Technical Physics, 2022, Vol. 67, No. 12

08

Josephson effect in nanographite films

© S.G. Lebedev

Institute for Nuclear Research, Russian Academy of Sciences,
117312 Moscow, Russia
e-mail: lebedev@inr.ru

Received June 1, 2022
Revised June 1, 2022
Accepted September 26, 2022

In nanographite films, for the first time the Josephson current at room temperature has been obtained when measuring the current−voltage characteristics. Sach measurement confirms the earlier observations in nanographite film the effects of weak superconductivity: zeroing of the temperature dependence at 650 K of constant voltage on the sample when it exposed to an alternating microwave voltage due to the inverse Josephson effect, as well as the observation of local areas with the structure of magnetic vortices in a magnetic force microscope at room temperature. The resulting critical current value of $0.8\,\mu$A is significantly lower than expected values for the superconducting gap, as well as for pinning at the Bean–Levingston barrier. The measures for increasing the critical current is proposed.

Keywords: Josephson effect, nanographite film, superconductivity, room temperature.

DOI: 10.21883/TP.2022.12.55200.149-22

Introduction

Research on superconductivity has been going on for more than 110 years. First, pure metals were studied, in which the superconducting transition temperatures T_c were relatively low < 20 K. Then the era of high-temperature superconductivity (HTSC) began, represented by perovskites and layered compounds whose T_c now approaches 200 K. At high pressures in sulfur, lanthanum and yttrium hydrides T_c is even higher (see, for example, [1,2]). In 2020 a new record for sulfur hydride $T_c = 15^\circ$C at 267 GPa [3] has been published in the journal Nature.

Recently, there was considerable interest in the electromagnetic properties of nanostructures. From the theoretical point of view, the studies of V.Z. Kresin and Yu.N. Ovchinnikov [4,5] on giant enhancement of superconducting pairing in metal nanoclusters are significant. The theoretical study of K.N. Yugai [6] describes the features of superconductivity of nanoclusters. In low-dimensional systems it is necessary to take into account boundary effects, which begin to play a fundamental role. If in bulk systems on electron the ions act on the average by identical but differently directed forces, then this symmetry is violated at the boundary. An electron located, for example, on the left boundary of the nanocluster, is affected by the Coulomb force of attraction from the side of the ions directed from the boundary to the right deep into the system. On the other hand, the electron located on the right boundary of the nanocluster is subject to the same Coulomb force directed from the boundary deep into the system, i. e. from right to left. So, the electrons at the left and right boundaries of the system are effectively attracted to each other. It is shown that superconducting pairing in this system can be maintained at temperatures of 300 K and above.

Studies of nanographite films carried out for 30 years [7-12] demonstrated the presence of the so-called „weak superconductivity“ at room temperature and even higher up to 650 K (Fig. 1).

This result was obtained in the study of the temperature dependence of the inverse Josephson effect: induction of a constant voltage under the influence of a microwave signal. The picture is similar to the processes recorded many times in studies of traditional low-temperature [13] and high-temperature [14] superconductors.

According to the available experimental data [12], nanographite films are nanosized graphite granules 30−50 Å in size embedded in the amorphous carbon matrix. The presence of weak superconductivity may indicate the existence of a network of superconducting granules in

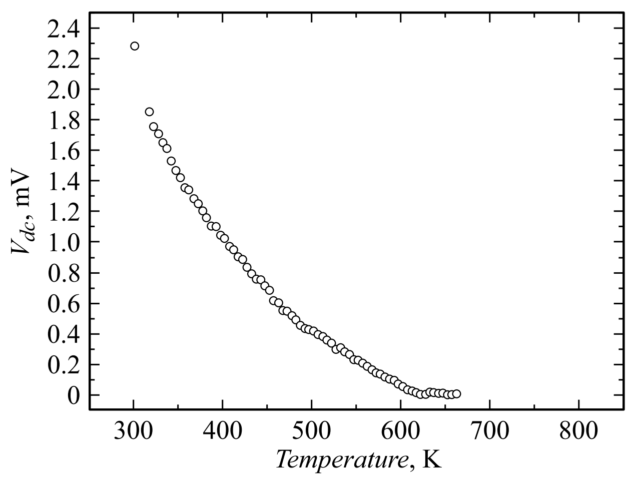

Figure 1. Temperature dependence of the inverse Josephson effect. The DC voltage induced by the microwave signal is equal to zero at $T = 650$ K.

