Flux flow in high-Tc Josephson junctions

Filatrella, G.; Pedersen, Niels Falsig

Published in:
Applied Physics Letters

Link to article, DOI:
10.1063/1.109696

Publication date:
1993

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Filatrella, G., & Pedersen, N. F. (1993). Flux flow in high-Tc Josephson junctions. Applied Physics Letters, 63(10), 1420-1422. DOI: 10.1063/1.109696

Flux flow in high-T_c Josephson junctions

G. Filatrella
Department of Physics, The Technical University of Denmark, DK-2800 Lyngby, Denmark and Physikalisches Institut Lehrstuhl Experimentalphysik II, Universität Tübingen Morgenstelle 14, D-72076 Tübingen, Germany

N. F. Pedersen
Department of Physics, The Technical University of Denmark, DK-2800 Lyngby, Denmark

(Received 16 February 1993; accepted for publication 24 June 1993)

The possibility of achieving fluxon nucleation in nonhysteretic high-T_c Josephson junctions due to the presence of inhomogeneities is investigated numerically. For a large range of parameters the I-V characteristics in presence of such discontinuities show a strong similarity with those obtained experimentally. The spatial inhomogeneities considered are on the scale of the Josephson penetration depth (μm). It is demonstrated that the topic is of interest for the construction of amplifiers. Thus when fluxons are generated the resulting flux flow regime proves to be much more sensitive than the uniform solution to external fields.

Wide high-T_c Josephson junctions fabricated with the grain boundary technique[1] and with the step edge procedure[2] show almost all the typical characteristics of usual, nonhysteretic Josephson junctions, but often with a pronounced flux flow signature. Here, wide refers to the junction dimension along the grain boundary or step edge. In the terminology of low-T_c, such junctions are usually referred to as long. The flux flow signature is particularly evident in the low voltage part of the I-V characteristics, where the flux flow nature is seen as a bump in the I-V curve. This effect is more evident when the junction is longer than the Josephson penetration depth λ_j; in the opposite limit the usual resistively shunted junction (RSJ)[3] behavior is typically observed. The result is surprising; when considering the properties of the sine-Gordon equation describing the uniform long junction;[3,4] as the junction is heavily damped, one would expect only spatial uniform solutions to be present. Therefore neither any dependence on the length of the junction, nor any signature of a flux flow state are to be expected. Quite naturally one has to consider a more refined model for the high-T_c long Josephson junctions, while the RSJ model (spatially uniform) seems to be appropriate for short junctions.

We have therefore investigated the effect of inhomogeneities on various scales to break the symmetry that prevents any spatial structure from appearing. The possibility that substantial effects on the μm scale occur in the fabrication of high-T_c Josephson junctions is known both for bicrystal junctions[5] and step edge junctions.[6] Such inhomogeneities are of a different length scale and nature than those discussed, e.g., in Ref. 7. The influence of inhomogeneities on the propagation of fluxons has been extensively studied theoretically (see Ref. 8 for a review) and experimentally in low T_c systems.[9] In this letter we investigate the overdamped case that is appropriate for high-T_c Josephson junctions. The standard mathematical treatment of impurities on the Josephson line often refers to a periodic infinite-length lattice of inhomogeneities. Since the purpose of this work is to investigate how randomly distributed defects can modify the properties of the junctions, we have to do investigation by numerically solving an appropriate model equation. Moreover, essential for this investigation is the problem of flux creation, that cannot be dealt within the framework of the usual perturbative treatments that *assumes* the presence of a fluxon.[4]

The numerical method employed for the simulation is based on a three point discretization in space and a fourth order Runge–Kutta algorithm in time. The model equation for a long Josephson junction is (here subscripts denote partial derivatives as usual):[3]

$$\phi_{xx}-\phi_{tt}-\sin\phi=\alpha\phi_t-\beta\phi_{xxt}-\gamma, \tag{1}$$

with boundary conditions:[10]

