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Influence of Quantized Vortex Dynamics on Superconducting Detectors

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Abstract: Superconducting materials are currently the subject of interest in modern electronic technologies, especially because they exhibit quantum phenomena on a macroscopic scale. The most evident examples are quantized vortices transporting magnetic flux, which movement determines the macroscopic current carrying phenomena in the superconducting materials. The present paper is intended to an analysis of the influence vortex dynamics, it is of the movement of the pancake type vortices in HTc multilayered superconductors in the flux creep process on their current-voltage characteristics and then critical current density. These are the essential parameters characterizing the superconducting electronic quantum devices, such as Josephson junctions detectors, bolometric or SQUiD type, current leads and superconducting magnets. In the paper is shown how various initial states of the captured vortices and their shape influence the pinning potential barrier and then current-voltage characteristics. It has been presented how fitting the current-voltage characteristics obtained in model to experimental data allows to determine the material parameters of the HTc superconductors such as nano-sized defects concentration, parameter influencing significantly the properties of sensitive superconducting detectors working in irradiation environment. Next critical current density of the superconducting materials in the vortex dynamics model has been analyzed as the function of the irradiation dose creating the nano-sized defects, for various values of the magnetic induction. Initial enhancement of the critical current results from the new pinning centers creation during irradiation. At the same time, the characteristic maximum of this dependence and following it decrease has been interpreted as related to the destructive action on the crystal lattice of the high dose of irradiation. Then the vortex dynamics analysis of HTc superconductors was applied for the interpretation of the dynamic anomalies of the current-voltage characteristics in a slowly varying magnetic field, which effect can be used in superconducting electromagnetic sensors, as well as for the description of the irradiation from long

Josephson's junctions with rotating vortex between the Josephson's junctions covers. Finally, the results of the previous investigations of the superconducting semiconductors with vacancies of lanthanum $La_{3-x}Vac_xSe_4$ are enclosed, possible class of the materials useful for the construction of the joined superconducting – semiconducting electronic quantum devices.

Keywords: quantized vortices in superconducting materials, static and dynamic current-voltage characteristics, superconducting detectors, Josephson's junctions; superconducting semiconductors

1. Introduction

Superconductors offer new opportunities to construct quantum electronic devices, which most famous examples are superconducting quantum interference devices - SQUIDS used for sensitive magnetic field measurements and quantum computing. Especial interest in the paper is intended for an analysis of the electromagnetic phenomena connected with the dynamics of movement of the quantized magnetic vortices, pancake type in HTc multilayered superconductors, which effects will influence the work of various sensitive electronic type superconducting devices as for instance superconducting sensors as bolometers, SQUID-s but also current leads to superconducting electromagnets. So this paper is intended to analysis of the topic of using superconducting materials in electronic quantum devices. At that aim, various models are in the paper investigated, based too on own authors' research.

2. The vortex dynamics in irradiation environment

The development of modern electronic superconducting devices is dependent on progress in the current properties of new superconductors. Therefore the vortex dynamics in superconducting materials is further intensively investigated, especially because it determines the critical current, main parameter from applied point of view, which is important in power applications and electronic quantum apparatus. Few interesting research in vortex dynamics is given in Ref. [1-10]. This part of the present paper is investigated important, from a scientific and applied point of view, the issue of the influence of irradiation on the current carrying properties of the superconductors, just by considering the dynamics of the pancake vortices in the high temperature multilayered superconductors, especially important topic influencing the proper work of superconducting detectors in nuclear devices. For analysis of the quantized vortices movement in the superconducting material, with appearing there nano sized defects created by irradiation in nuclear apparatus, we have proposed the following energy balance function F, given by Equation 1:

$$F(r_1, ..., r_N) = \sum_{i=1}^{N} U(r_i) + \frac{1}{2}\sum_{i\neq j}^{N} F_{inter}(r_i - r_j) - Jx\emptyset_0 \sum_{i=1}^{N} \delta r_i \, l_i - \sum_{i=1}^{N} \frac{C\delta r_i{}^2}{2} V_i \qquad (1)$$

