu deposition rates. The bilayer film was patterned by photolithography and ion etching (CF4 reactive ion etching for Nb and Ar-milling for CuNi). The width of the junction was \(w \approx 5 \mu m\). Details of the Nb/CuNi/Nb planar junction fabrication can be found in Refs. [14-16]. Measurements were performed in a cryogen-free cryostat using a four-probe configuration. Magnetic field was applied perpendicular to the films, as illustrated in Fig. 1(b).

Figure 1(e) and (f) represent measured \(I_c(H)\) modulation patterns at different temperatures for the YBCO and the Nb planar junctions, respectively. At low \(T\), the central maxima at \(H = 0\) are significantly wider than subsequent lobes in \(I_c(H)\) and exhibit a characteristic linear decrease with field. Such behavior is typical for long junctions, \(w > 4 \lambda\). In this case the external magnetic field can be screened within the junction. The linear-in-field central maximum corresponds to the Meissner state without Josephson vortices inside the long junction. It ends at the Josephson lower critical field \(H_{c1}\) [9]. At \(H > H_{c1}\) Josephson vortices penetrate the junction and the \(I_c(H)\) modulation is restored. Thus defined \(H_{c1}\) is marked by the horizontal arrow for the curve at \(T = 75 K\) in Fig. 1(e). For the Nb junction, Fig. 1(f), the linear-in-field central maximum is seen only at the lowest temperatures. At elevated \(T\) the \(I_c(H)\) starts to resemble a Fraunhofer pattern, characteristic for short junctions, \(w \leq \lambda\). However, that \(I_c(H)\) modulation for short nonlocal junctions deviates from the Fraunhofer modulation with constant flux quantization field \(\Delta H\), typical for overlap junctions [11]. Indeed, from Fig. 1(f) it can be seen that at high \(T\) the first minima (half the width of the central maximum) is narrower than the subsequent lobes: \(H_1/\Delta H \approx 0.83\). This is close to the theoretical value 0.8173, calculated by J.R. Clem for short planar junctions [7]. The same ratio \(H_1/\Delta H \approx 0.83\) is observed for the YBCO junction very close to \(T_c\), when the junction becomes short, see the curve at \(T = 84 K\) in Fig. 1(e).
Triangles in Figs. 2(a) and (c) represent the T-dependence of \( \Delta H \) for Nb and YBCO junctions, respectively, obtained from the widths of the first and the third side-lobes of \( I_c(H) \) at positive (filled) and negative (open symbols) fields. It is seen that \( \Delta H(T) \) is almost constant. It does not show a tendency to vanish at \( T \to T_c \), as expected for local junctions, but rather even slightly increases with increasing \( T \). The absolute value \( \Delta H \sim 1 \) Oe is consistent with the prediction from Table I for nonlocal planar junctions. As seen from Table I, in the nonlocal model \( H_{c1}(T) \) is almost constant. This provides a clear evidence for nonlocal electrodynamics. The dotted horizontal line in Fig. 2(e) demonstrates that the divergence between the two models, which is probably the reason why a clear distinction could not be made from previous similar studies [3, 9]. However, such a distinction becomes apparent from our data at elevated temperatures. From Figs. 2(e) and (f) it is seen that at \( T > 70 \) K the local theory provides totally erroneous results with vanishing \( \lambda(T) \) at \( T \to T_c \). To the contrary, the nonlocal theory provides both a quantitatively correct absolute value of \( \lambda(0) \sim 0.2 \mu \text{m} \) at low \( T \) and a qualitatively correct \( T \)-dependence at \( T \to T_c \) with diverging \( \lambda(T) \to T_c \) and linearly vanishing \( \lambda^2(T) \sim T_c - T \) [25, 26]. This provides a clear evidence for nonlocal electrodynamics.