$$\phi_x(0,t)+\beta\phi_{xt}(0,t)=\eta(0), \tag{2a}$$

$$\phi_x(L,t)+\beta\phi_{xt}(L,t)=\eta(L). \tag{2b}$$

In these formulas all the distances are normalized to λ_j, and times to $\omega_j^{-1},=\lambda_j/\bar{c}$. the inverse plasma frequency, ($\bar{c}$ is the speed of the light in the junction); η is the normalized external field at the edges of the junction, $\alpha=(\phi_0/2\pi CI_0)^{1/2}/R$ and $\beta=L/R_p(2\pi I_0/C\Phi_0)^{1/2}$ are loss parameters (R, C, L, and R_P are the normal resistance, the capacitance, the inductance, and the surface impedance per unit length, respectively), γ is the bias current normalized to the maximum Josephson current I_0. In the following we will for simplicity neglect the surface impedance ($\beta=0$). The initial conditions were assumed to be the static solution $\phi(x)=\sin^{-1}\gamma$. We assume that the junction is nonuniform in a twofold sense: the maximum Josephson current and the normal resistance are position dependent, i.e., $I_0\rightarrow I_0(x)$ and $R\rightarrow R(x)$. Consequently, Eq. (1) is modified as follows:

$$\phi_{xx}-\phi_{tt}-\frac{I_0(x)}{I_0}\sin\phi=\frac{R}{R(x)}\alpha\phi_t-\beta\phi_{xxt}-\gamma, \tag{3}$$

[that obviously reduces to Eq. (1) if $I_0(x)=I_0$ and $R(x)=R$]. We moreover assume that the current and the resistance profile are such that when the maximum current increases the resistance decreases and vice versa, as one would expect from the RSJ model, where the product RI_0 follows the simple law $RI_0\simeq\Delta/e$ (Δ being the energy gap

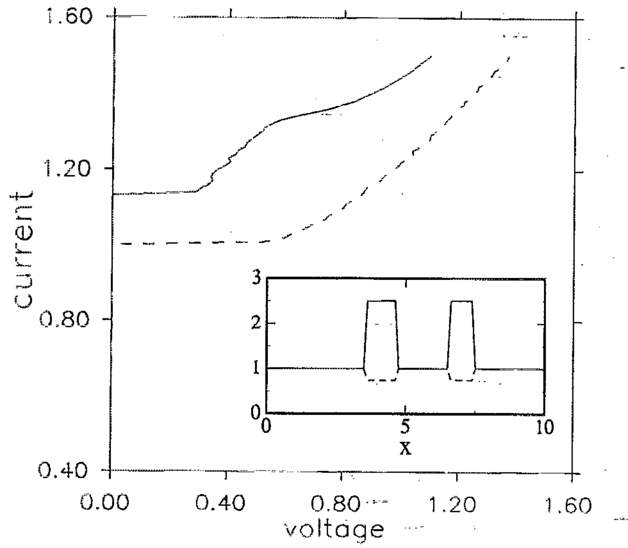

FIG. 1. I-V characteristic profile for homogeneous (dotted line) and inhomogeneous (solid line) junctions. The inhomogeneous junction contains two discontinuities. The parameters of the simulations are $L=10$, $\alpha=1$, $\eta=0$. In the inset is shown the behavior along the junction of $I_0(x)/I_0$ (solid line) and $R(x)/R$ (dotted line).

parameter).[3] We do not imply this to be strictly true for the junctions under examination, but as a heuristic indication of the relative behavior of the two quantities.

Under the hypothesis that $I_0(x)$ and $R(x)$ change significantly on a scale that is larger than or comparable to λ_j we systematically find that the I-V characteristic is modified from the usual unperturbed RSJ model to show the typical signature of flux flow junctions. This result is independent of the number of defects (we have tried up to five defects), and to their distribution. As an example we show in Fig. 1 an I-V curve in presence of two inhomogeneities (continuous line) compared to the one obtained for homogeneous case (dotted line). In the inset is shown the profile of the maximum Josephson current and of the resistance. We have also verified that the simulations do not show any hysterisis, i.e., that either increasing or decreasing the bias current leaves the I-V unchanged. The difference in the critical current (the homogeneous case is normalized to 1) indicates that the extra current due to the discontinuities is roughly 10% of the total current.