Function $F(r_1, ..., r_N)$ describes the energy of the system of N vortices captured on the pinning centers. In the present paper, we have investigated the influence of the irradiation just according to the energy approach, assuming that neutrons crossing through a continuous superconducting medium produce the local normal regions of the larger energy, according to Ginzburg-Landau theory, which due to their small size are called as a nano-defects. The shape of these defects will be near to cylindrical, as is in the columnar defects case. However, due to mathematical difficulties with insertion into the model of the exact shape of nano-defect, in the present paper, it has been applied in an analysis the approximation of nano-defects by the rectangular shape, which already allows to follow the variations of the superconducting parameters under the irradiation procedure. The cylindrical defects were considered briefly too. The proposed above form of the energy equation is specified for the pancake type vortices characteristic in HTc superconductors. Summation in Eq. 1 proceeds over the positions of N vortices captured on the nano-scale pinning centers, localized at the positions r_i due to the action of the pinning potential U, specified in the first part of Eq. 1, which is responsible for such anchoring. The second term of Eq. 1 describes the interaction between vortices, which in the case of the multilayered structure, characteristic of high temperature superconductors, also includes the interaction of vortices from neighboring planes. The shape of these vortices in contradiction to the long Abricosov type flux lines, brings now the form of a short pancake. Such shape influences too the physical properties of magnetic vortices, which due to their short length, will not undergo the bending process and then flux cutting, effects appearing in low temperature bulk superconductors. The third expression in Eq. 1 is the Lorentz term connected with the displacement of the pancake vortex of the thickness l_i on the distance δr_i against the equilibrium initial position, under the Lorentz force arising during the flow of the current density j, interacting with the quantized magnetic flux Φ_0. Symbol x is a vector product. The last factor in Eq. 1 is connected with the elasticity forces of the vortex lattice, described by the spring constant C, acting in the deformed volume V_i.

The geometrical view of the vortex captured on the rectangular defect acting as pinning center is shown in Fig. 1a), while Fig. 1b), presents the vortex anchoring on the cylindrical pinning center.

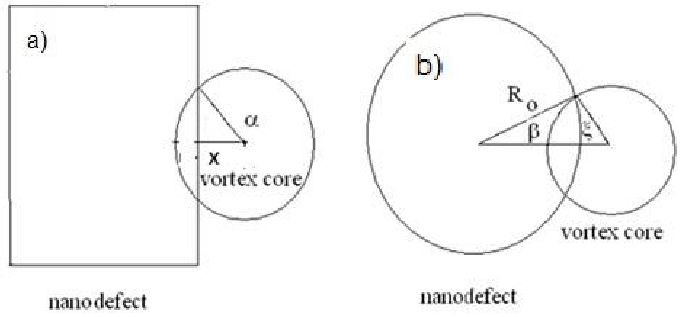

Figure 1. Graphical presentation of the pancake type vortex captured on (a) the rectangular and (b) cylindrical nano-sized defect.

The pinning potential U of vortex captured on the cylindrical defect, as shown in Fig. 1b, is given by the following relation:

$$U = \frac{\mu_0 l_i H_c^2}{2}\left\{\xi^2\left(\alpha - \pi - \frac{sin2\alpha}{2}\right) - R_0^2\left(\beta - \frac{sin2\beta}{2}\right)\right\} \qquad (2)$$

Here H_c is the thermodynamic critical magnetic field, l_i denotes the thickness of the superconducting layer in the multilayered structure of HTc superconductors. ξ is the coherence length, while meanings of the angles α and β as shown in Fig 1. The geometry and size of the presented in Fig. 1a defects refer especially to the mechanically created defects. Case Fig.1a corresponds to the defects in the form of dislocations, while defect shown in Fig.1b, of the type columnar defect, is created by heavy ions irradiation, which leads to the rise of the defects of the larger dimensions than the vortex core.

Currently, we investigate the defects of the nanometric size, initially approximated by the cuboid shape of the width smaller than the vortex core 2ξ, as shown in Fig. 2. Defects of such dimensions are created especially by the neutrons and light ions irradiation or as in the case of the PolFEL, by electron beam irradiation. Parameter $d < 2\xi$ is just the width of the nano-defect, which is dependent on the kind of irradiation.

