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Superconducting transition in Nb_3Ge irradiated by neutrons in the superconducting state

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Abstract

The results of superconducting transition investigations of intermetallic compound Nb_3Ge irradiated in superconducting state in the nuclear reactor cryochannel are presented. Superconducting transition temperature T_c of the thin intermetallic layer (2 μm) deposited on the molybdenum wire of 0.5 mm diameter was determined by the resistivity method. It is shown that T_c of Mo–Nb_3Ge composition changes insignificantly up to the fast neutron fluence $\sim 2.3 \times 10^{18}$ cm^{-2} ($E > 1$ MeV) at the irradiation temperature 12 K. It decreases from 19.5 to 18.8 K. It is established that significant degradation of T_c takes place as a result of subsequent long-duration annealing at 300 K with simultaneous increase of the superconducting transition width. This indicates the appearance of inhomogeneities in the matrix in the form of disordered or nonstoichiometric clusters. © 1999 Elsevier Science B.V. All rights reserved.

1. Introduction

The superconductors with A-15 structure are considered as priority materials in superconducting magnetic systems for thermonuclear reactors.

Predominant majority of investigations of T_c radiation degradation were carried out under irradiation in normal state (*N*-state), i.e. at considerably high temperatures, when radiation defects generation takes place simultaneously with their thermoactivated annealing. Therefore, the investigation of T_c behaviour under irradiation in superconducting state (*S*-state) is of considerable interest as these conditions are close to the real conditions of magnetic systems operation in the irradiation field.

The radiation effects in superconducting intermetallics with A-15 structure are sufficiently well studied nowadays. It is known that the critical temperature T_c of superconducting transition under irradiation by neutron fluence of $\sim 10^{18}$ cm^{-2} practically does not change. Subsequent increase of irradiation dose up to $\sim 10^{19}$ cm^{-2} leads to T_c degradation almost by 80% [1–4].

To explain such T_c behaviour the series of models were offered, connecting T_c degradation with changes of crystal lattice parameter [5], long-range order parameter [6], mean square atomic displacements [7], electron and phonon spectra [8,9], with appearance of disordered regions [10,11] etc. In spite of the fact that each of these models explains well enough (to some extent) the radiation degradation of T_c there is not as yet a single opinion on the nature of this phenomenon.

The present work is devoted to experimental investigations of superconducting transition in Nb_3Ge irradiated by reactor spectrum of neutrons in the superconducting state, as well as to the studying of the intermediate annealing effects and repeated irradiations in *S*-state.

2. Experimental

Nb_3Ge samples represented the layers of 2 μm width deposited on molybdenum wire of 0.5 mm diameter [12].

Superconducting transition in such compositions (Mo–Nb_3Ge) was determined by four contact (potentiometric) resistivity measurements with automatic record. The parameters of *S–N* transition of investigated samples before irradiation are given in Table 1.

Investigated samples were irradiated in the cryochannel of the nuclear reactor. Preliminarily cooled gaseous helium was used as refrigerant [13–15]. To

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Table 1

T_c^s, T_c and T_c^f are temperatures at which electrical resistance is equal to 0.05 R_N, 0.5 R_N, and 0.95 R_N, where R_N is the electrical resistance in normal state

Number of samples	Neutron fluence (cm^{-2})	T_c^s (K)	T_c (K)	T_c^f (K)
1–2	0	19.2	19.5	20.2
1–2	5.3×10^{18}	14.4	16.6	17.5
2–3	0	19.0	19.5	19.9
2–3	5.3×10^{18}	14.1	16.1	17.5

decrease the temperature of irradiated samples, refrigerator machine and compressor were switched in the cryochannel down to 12 K at a reactor power of 4 MW. Temperature oscillations during the whole period of irradiation do not exceed ±0.1 K.

As can be seen from Fig. 1, the container with samples and temperature sensors 1, attached to the mobile rod 2 was located in the irradiation zone of the cryochannel (position A). To carry out the resistivity measurements of irradiated samples as well as isochronic and isothermal annealings, the container with samples, by means of mobile rod, have been taken out from the irradiation zone and transferred to the testing zone (position B), representing the tubular furnace 11, located in the cold part of the cryochannel at the distance of 2.5 mm from the irradiation zone. The given temperature with precision ±0.03 K measured by means of a thermoregulator. After measurements, the container with samples was transferred back to the irradiation zone (position A) for subsequent irradiation. The precision of resistivity measurements was ±0.2%.

The irradiation of samples at 12 K was carried out at neutron intensity 8×10^{12} cm^{-2} s^{-1} ($E > 1$ MeV).

3. Results and discussion

The results of carried investigations are presented in Fig. 2. It is seen that up to the neutron fluence 2.3×10^{18} cm^{-2}, the decrease of the critical temperature of superconducting transition does not exceed 3.6% (point a), and the radiation increment of the resistivity (being the substance) measured at 21 K increases approximately by 60%. On achieving the mentioned neutron fluence, the samples were annealed (position B) at 300 K during nine days. As a result, T_c decreased again by 3.6% (point b) whereas the radiation resistivity increment of Mo decreased down to ∼12% at the expense of the radiation defects annealing.

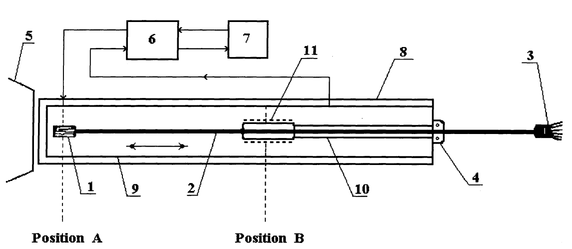

Fig. 1. Schematic representation of the experimental apparatus: 1 – sample, 2 – mobile rod, 3 – electrical plug, 4 – stuffing-box, 5 – active zone, 6 – refrigerator machine, 7 – compressor, 8 – cryochannel casing, 9 – cryochannel, 10 – stationary rod, 11 – heater.

