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Influence of Nano-defects on Current-voltage Characteristics of HTc Superconductors

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Theoretical analysis is presented of the influence on the current-voltage characteristics of the nano-sized defects, which may be created by heavy ions irradiation or can arise in technological process, for instance during the winding procedure of the superconducting coil. Results of calculations, performed basing on developed model of the interaction of pancake type vortices appearing in HTc superconductors with nano-sized defects are presented. The energy balance for flux creep process is deduced and current-voltage characteristics calculated in the function of static magnetic field, in accordance with experimental behavior. This static analysis has been extended further on the case of the time-varying magnetic field in which existence of dynamical anomalies is predicted, according to our previous experimental data.

Keywords: Nano-sized defects, Current-voltage characteristics, Vortex dynamics, HTc superconductors, irradiation effects in solids, Critical current.

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1. INTRODUCTION

More and more intensively developing applications of HTc superconductors require careful knowledge on the characteristics of these materials, especially concerning the influence of conditions of their work on their performance [1]. In the present paper is given analysis of the influence of the nano-scaled defects on the current-voltage characteristics and therefore critical current of HTc superconductors. This subject is especially important for superconducting coils working in the nuclear accelerators, exposed to the heavy ions irradiation or in nuclear fusion It is relevant also in the superconducting wires, in which are created nano-defects in the form of micro-crushes in the process of coil winding and in technological process, as intrinsic defects. Nano-sized defects influence transport current flow, because they capture the pancake vortices but from other side damage layered structure of planar HTc superconductor, decreasing in this way critical current and therefore current-voltage characteristics.

2. MODEL PRESENTATION

In the model the columnar type nano-defects have been considered, created by the heavy ions irradiation of HTc superconductors. The geometry of interaction of such defect with the vortex is shown in Fig. 1. Total capturing of the pancake vortex decreases the energy of system, up to the level of the condensation energy. During deflection of the pancake vortex from the pinning center, energy increases up to the normal state value, chosen in energy scale units on zero level, for totally free vortex, as it indicates Eq. 1. Meanings of angles α and β are explained in Fig. 1, as well as radii of pinning center R_0 and vortex ξ. An increase of the system energy related to the normal state development during the movement of the pancake type vortex against cylindrical nano-sized defect, is given by an expression:

$$U = \frac{\mu_0 H_c^2 l}{2}[\xi^2(\alpha - \pi - \frac{\sin 2\alpha}{2}) - R_0^2(\beta - \frac{\sin 2\beta}{2})] \quad (1)$$

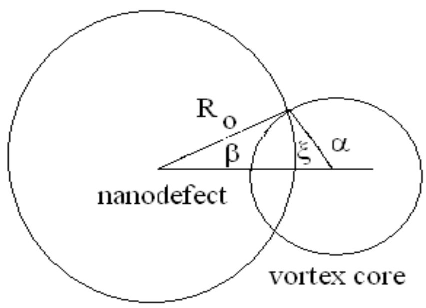

Fig. 1 – Schematic geometry of the interaction of the vortex with the core radius equal to the coherence length ξ captured on the columnar nano-sized defect

H_c is thermodynamic magnetic field, l pinning center thickness, which is equal now to the thickness of the CuO_2 layer in the oxide HTc superconductors. The potential well described by Eq. 1 is then tilted by the Lorentz force and elasticity forces of vortices lattice. Finally it is obtained then the potential barrier in the function of the transport current, temperature, magnetic field and elasticity constant of vortex lattice. Current at which energy barrier vanishes can be treated as critical one for the flux creep – flux flow process and is given by the formula:

$$j_c = \frac{\mu_0 H_c^2}{\pi\xi B} \cdot \frac{S(1 - S/d^2)}{d^2} \quad (2)$$

B is applied magnetic induction, μ_0 magnetic permeability. Parameter S is the cross-section of nano-defect, while d the lattice constant of the regularly arranged nano-defects into the square lattice. Predicted in the model current dependence of the energy barrier allows then to calculate current-voltage characteristics in function of magnetic field, temperature and others parameters. The results of calculations dependence of current-voltage characteristics on magnetic field for Bi-based superconductor with nano-sized defects is given in Fig. 2. Values of magnetic field correspond to the experimental data presented in Fig. 3 and allow to confirm qualitatively the agreement in shape of these curves - experimental and in theoretical model.