a nonsuperconducting matrix. In this case, options for combining superconducting granules into a single superconducting cluster or isolated superconducting granules are possible. The detection of a constant voltage on a granular structure when it is irradiated with alternating electromagnetic radiation is the essence of the non-stationary inverse Josephson effect. This effect supposes the formation of a single superconducting cluster with a common phase coherence, which is preserved at sufficiently low flowing currents, when the structure of magnetic vortices found in nanographite films [12] (Fig. 2) remains immobile at relatively weak Lorentz forces, which are not capable of detaching the vortices from the pinning centers. At higher currents, the Lorentz forces detach the vortex lattice from the pinning centers, the vortex structure begins to move, the electrical resistance increases, the overall phase coherence is destroyed, and superconductivity disappears.

Another manifestation of the superconducting coherence of the nanographite structure would be the observation of

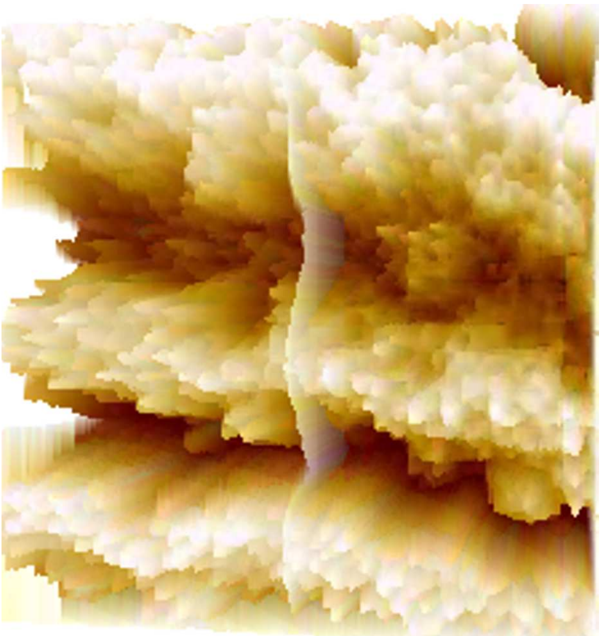

Figure 2. Structure of magnetic vortices detected with magnetic force microscope in a local area $1 \times 1\,\mu$m of a nanographite film at room temperature.

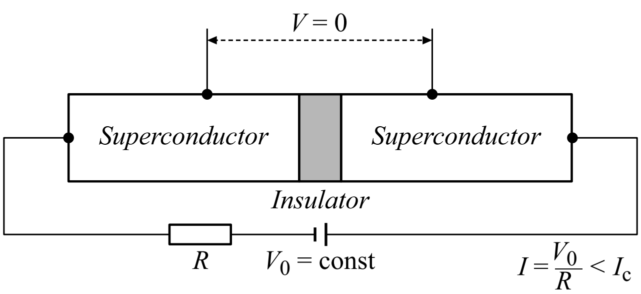

Figure 3. Scheme for measuring the CVC of a contact superconductor - insulator - superconductor

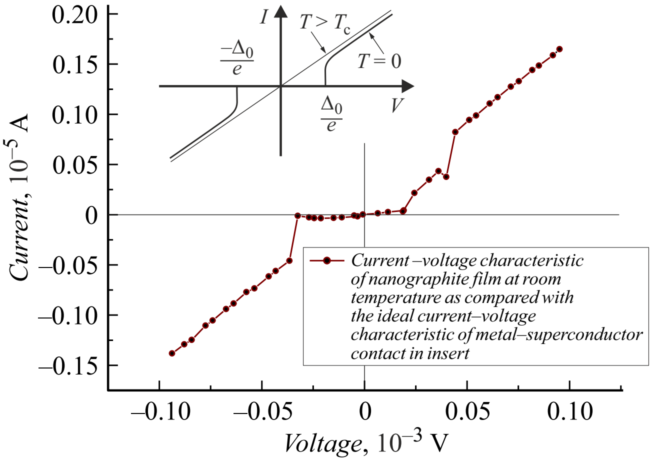

Figure 4. CVC of nanographite film at low currents and room temperature.

the stationary Josephson effect, i. e. flow of superconducting current at zero voltage. Fig. 3 shows the measuring scheme for the current-voltage characteristic (CVC) of a superconductor-insulator-superconductor (SIS) contact.