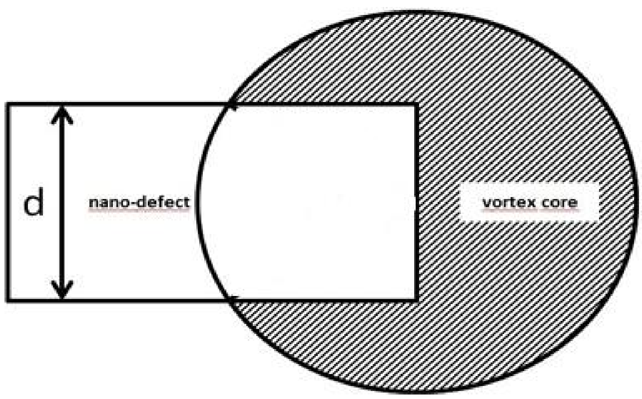

Figure 2. View of the half-captured initially vortex on the nano-sized defect of the width d.

The initial pinning potential energy, which leads to the capturing of the vortices, for the geometry presented in Fig. 2, is equal to:

$$U(0) = \frac{-\mu_0 H_c^2}{2} l\xi^2 \left(arcsin\frac{d}{2\xi} + \frac{d}{2\xi}\sqrt{1-\left(\frac{d}{2\xi}\right)^2} \right) \quad (3)$$

Determined on this base, the pinning potential barrier ΔU, which should pass vortex during its movement in the flux creep process during current flow, is given then in the current representation in the form:

$$U(\mathrm{i}) = \frac{\mu_0 H_c^2}{2} l\xi^2 \begin{pmatrix} -\arcsin(i) + arcsin\left(\frac{d}{2\xi}\right) \\ +\frac{d}{2\xi}\sqrt{1-\left(\frac{d}{2\xi}\right)^2} - i\sqrt{1-i^2} \end{pmatrix} + \propto_e \xi^2\left(\sqrt{1-i^2}-2\right)\sqrt{1-i^2} \quad (4)$$

The symbols in Eq. 4 were explained before, while last expression in Eq. 4 gives just the contribution to the potential barrier height ΔU, of the elasticity forces of the vortex lattice. Fig. 2 shows the case of the half-captured initially pancake vortex. However, analysis was performed too for others initial capturing pancake vortices positions. For instance in next Fig.3 is shown the geometry of the deeply captured vortex on the defect of the cross-section of the rectangular shape, which should be preferable for smaller defects width.

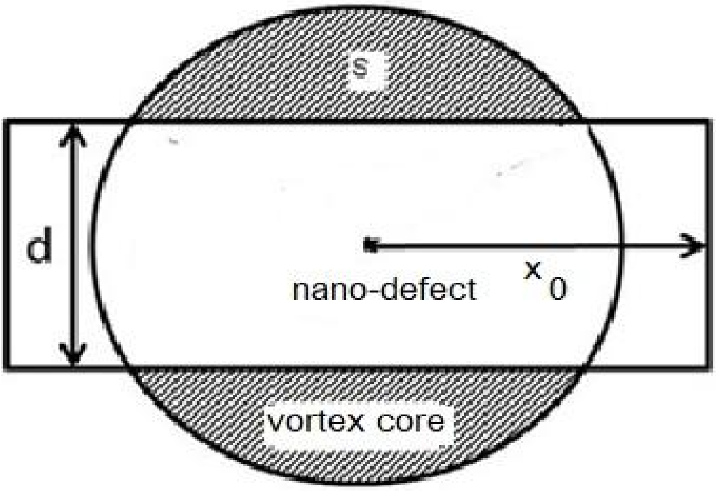

Figure 3. View of the deeply captured pancake vortex on the nano-sized pinning center of the width d. x_0 is vortex capturing depth, calculated from the edge of the defect, S vortex core area.

Calculating according to this vortex dynamics approach the dependence of the pinning potential barrier ΔU on the reduced transport current density i = j/jc, for various initial captured vortex positions, we obtain results presented in Fig. 4. It is seen here smooth decrease of the potential barrier ΔU, reaching finally zero at critical current. Based on this pinning potential barrier shape, the current-voltage characteristics are determined in the flux creep process according to relation 5, describing both the forward and backward quantized magnetic flux movement:

$$E = -B\omega a\left(e^{\frac{-\Delta(0)(1+i)}{k_B T}} - e^{\frac{-\Delta(i)}{k_B T}}\right) \qquad (5)$$