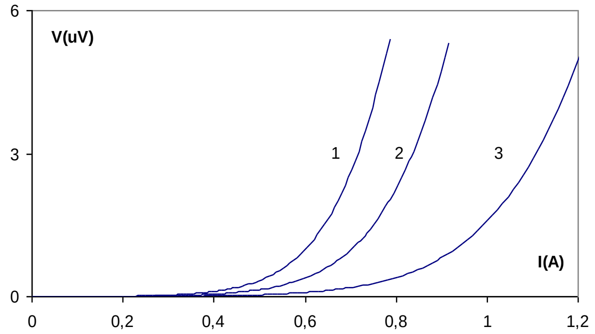

Fig. 2 – Calculated current-voltage characteristics of the HTc superconductor in static magnetic field: (1) B= 21,5 mT, (2) 16,3 mT, (3) 8,5 mT

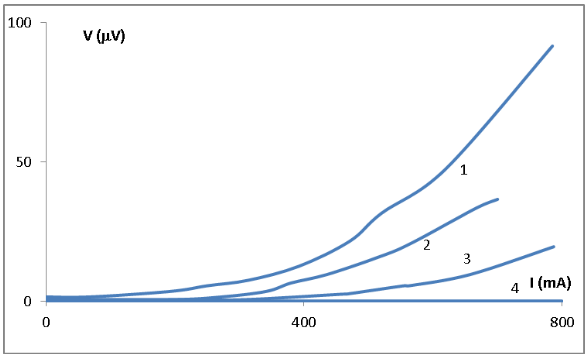

Fig. 3 – Measured current-voltage characteristics of the BiSrCaCuO ceramic in static magnetic field and T=77K: (1) B= 21,5 mT, (2) 16,3 mT, (3) 8,5 mT, (4) 0

In Fig. 4 is shown the superconducting temperature transition of this BiSrCaCuO sample, indicating its quality. This static analysis of the current-voltage characteristic of HTc superconductors was based on interaction of pancake vortices with external nano-defects, it is created by heavy ions irradiation or internal nano-defects created in technological process. Now we extend these considerations on the dynamic case of the slowly time-varying external magnetic field. Then generated in the superconducting slab electric field is related to the dynamic flux motion inside it, which has been theoretically calculated solving the magnetic diffusion equation. For linearly time-varying external magnetic field the solution of diffusion equation has been found in the polynomial form, of the second range. Additionally the physical conditions have been taken into account, by specifying considerations to the superconducting materials, in which critical current magnetic field dependence is described in an elaborated

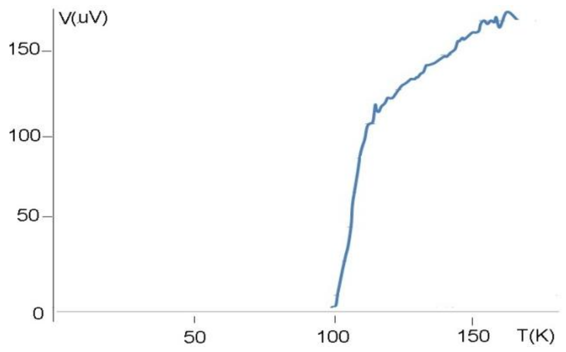

Fig. 4 – Resistively measured temperature transition to the superconducting state for BiSrCaCuO sample

model according to Eq. 2. In this model, calculations have been performed for the case of non-total and total penetration of magnetic induction into the superconducting slab. The shift of magnetic induction on both surfaces of slab, which effect is connected with the transport current flow has been taken into account. This effect leads to the asymmetry of the magnetic vortices penetration into the HTc superconducting sample and therefore to the generation of electric field on an axis of slab. Additionally the transition between these both regions non-saturated with vortices and saturated one with other shape of generated electric field in each of them leads to formation of some peak. Numerical results of calculations the generated electric field in the slowly varying magnetic field is presented in Fig. 5 in the function of magnetic field sweep rate. Such dependence really indicates on the dynamic character of this effect, which can be therefore useful for analysis of vortices penetration and diffusion it into superconductors. This effect observed us previously experimentally [2], can be therefore useful as a new tool for characterizing the properties of superconductors.

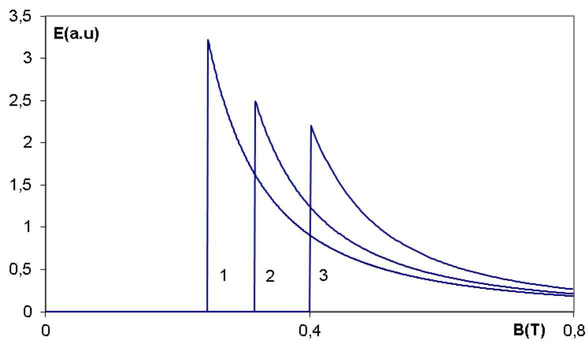

Fig. 5 – Calculated dynamical current-voltage characte-ristics of HTc superconductor in time-varying magnetic field: (1) dB/dt = 30 mT/s, (2) 50, (3) 80

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