In the absence of a load resistance, which is the resistance of the measuring device, current will flow through the contact in the absence of voltage. However, when measuring the voltmeter will show a non-zero voltage $V = IR_{\mathrm{N}}$ at $I < I_c$, where I_c is the critical current of the Josephson junction, and R_{N} is meter internal resistance. At $I > I_c$ the CVC becomes ohmic. The corresponding CVC is shown in the insert in Fig. 4.

The main frame in Fig. 4 shows the experimental CVC of the nanographite film measured at room temperature. The two indicated CVCs are similar. The difference lies in the voltage value of the CVC transition to the ohmic branch. For a nanographite film, this value is not equal to the value of the superconducting gap, since the junction voltage corresponds to the beginning of the magnetic vortices movement when they are detached from the pinning centers.

To analyze CVC in Fig. 4 we will carry out the necessary estimates of the parameters of the nanographite film. Based on the data in Fig. 1 for the critical temperature of the nanographite film 650 K, the coherence length will be

$$\xi(0) = \frac{\hbar v_F}{\pi \Delta(0)} \sim 2\,\mathrm{nm}, \quad (1)$$

where $v_F = 10^6$ m/s is the electron velocity at the Fermi level, $\Delta(0) = 56$ meV is the superconducting gap at zero temperature. Magnetic field penetration depth in nanographite film

$$\lambda(0) = \left(\frac{mc^2}{4\pi e^2 n_s}\right)^{1/2} = 0.95\,\mathrm{mm}, \quad (2)$$

where $m = 0.03 m_e$ the effective electron mass in graphite structures [15], $n_s = 10^{28}\,\mathrm{m}^{-3}$ is the number of superconducting electrons. The obtained value of $\lambda(0)$ exceeds the thickness of the nanographite film $\sim 1\,\mu$m by several orders of magnitude. The first critical field for the beginning of magnetic vortices penetration into the nanographite film is

$$H_{C1} = \frac{\Phi_0}{4\pi\lambda(0)^2} \ln\left(\frac{\lambda(0)}{\xi(0)}\right) = 0.22 \cdot 10^{-8}\,\mathrm{T}, \qquad (3)$$

where $\Phi_0 = 2 \cdot 10^{-15}$ Wb is the magnetic flux quantum. As can be seen, the first critical field is very low, which allows the Earth's magnetic field to easily penetrate into the nanographite film. The upper critical field of superconductivity collapse will be

$$H_{C2} = \frac{\Phi_0}{2\pi\xi(0)^2} = 78\,\mathrm{T}. \qquad (4)$$

The vortices penetrating into the nanographite film are fixed by the Bean–Lewingston barrier [16], which is overcome by increasing the magnetic field to a value corresponding to 70% of the thermodynamic magnetic field [17]:

$$0.7H_{\mathrm{cm}} = 0.7\,\frac{\Phi_0}{2\sqrt{2}\pi\lambda\xi} = 4.41 \cdot 10^{-6}\,\mathrm{T}, \qquad (5)$$

which is more than by thousand times greater than the value of the lower critical field (3). The critical current of vortex depinning from the Bean–Lewingston barrier will be $I = 2H_{\mathrm{cm}} \sim 9\,\mu$A, which is an order of magnitude higher than the critical current $\sim 0.8\,\mu$A, which can be extracted from the data in Fig. 4. One of the possible explanations for the obtained difference may be related to the thermally activated mechanism of overcoming the Bean–Lewingston barrier at high critical temperatures.

