Pis'ma v ZhETF, vol. 122, iss. 2, pp. 123 – 124

Estimation of intergranular transparency of diffusive superconducting films from the shape of the density of states of the Abrikosov vortex

M. M. Khapaev[a 1)], *M. Yu. Kupriyanov*[b, c], *A. A. Golubov*[d], *V. S. Stolyarov*[e,f]

[a]*Computational Mathematics and Cybernetics, Department of Numerical Methods, Lomonosov Moscow State University, 119991 Moscow, Russia*

[b]*Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, 119991 Moscow, Russia*

[c]*Moscow Institute of Physics and Technology, 141700 Dolgoprudny, Russia*

[d]*Moscow Institute of Physics and Technology, 141700 Dolgoprudny, Russia*

[e]*Moscow Institute of Physics and Technology, 141700 Dolgoprudny, Russia*

[f]*All-Russian Research Institute of Automatics n.a. N.L. Dukhov (VNIIA), 127030 Moscow, Russia*

Submitted 27 May 2025
Resubmitted 10 June 2025
Accepted 10 June 2025

A technique has been developed for the evaluation of the transparency of grain boundaries in polycrystalline superconducting films. The model is founded upon a numerical algorithm for calculating the density of states of an Abrikosov vortex located in the center of a cylindrical granule, separated from the main superconducting matrix by a boundary with finite transparency. The present study calculates the dependencies of the gap difference in the density of states on both sides of the boundary and uses this difference to estimate the transparency of the interface.

DOI: 10.31857/S0370274X25070181, EDN: TIQMCN

Scanning tunneling microscopy (STM) and its unique capabilities in the field of tunneling spectroscopy with subnanometer spatial resolution have opened up new possibilities for studying the spatial variations of superconducting correlations both in multilayer structures with superconducting interlayers and in granular superconducting films [1–3]. In the former case, such studies make it possible to make certain judgments about the transport properties of the boundaries between superconducting layers and interlayers that do not have their own superconductivity [4–7]. In the second case, STM provides an original way to locally study both the spatial structure of magnetic flux lines [3, 8–17] and their interaction with structural features such as the behavior of pinning on defects [18–24].

The goal of this work is to propose a methodology for the assessment of the transparency of grain boundaries, derived from studies employing the STM to analyze the shape of the density of states of Type II Abrikosov vortices. Our calculations show that the grain boundaries located at distances of the order of superconducting coherence length from the center of the vortex core, are the most informative for such studies. Our results can be used to estimate intergranular transparency in superconducting thin films.

Funding. This work is supported by the Ministry of Science and Higher Education of the Russian Federation under grant # 075-15-2025-010.

Conflict of interest. The authors of this work declare that they have no conflicts of interest.

1) e-mai: vmhap@cs.msu.ru

1. C. Renner, I. Maggio-Aprile, and Ø. Fischer, *Vortex lattice imaging and spectroscopic studies of flux lines by scanning tunneling microscopy*, in *The Superconducting State in Magnetic Fields: Special Topics and New Trends*, World Scientific (1998), p. 226.
2. Ø. Fischer, M. Kugler, I. Maggio-Aprile, C. Berthod, and C. Renner, Rev. Mod. Phys. **79**(1), 353 (2007).
3. H. Suderow, I. Guillamón, J. G. Rodrigo, and S. Vieira, Supercond. Sci. Technol. **27**(6), 063001 (2014).
4. A. Golubov, Czechoslovak Journal of Physics **46**(2), 569 (1996).
5. V. S. Stolyarov, T. Cren, C. Brun, I. A. Golovchanskiy, O. V. Skryabina, D. I. Kasatonov, M. M. Khapaev, M. Y. Kupriyanov, A. A. Golubov, and D. Roditchev, Nat. Commun. **9**(1), 2277 (2018).
6. A. Vargunin and M. A. Silaev, Appl. Phys. Lett. **116**, 092601 (2020).

7. A. V. Bodyagin and D. Y. Vodolazov, ZhETF **167**(4), 544 (2025).
8. H. Hess, R. Robinson, R. Dynes, J. Valles Jr, and J. Waszczak, Phys. Rev. Lett. **62**(2), 214 (1989).
9. U. Klein, Phys. Rev. **41**(7), 4819 (1990).
10. H. Hess, R. Robinson, and J. Waszczak, Phys. Rev. Lett. **64**(22), 2711 (1990).
11. C. Renner, A. Kent, P. Niedermann, Ø. Fischer, and F. Lévy, Phys. Rev. Lett. **67**(12), 1650 (1991).
12. A. Golubov and U. Hartmann, Phys. Rev. Lett. **72**(22), 3602 (1994).
13. U. Hartmann, A. A. Golubov, T. Drechsler, M. Y. Kupriyanov, and C. Heiden, Physica B: Condensed Matter **194**, 387 (1994).
14. A. Volodin, A. Golubov, and J. Aarts, Zeitschrift für Physik B Condensed Matter **102**, 317 (1997).
15. A. Fente, E. Herrera, I. Guillamón, H. Suderow, S. Manas-Valero, M. Galbiati, E. Coronado, and V. Kogan, Phys. Rev. B **94**(1), 014517 (2016).
16. A. V. Putilov, C. Di Giorgio, V. L. Vadimov, D. J. Trainer, E. M. Lechner, J. L. Curtis, M. Abdel-Hafiez, O. S. Volkova, A. N. Vasiliev, D. A. Chareev, G. Karapetrov, A. E. Koshelev, A. Yu. Aladyshkin, A. S. Mel'nikov, and M. Iavarone, Phys. Rev. B **99**(14), 144514 (2019).
17. M. Fernández-Lomana, P. O. Aguilera, B. Wu, E. Herrera, H. Suderow, and I. Guillamón, J. Phys. Condens. Matter **37**(2), 025604 (2024).
18. S. Kashiwaya, M. Koyanagi, and A. Shoji, Appl. Phys. Lett. **61**, 1847 (1992).
19. M. Zehetmayer, Sci. Rep. **5**(1), 9244 (2015).
20. S. Bakurskiy, M. Kupriyanov, N. V. Klenov, I. Soloviev, A. Schegolev, R. Morari, Y. Khaydukov, and A. Sidorenko, Beilstein J. Nanotechnol. **11**, 1336 (2020).
21. R. A. Hovhannisyan, S. Yu. Grebenchuk, S. A. Larionov, A. G. Shishkin, A. K. Grebenko, N. E. Kupchinskaya, E. A. Dobrovolskaya, O. V. Skryabina, A. Yu. Aladyshkin, V. V. Dremov, I. A. Golovchanskiy, A. V. Samokhvalov, A. S. Mel'nikov, D. Roditchev, and V. S. Stolyarov, Commun. Mater. **6**(1), 42 (2025).
22. D. Kiselov, M. A. Skvortsov, and M. V. Feigel'man, SciPost Physics **15**(1), 008 (2023).
23. A. Mel'nikov and A. Samokhvalov, J. Low Temp. Phys. **217**(1), 82 (2024).
24. C. Chen, Y. Liu, Y. Chen, Y. N. Hu, T. Z. Zhang, D. Li, X. Wang, C. X. Wang, Z. Y. W. Lu, Y. H. Zhang, Q. L. Zhang, X. L. Dong, R. Wang, D. L. Feng, and T. Zhang, Phys. Rev. X **14**(4), 041039 (2024).