Circles in Fig. 2(c) represent the critical field \( H_{c1}(T) \) at the third side-lobe maximum \( I_c \). From this plot it is clearly seen that the field scale of \( I_c(H) \) modulation is indeed almost \( T \)-independent.

For \( T \to T_c \), the local model \( H_{c1}(T) \) at the third side-lobe maximum \( I_c \) (scaled by a factor 4). Using the measured \( H_{c1}(T) \), \( I_c(T) \) and the expressions for \( H_{c1} \) from Table I we calculate the \( \lambda(T) \) dependence. Figs. 2(e) and (f) represent the obtained \( \lambda(T) \) and \( \lambda^2(T) \) for overlap (local) [24] and nonlocal (local) cases. It is seen that \( \lambda(T) \) does not vanish at \( T > 70 \) K the local theory provides totally erroneous results with vanishing \( \lambda(T) \) at \( T \to T_c \). To the contrary, the nonlocal theory provides both a quantitatively correct absolute value of \( \lambda(0) \sim 0.2 \mu \text{m} \) at low \( T \) and a qualitatively correct \( T \)-dependence at \( T \to T_c \) with diverging \( \lambda(T) \to T_c \) and linearly vanishing \( \lambda^2(T) \sim T_c - T \) [25, 26]. This provides a clear evidence for nonlocal electrodynamics. The dotted horizontal line in Fig. 2(e) demonstrates that the divergence between local and nonlocal models occurs when \( \lambda(T) \) becomes larger than the electrode thickness \( d = 300 \) nm. This indicates that a temperature-driven crossover from local to nonlocal electrodynamics takes place.

Now we can understand why \( H_{c1} \) does not vanish at \( T \to T_c \) in our planar junctions. As seen from Table I in the nonlocal model \( H_{c1}(T) \propto I_c(T)\lambda^2(T) \). From Figs. 2(d) and (f) it is seen that \( I_c(T) \propto \lambda^2(T) \propto T_c - T \) close to \( T_c \). Therefore, \( H_{c1} \) is determined by the ratio of two similar vanishing
functions and remains finite at $T_c$. This is an intrinsic property and a consequence of nonlocal the electrodynamics in planar thin-film Josephson junctions.

To conclude, we have studied the temperature dependence of the critical current modulation for low-$T_c$ and high-$T_c$ thin film planar Josephson junctions. We observed a temperature-driven crossover from local to nonlocal electrodynamics. It takes place when $\lambda(T)$ becomes larger than the electrode thickness $d$. At elevated temperatures both junctions exhibited a similar unusual behavior, which is in drastic discrepancy with that for conventional overlap-type junctions, described by the local sine-Gordon equation: (i) The flux-quantization field $\Delta H$ of $I_c(H)$ modulation was $T$-independent, did not vanish at $T_c$ and was determined not by the London penetration depth $\lambda$ but solely by the junction geometry $w$. (ii) The critical field for penetration of Josephson vortices $H_{c11}$ remained finite at the critical temperature $T_c$. These observations provided clear evidence for nonlocal electrodynamics in thin film planar Josephson junctions in good agreement with theoretical predictions [4,7]. Our results indicate that the nonlocality indeed deeply affects properties of planar junctions.

The work was supported by the Ministry of Education and Science of Russian Federation project Nr. 8837 and the STINT foundation. We are grateful to R.G. Mintz for valuable remarks and to the Core facility in Nanotechnology at Stockholm University for technical support.

[1] A. Barone and G. Paterno, *Physics and Applications of the Josephson effect*, A Wiley Intersc. Publ. (1982), ISBN 0-471-01469-9.

[2] Y.M. Ivanchenko and T.K. Soboleva, *Phys. Lett. A* 147, 65 (1990).

[3] R.G. Humphreys and J.A. Edwards, *Physica C* 210, 42 (1993).

[4] R.G. Mints, *J. Low Temp. Phys.* 106, 183 (1997).