The obtained value of the Josephson current (Fig. 4) is very small in comparison with both the superconducting gap and with the depairing current. The critical current increasing can be expected after the nanographite film irradiation in ion beams, which create column defects — cylindrical regions of the insulator that cross the film through thickness and are effective pinning centers for magnetic vortices. As shown in the papers jcite18-20: with a diameter of column defects close in size to the coherence length ξ, the depinning current is

$$j_d = 0.252\,\frac{a^2 e H_{\mathrm{cm}}^2}{\pi\hbar\xi} = 10^9\ \mathrm{A/m^2}, \qquad (6)$$

where a is the radius of cylindrical defect. This value exceeds the critical current in Fig. 4 by 7 orders of magnitude, which opens up the possibility of increasing the critical currents of nanographite films upon ion irradiation.

Conflict of interest

The author declares that he has no conflict of interest.

References

[1] A.P. Drozdov, M.I. Eremets, I.A. Troyan, V. Ksenofontov, S.I. Shilin. Nature, **525**, 73 (2015).

[2] M. Somayazulu, M. Ahart, A.K. Mishra, Z.M. Geballe, M. Baldini, Y. Meng, V.V. Struzhkin, R.J. Hemley. Phys. Rev. Lett., **122** (2), 027001 (2019). https://doi.org/10.1103/PhysRevLett.122.027001

[3] E. Snider, N. Dasenbrock-Gammon, R. McBride, M. Debessai, H. Vindana, K. Vencatasamy, K.V. Lawler, A. Salamat, R.P. Dias. Nature, **586** (7829), 373 (2020). DOI: 10.1038/s41586-020-2955-8

[4] V.Z. Kresin, Yu.N. Ovchinnikov. UFN, **178** (5), 449 (2008) (in Russian). DOI: 10.3367/UFNr.0178.200805a.0449

[5] V.Z. Kresin, Y.N. Ovchinnikov. Phys. Rev. B, **74** (2), 024514 (2006). DOI: 10.1103/PhysRevB.74.024514

[6] K.N. Yugaj. Vestnik Omskogo un-ta, **2** (68), 104 (2013); K.N. Yugaj. Vestnik Omskogo un-ta, (4), 88 (2010). (in Russian)

[7] S.G. Lebedev, S.V. Topalov. Bull. Lebedev Phys. Institute, **12**, 14 (1994).

[8] S.G. Lebedev. J. Phys. Chem. Solids, **75** (9), 1029 (2014).

[9] S.G. Lebedev. Nucl. Instruments and Methods Phys. Res., A, **521**, 22 (2004).

[10] S.G. Lebedev. Interna. Rev. Phys. (IREPHY), **2**, 312 (2008).

[11] S.G. Lebedev. *Unconventional Electromagnetics in Carbonaceous Materials* (Nova Science Publishers, Inc., 2010), ISBN: 9781616681746

[12] S.V. Lebedev. J. Materials Science: Mater. Electron., **31** (23), 20883 (2020).

[13] J.T. Chen, L.E. Wenger, C.J. McEwan, E.M. Logothetis. Phys. Rev. Lett., **58** (19), 1972 (1987).

[14] R. Munger, H.J.T. Smith. Phys. Rev. B, **44** (1), 242 (1991).

[15] B.T. Kelly. Physics Graphite. (1981), 477 p. ISBN: 0 85334 960 6

[16] C.P. Bean. Phys. Rev. Lett., **8** (6), 250 (1962).

[17] C.P. Bean. Rev. Modern Phys., **36** (1), 31 (1964).

[18] G.P. Mikitik. Phys. Rev. B, **104** (9), 094526 (2021). https://doi.org/10.1103/PhysRevB.104.094526

[19] K.R. Joshi, N.M. Nusran, M.A. Tanatar, K. Cho, W.R. Meier, S.L. Bud'ko, P.C. Canfield, R. Prozorov. Phys. Rev. Appl., **11** (1), 014035 (2019). https://doi.org/10.1103/PhysRevApplied.11.014035

[20] A.V. Samokhvalov, A.S. Melnikov. J. Experiment. Theor. Phys., **126** (2), 224 (2018). https://doi.org/10.1134/S1063776118020048