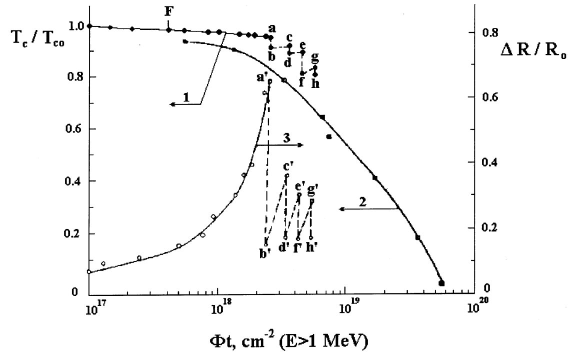

Fig. 2. T_c/T_{c_0} and $\Delta R/R_0$ vs. fast neutron fluence: 1 – $T_{irradiated} = 12$ K for Nb_3Ge (Institute of Physics, Georgian Academy of Sciences), 2 – $T_{irradiated} = 413$ K for Nb_3Ge (Brookhaven National Laboratory), 3 – $T_{irradiated} = 12$ K for Mo (Institute of Physics, Georgian Academy of Sciences). a, c, e, g – T_c/T_{c_0} after irradiation by different neutron fluences; b, d, f, h – T_c/T_{c_0} after annealing at 300 K for many days; a′,c′,e′,g′ – $\Delta R/R_0$ after irradiation by different neutron fluences; b′,d′,f′,h′ – $\Delta R/R_0$ after annealing at 300 K for many days; F –T_c/T_{c_0} for Nb_3Ge (Nuclear Center, France).

Then the samples were again introduced in the irradiation zone and the irradiation process was continued at 12 K up to the total neutron fluence of 3.3×10^{18} cm^{-2}. As a result T_c slightly increased (point c) and the radiation increment of Mo resistivity achieved almost 35% (point c′). Subsequent annealing at 350 K during 12 h led again to T_c decrease down to the value corresponding to point d.

After the third cycle of the samples' irradiation at 12 K and annealing at 300 K during 90 days, T_c decreased to the value corresponding to point f. At the end of the fourth cycle of irradiation up to the neutron fluence of 5×10^{18} cm^{-2} and subsequent annealing at 300 K during seven days, the total T_c degradation was 17% of the initial value and the total radiation resistivity increment of Mo constituted 15%.

So it turned out that the irradiation of Nb_3Ge by S-state fast neutrons of 2.3×10^{18} cm^{-2} fluence leads to slight T_c decrease (3.6% in all). But when irradiation was carried out at the same neutron fluence at higher temperatures, the degradation of T_c achieved ∼18% (see curve 2 in Fig. 2) [1].

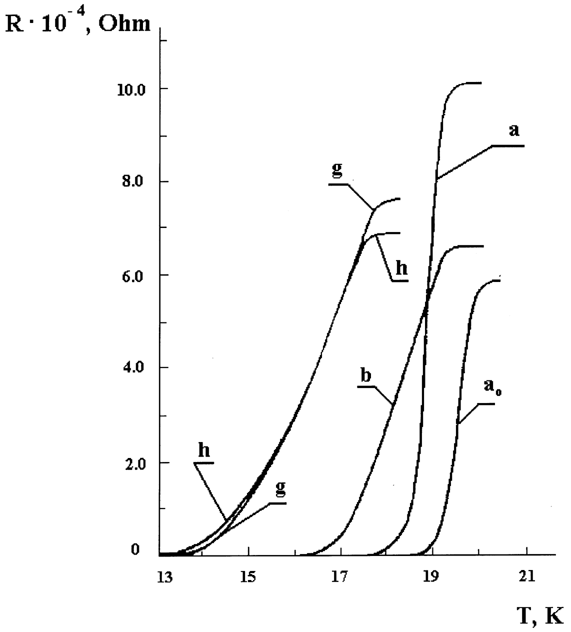

Fig. 3. *S–N* transition vs. radiation heat treatment. a_0 – before irradiation, the other symbols are analogous to the ones in Fig. 2.

The same slight T_c degradation was observed for Nb_3Ge irradiated by neutrons of nuclear reactor at the temperatures 18–21 K (see point F on the curve 1 in Fig. 2) [16].

The annealing of the samples at 300 K irradiated up to the various neutron fluences showed that T_c was not restored its value and further degradation was observed. The same result was observed in Ref. [17] for Nb_3Ge irradiation by oxygen ions.

It is seen from the table and Fig. 3 that the width of *S–N* transition is ~1 K. This indicates that investigated samples contained the inclusions i.e. of Nb_3Ge tetragonal phase having low T_c value [18].

The results of our investigations have showed that low-temperature neutron irradiation of Mo–Nb_3Ge composition practically does not lead to the change of the temperature width of *S–N* transition, while the subsequent annealing at 300 K along with T_c decrease causes nearly three times broadening of transition.

It should be noted also that after annealing, the low-temperature 'tail' appears on the curve of superconducting transition (curve b on Fig. 3) indicating the appearance and development of inhomogeneities in the crystal matrix.

Thus the conclusion may be drawn that the high T_c degradation of superconductors with A-15 structure takes place only under such irradiation conditions when the processes of clusters formation or inclusions of other phase occur along with point defects generation, that is at higher temperatures. That means that at low-temperature irradiation when point defects are practically frozen, the radiation resistance of superconductors with respect to T_c should be considerably higher. That is confirmed by comparison of the curves 1 and 2 in Fig. 2.

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