Figure 2(a) shows the details of the dynamics of the inhomogeneous case, compared with the uniform case. The passage of a fluxon is clearly indicated by a spike in the instantaneous voltage in the middle of the junction. For the same parameters, Fig. 2(b) shows the nucleation process of the fluxon by showing the instantaneous voltage at three different times ($t_1<t_2<t_3$) along the junction. The dotted line represents the chosen profile of the maximum Josephson current. Figure 2 suggests that, if the impurities are too densely distributed, fluxons cannot be formed; i.e., if the distance between the impurities is less than λ_j, the length scale of the fluxon, the parameters are averaged by the fluxon and are not "seen." For the very same reason impurities located near the edges are not relevant for the fluxon nucleation. This does not mean that the spatial in-

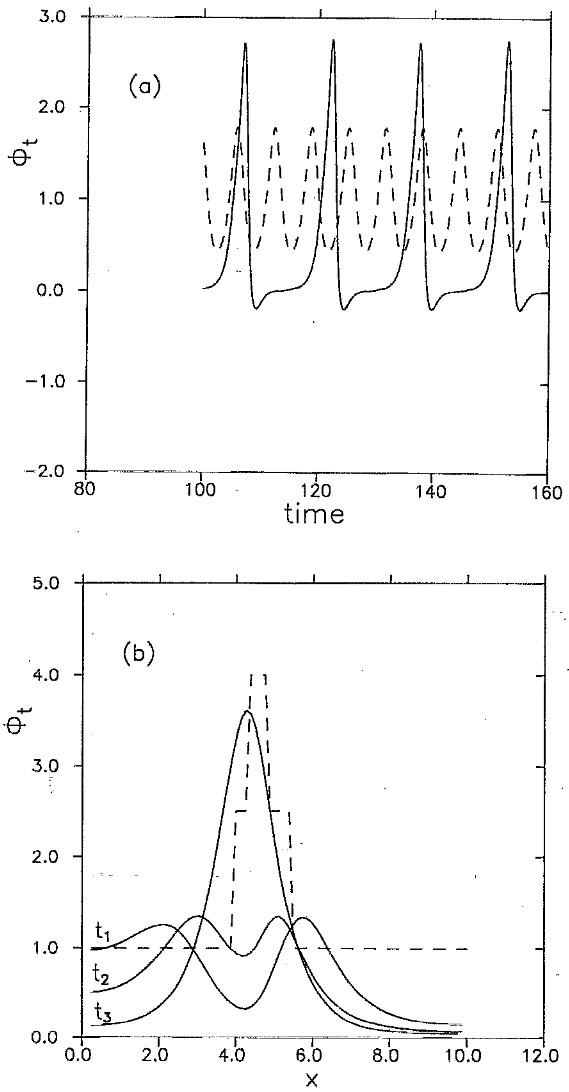

FIG. 2. (a) Internal dynamics of the homogeneous (dotted line) and inhomogeneous (solid line) junctions. The instantaneous voltage in the center of the junction is recorded as a function of time, (b) the nucleation process of a fluxon. The instantaneous voltage as a function of the position along the junction shown at three different instants ($t_1<t_2<t_3$). The discontinuous line represents the profile of the maximum Josephson current along the junction. The parameters of the simulations are: $L=10$, $\alpha=1$, $\eta=0$.

homogeneities on a smaller length scale are unimportant for high-T_c Josephson junctions. In Ref. 7 inhomogeneities on a length scale small compared with λ_j are discussed. Those have a profound influence on the junction properties, however in our opinion the effects discussed in Ref. 7 are not directly related to the topic discussed here.

The presence of flux flow in the inhomogeneous junctions is of particular interest for practical applications. In fact it is well known that the fluxon dynamics in hysteretic low-T_c Josephson junctions are very sensitive to external magnetic fields, for example, supplied by a control line.[11] A number of devices have been proposed, based on the manipulation of fluxons[12] in the long high-T_c Josephson junction. We recall here the flux flow amplifier that converts a current applied by a control line at one edge of the junction into a change in the voltage of the junction itself. A com-