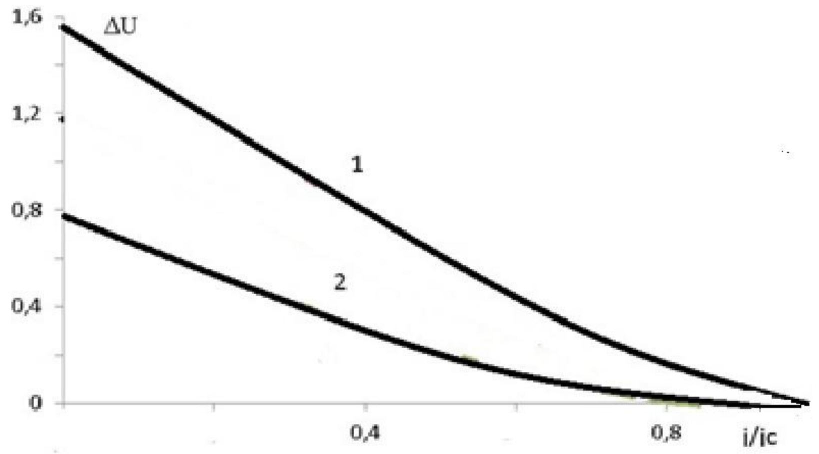

Figure 4. The dependence of the pinning potential barrier *ΔU* on the reduced transport current density for two initial positions x_0 of the captured vortex inside the pinning center of the size d/2ξ = 0,4: (1) fully captured case x_0= ξ, (2) half-captured x_0 = 0.

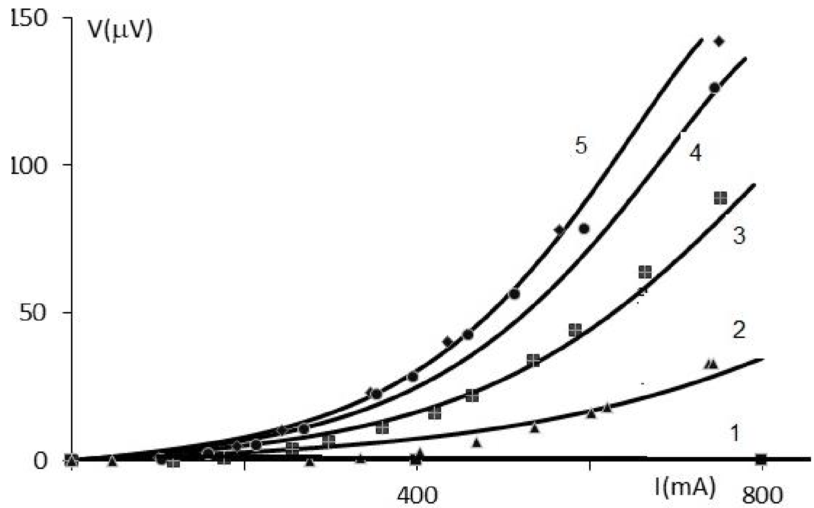

Figure 5. The comparison of the theoretical and experimental current-voltage characteristics for synthesized $Bi_{1.6}Pb_{0.3}Sr_2Ca_2Cu_{3.06}O_{10}$ ceramic superconductor, in liquid nitrogen temperature as function of applied magnetic induction: (1) B=0. (2) 13,5 mT, (3) 24 mT, (4) 33 mT, (5) 35 mT, (according to data in Ref. [11]).

In Fig. 5 are shown the results of calculations, according to Ref. [11] current-voltage characteristics of the HTc superconductor fitted to the experimental data measured on the $Bi_{1.6}Pb_{0.3}Sr_2Ca_2Cu_{3.06}O_{10}$ superconductor in liquid nitrogen temperature. This comparison shows that the inherent concentration of defects in the synthesized sample is equal to n = $3{\cdot}10^{10}$ cm^{-2}. So this vortex dynamics analysis and its results, applied to the current-voltage characteristics of the superconductors, one of the essential tools in quantum computing experiments, clearly indicate the usefulness of using the present approach for determining the superconducting sample quality. Here it is realized through the prediction of the concentration of the appearing in the ceramic sample inherent nano-defects but other information, for instance, concerning the average size of nano-defects can be obtained too.

