Superconducting Properties of 3-Dimensional Indium Wireframe in Opal Structure

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Abstract

Regular 3-dimensional ensembles on interconnected indium nanograins have been prepared in the voids of artificial opal. With the decrease of the In volume fraction in nanocomposite from 26% to 8% the increase of the superconducting transition temperature (up to 4.2K) and the critical magnetic field (up to few tens of the bulk In value) have been observed. The enhancement of the critical superconducting parameters in nanosize grains and the reduced screening of the external magnetic field are proved to be main contributions to the observed phenomena. Resistance anomaly at the normal-superconducting transition along the temperature or the magnetic field has been observed and assigned to the non-equilibrium processes at multiple superconducting - normal boundaries in In-opal nanocomposite.

Key words: opal; superconductivity; nanostructure

1. Introduction

Superconductivity of 3-dimensional regular arrays of superconductor grains is far less studied as compared with that of 2-dimensionally layers or assembling nanograins. In particular, large 3-dimensional arrays of superconducting nanoparticles have been prepared by embedding metal in voids of artificial opals. These ordered nanocomposites have shown unprecedented current-voltage characteristics, magnetoresistance and microwave response [1]. Further development of these materials requires understanding of their behaviour upon changing the lattice characteristics. The aim of this paper is to discuss the critical superconducting (SC) parameters of the In-opal nanocomposite observed when the filling fraction of the superconductor is reduced from 26% to 8%.

2. Experimental results and discussion

Opals used as templates in our studies have been assembled from silica spheres of diameter D=234 nm. In a face centred cubic (FCC) package of spheres there are two types of interstitial voids: O-voids with characteristic size d_O=0.41D connected with T-voids (d_T=0.23D) via bridges (d_b=0.15D). The porosity of the ideal FCC package of spheres is about 26% (sample A). It can be reduced by deposition of an additional dielectric on the inner surface of opal voids. We used a liquid phase deposition of amorphous SiO_2 for a rough infilling and a chemical vapour deposition of TiO_2 for a fine fitting the opal inner volume. 23 and 54 monolayers of TiO_2 were deposited in samples B and C, respectively. The free volume of the sample D was initially reduced down to 13% with amorphous silica and further by depositing 34 TiO_2 monolayers. Finally, the characteristic diameters of voids in investigated samples ranged from d_O=95 nm, d_T=54 nm and d_b=36 nm (sample A) to d_O=67 nm, d_T=26 nm and d_b=8 nm (sample

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D). Diameters were estimated from opals free volumes, which were obtained from the optical diffraction measurements. Infiltration of In melt in opals has been performed under the hydrostatic pressure to ensure the formation of the precise 3-dimensional indium replica of opal voids [2]. DC conductivity of samples has been studied in the liquid He4 bath at temperatures between 4.2K and 1.4K under the external magnetic field up to 65 kOe.

Fig.1 shows changing of critical temperature of SC transition T_c vs d_b. T_c was determined as a temperature at the middle point of the transition $\rho=0.5\rho_N$, where ρ_N is the normal state resistivity at T=4.2K. T_c exceeds sufficiently that of the bulk indium T_c =3.41K and increases progressively with the decrease of the conductive path cross-section in agreement with McMillan theory [3]. The R(T) curves of samples A, B, C and D are shown in the insert Fig.1 in the vicinity of the normal- SC transition. The resistive transition of the sample D starts at T=4.4K, then the resistance curve shows the peak at T=4.24K followed by a slow drop before it finally vanishes at T=3.7K. The onset of the resistance drop can be associated with the development of SC fluctuations in intergrain bridges since the superconductivity nucleates at the narrowest part of the conducting path. The larger temperature range of the SC transition of the sample D supports this model. At temperatures just below the onset, the conductive path in In-opal consists of S- and N-parts. The non-equilibrium give rise to the resistance peak at the high-temperature end of the transition. The development of similar resistive anomaly is known for the microscopically inhomogeneous superconductors and was reported earlier [4].

The dependencies of the critical fields on the temperature $H_c(T)$, where H_c is the field where $\rho=0.5\rho_N$, was extracted from the set of magnetoresistance curves for sample A, B, C and D and are shown in Fig. 2. Note that the resistive state occurs at much higher magnetic field than H_c of the bulk In, which is only 280 Oe at T=0K. Apparently, both the confinement of the superconductivity in nanograins and lattice-defined loops are responsible for the observed enhancement of the critical magnetic field. In In-opal all loops possess fixed radii, therefore under applied external magnetic field the screening supercurrent will flow along the loop circumference. To fulfil the fluxoid quantization conditions in the loop, the screening current either adds or subtracts the field in the loop if the external field corresponds to the non-integer number of flux quanta per loop. These currents can be described in the same manner as magnetic vortices. The thickness of the superconductor, which forms the loop, is much less than the field penetration depth; therefore, there is always the field in the loop interior. Correspondingly, the actual field to screen is greatly reduced. Moreover, due to

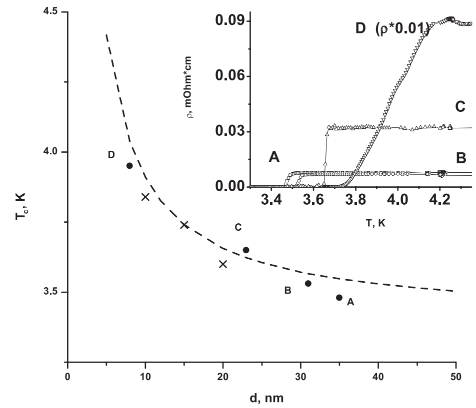

Fig. 1. T_c vs bridge diameter d_b of In replica in opal matrix. A, B, C and D points - experimental results for investigated samples. Dash curve was calculated according [3]; x - data [3].

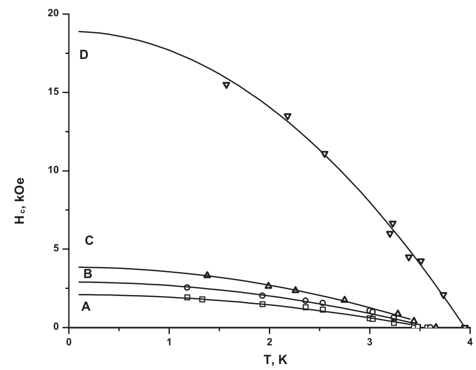

Fig. 2. Temperature dependencies of H_c for A, B, C and D samples. Solid lines are $H(T)=H(0)*(1-(T/Tc)^2)$ approximations.

the weak links incorporated in each loop, the next flux quantum can slip into the loop well before the external field will be able to suppress the SC in nanograins. As the result of the partial screening the in the In-opal SC withstand the high external field, moreover, the thinner the loop arms, the less the field difference between exterior and interior of the loop. This mechanism is in accord with experimentally observed increase of the H_c in In-opals of lower filling fraction.

Acknowledgements

This work was supported by RFBR 02-02-17685.

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