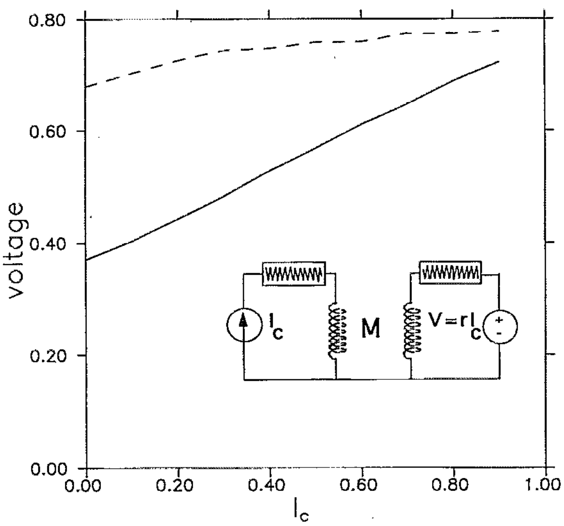

FIG. 3. Amplifier performance of the flux flow device: the voltage of an homogeneous (dotted line) and inhomogeneous (solid line) junction as a function of an external control current producing a magnetic field at one edge (see the insert for the electrical model). The inhomogeneous junction contains two discontinuities with the same profile as in Fig. 1. The parameters of the simulations are: $L=10$, $\alpha=1.0$, $\eta(0)=I_c$, $\eta(L)=0$.

parison between the performance of the homogeneous (dotted line) and inhomogeneous (solid line) junctions in such a configuration is shown in Fig. 3. As expected the presence of fluxons greatly improves the performance of the device: the transresistance is higher and the response is linear to a much higher voltage.

We propose, on the basis of numerical simulations, that defects on the scale of the Josephson penetration depth are responsible for the appearance of the flux flow characteristics of the *I-V* curve of nonhysteretic long high T_c Josephson junctions. We also suggest that such dynamics are important for practical purposes, such as the design of flux flow amplifiers.

We wish to thank P. Chaudhary, R. Gross, R. P. Huebener, and E. Sarnelli for interesting discussion. The work was supported by the European Community Esprit Project No. 7100.

[1] P. Chaudhary, J. Mannhart, D. Dimos, C. C. Tsuei, C. C. Chi, M. M. Oprysko, and M. Scheurmann, Phys. Rev. Lett. **60**, 1653 (1988); R. Gross, P. Chaudhary, M. Kawasaki, and A. Gupta, Phys. Rev. B **42**, 10735 (1990).
[2] K. P. Daly, W. D. Dozier, J. F. Burck, S. B. Coons, R. Ho, C. E. Platt, and R. W. Simon, Appl. Phys. Lett. **58**, 543 (1991); Y. Zhang, H. M. Mück, K. Herrmann, J. Schubert, W. Zander, A. I. Braginsky, and C. Heiden, *ibid.* **60**, 3048 (1992).
[3] See, e.g., A. Barone and G. Paterno', *Physics and Applications of the Josephson Effect* (Wiley, New York, 1982).
[4] D. W. McLaughlin and A. C. Scott, Phys. Rev. A **18**, 1652 (1978).
[5] Y. Divin and Z. Ivanov (private communication).
[6] F. Schmidl, L. Alff, R. Gross, K.-D. Husemann, H. Schneidewind, and P. Seidel, IEEE Trans. Supercond. **3**, 2349 (1993).
[7] M. Däumling, E. Sarnelli, P. Chaudhary, A. Gupta, and J. A. Lacey, Appl. Phys. Lett. **61**, 1355 (1992). E. Sarnelli, P. Chaudhari, and J. A. Lacy (unpublished).
[8] Yu. S. Kivshar and B. A. Malomed, Rev. Mod. Phys. **61**, 763 (1989).
[9] I. V. Vernik, V. A. Oboznov, and A. Ustinov, Phys. Lett. A **168**, 319 (1992).
[10] J. C. Eilbeck, P. S. Lamdhal, O. H. Olsen, and M. R. Samuelsen, J. Appl. Phys. **57**, 861 (1985).
[11] A. V. Ustinov, J. Mygind, N. F. Pedersen, and V. A. Obozonov, Phys. Rev. B **46**, 578 (1992). A. Petraglia, Master thesis, University of Salerno (unpublished).
[12] J. S. Martens, V. M. Mietala, T. A. Plut, D. S. Ginley, G. A. Vawter, C. P. Tigges, M. P. Siegal, J. M. Phillips, and S. Y. How, IEEE Trans. Magn. (to be published).