[5] V.G. Kogan, V.V. Dobrovitski, J.R. Clem, Y. Mawatari, and R.G. Mints, *Phys. Rev. B* 63, 144501 (2001).

[6] M. Moshe, V.G. Kogan, and R.G. Mints, *Phys. Rev. B* 78, 020510(R) (2008).

[7] J.R. Clem, *Phys. Rev. B* 81, 144515 (2010).

[8] P.A. Rosenthal, M. R. Beasley, K. Char, M.S. Colclough, and G. Zaharchuk, *Appl. Phys. Lett.* 59, 3482 (1991).

[9] B. Mayer, S. Schuster, A. Beck, L. Alff, and R. Gross, *Appl. Phys. Lett.* 62, 783 (1993).

[10] D. Winkler, Y.M. Zhang, P.A. Nilsson, E.A. Stepanov, and T. Claeson, *Phys. Rev. Lett.* 72, 1260 (1994).

[11] H. Hilgenkamp, and J. Mannhart, *Rev. Mod. Phys.* 74, 485 (2002).

[12] F. Tafuri and J.R. Kirtley, *Rep. Prog. Phys.* 68, 2573 (2005).

[13] T. Akazaki, H. Takayanagi, J. Nitta, and T. Enoki, *Appl. Phys. Lett.* 68, 418 (1996).

[14] V.M. Krasnov, T.Golod, T. Bauch, and P. Delsing, *Phys. Rev. B* 76, 224517 (2007); V. M. Krasnov, O. Eriksson, S. Intioso, P. Delsing, V. A. Oboznov, A. S. Prokofiev, and V. V. Ryazanov, *Physica C* 418, 16 (2005).

[15] R.S. Keizer, S.T.B. Goennenwein, T.M. Klapwijk, G. Miao, G. Xiao, and A. Gupta, *Nature* 439, 825 (2006).

[16] T. Golod, A. Rydh, and V.M. Krasnov, *Phys. Rev. Lett.* 104, 227003 (2010).

[17] R. W. Moseley, W. E. Booij, E. J. Tarte, and M. G. Blamire, *Appl. Phys. Lett.* 75, 262 (1999).

[18] T.E. Golikova, F. Hübler, D. Beckmann, N.V. Klenov, S.V. Bakurskiy, M.Yu. Kupriyanov, I.E. Batov, and V. V. Ryazanov, *JETP Lett.* 96, 668 (2012).

[19] D. Jeong, J.H. Choi, G.H. Lee, S. Jo, Y.J. Doh, and H.J. Lee *Phys. Rev. B* 83, 094503 (2011).

[20] Ceraco ceramic coating GmbH [http://www.ceraco.de].

[21] A. M. Klushin, C. Weber, M. Darula, R. Semerad, W. Prusseit, H. Kohlstedt, A. I. Braginski, *Supercond. Sci. Technol.* 11, 609 (1998).

[22] A. M. Klushin, W. Prusseit, E. Sodtke, S. I. Borovitskii, L. Amatuni, H. Kohlstedt, *Appl. Phys. Lett.* 69, 1634 (1996).

[23] V.M. Krasnov, V.A. Oboznov and N.F. Pedersen, *Phys. Rev. B* 55, 14486 (1997).

[24] In the field perpendicular to films the expression for $H_{c11}$ for overlap junctions should be corrected by the corresponding demagnetization factor, $H_{d1} = H/(1 - D)$. We have chosen $D = 0.91$ to obtain the correct absolute value of $\lambda$ at low-$T$. This value of $D$ is reasonable for our thin-film junctions.

[25] P. Zimmermann, H. Keller, S. L. Lee, I. M. Savic`, M. Warden, D. Zech, R. Cubitt, E. M. Forgan, E. kaldis, J. Karpinski, and C. Krüger *Phys. Rev. B* 52, 541 (1995).

[26] R. Prozorov and R.W. Giannetta, *Supercond. Sci. Technol.* 19, R41 (2006).