Quantum superconducting devices frequently work in the irradiation environment, in which nano-defects are created in addition to inherent defects discussed before. Therefore it is important to understand the influence of irradiation and generally created then defects on the properties of the delicate superconducting low dimensional multilayered HTc superconductors, which can be used in these devices. Selected results of these investigations, relevant both from scientific and applied point of view, received based on above presented vortex dynamics model, are shown in Fig. 6. It is presented here, in which way irradiation creating the nano-sized defects will influence the critical current density of layered superconductor, as the function of magnetic induction.

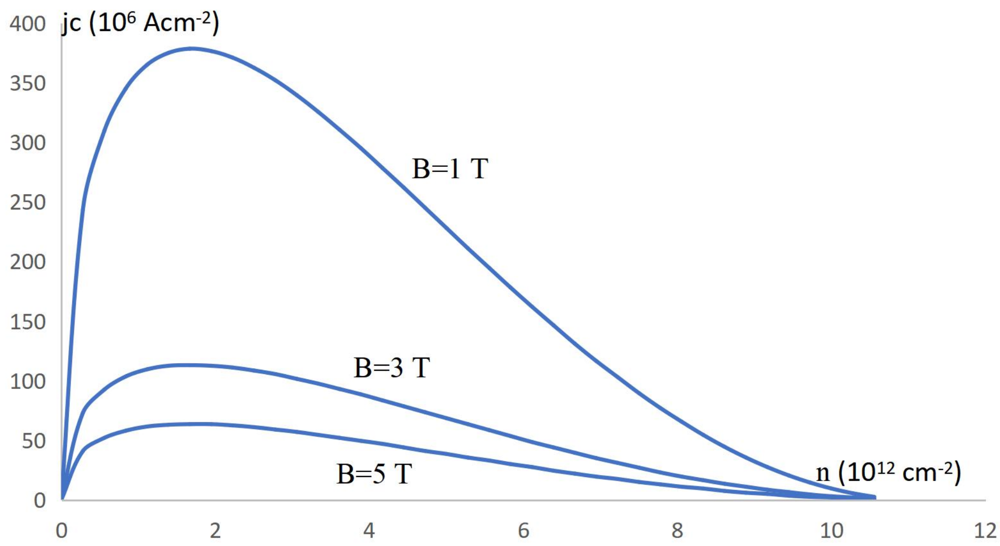

Figure 6. Theoretical dependence of the critical current density versus irradiation dose as the function of magnetic induction

An increase of the critical current in superconducting materials predicted theoretically, as is shown in Fig. 6 has been really experimentally observed on the irradiated by heavy ions HTc superconductors. The optimal surface concentration of ions in this experiment was about 10^{11} - 10^{12} cm^{-2}, which result is in agreement with the data shown in Fig. 6. As it has been indicated experimentally, most effective from the point of view of the critical current enhancement is irradiation by the fast neutrons or heavy ions of the energy loss 5-10 keV/nm, which produce the columnar defects, of the shape of the tracks with a diameter of the range 2-8 nm. Just this case corresponds to the investigated in the Fig. 6 dependences. Also, artificial insertion into HTc superconductors of the uranium U^{238} atoms leads after fast neutrons irradiation of concentration higher than 10^{18} cm^{-2} and energy larger than E > 1.4 MeV to their decay and creation this way new pinning centers. Sometimes applied method of enhancing the pinning centers concentration, increasing then the critical current of the superconducting tapes produced in 2G technology, is to evaporate on their substrates various normal metal spots as, for instance, gold dots, on which magnetic vortices are captured effectively. It is applied too also another artificial method of insertion the additional capturing centers into HTc superconductors, by the bombardment of the heavy atoms of BiPbSrCaCuO or HgBaCuO materials, by the protons or deuterium atoms of the energy in the range 200 – 1000 MeV, leading to the fission of heavy atoms producing then the new pinning centers.

The initial increase with irradiation of the critical current density in HTc superconductors shown in Figs. 6, is therefore directly related to an enhancement of the concentration of the pinning centers, more effectively interacting then with vortices. These pinning centers are created as the result of irradiation, as it was discussed above, while for higher irradiation dose the destructive influence of nano-defects, for instance caused by fast neutrons forming the vacuum bubbles (voids) in this structure and reducing the quantity of superconducting phase, starts to dominate. It also shows Fig. 6, in which way the critical current density decrease for larger irradiation dose. So presented here considerations should be helpful for analyzing the actions of superconducting detectors as for instance bolometers working in irradiation environments of nuclear physics apparatus as is the case of PolFEL - linear free electron laser and especially superconducting current leads or electromagnets coils of heavy ions accelerators.

3. Influence of the vortex dynamics on the superconducting sensors

Vortex dynamics is also the reason for the dynamic anomalies of the current-voltage characteristics of superconducting material in slowly varying magnetic field, which have been measured previously [12-13].

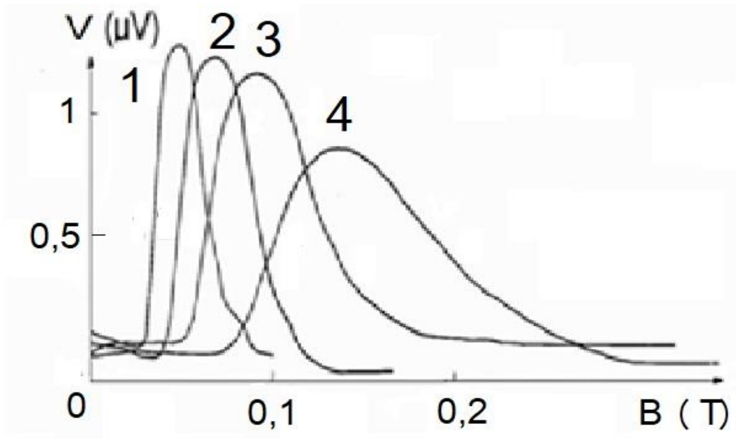

Figure 7. Measured dynamical anomalies of the I-V curves in YBaCuO superconductor for various values of the linearly sweeping magnetic field: (1) dB/dt= 1 mT/s, (2) 5 mT/s, (3) 10 mT/s, (4) 15 mT/s, (according to [12-13]).

Figure 7 shows an example of the experimental results of the dynamical anomalies of the I-V curves in YBaCuO superconductor for various values of the linearly sweeping magnetic field, while in Fig. 8 are the theoretical results calculated according to presented in point 2 vortex dynamics model, indicating the qualitative agreement with experimental data. As indicated in Figs 7 and 8, the above anomalies are sensitive to magnetic field sweep rate., its frequency, transport current amplitude and temperature, which suggests various possibilities of their applications in superconducting sensors. These anomalies depend on the diffusion velocity of magnetic quantized flux into superconductors and allow, therefore, to receive supplementary information on the penetration of magnetic vortices into superconductors. This feature can be useful in various sensors constructions, for instance, intended for determining superconducting sample quality and magnetic flux penetration and technically for determining the velocity of rotation of the rotor of the superconducting machine.

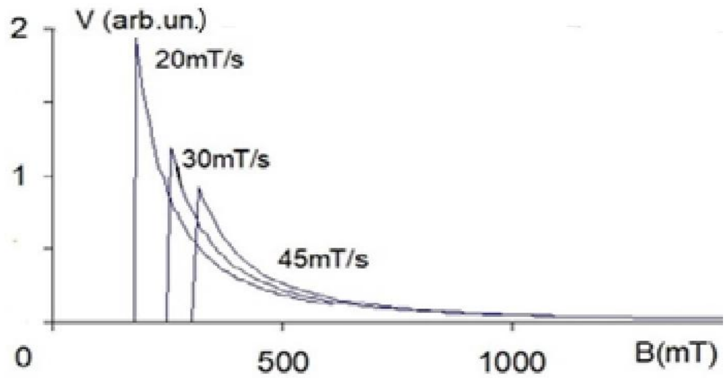

Figure 8. Theoretically predicted according to the vortex dynamic model, of the influence of the magnetic field sweep rate on the dynamic anomalies of the current-voltage characteristics of HTc superconductors.

Finally, the vortex dynamics influences too the Josephson junctions based electronic devices, as presented in Fig 9 annular long Josephson junction *with* rotating in it vortex, mathematically described by the modified sine-Gordon equation:

$$\frac{\partial^2 \Delta\phi}{\partial t^2} - \frac{\partial^2 \Delta\phi}{\partial x^2} + \propto \frac{\partial \Delta\phi}{\partial t} + sin\Delta\phi = \frac{I}{I_0} \qquad (6)$$

which solution is soliton in the form of rotating vortex.

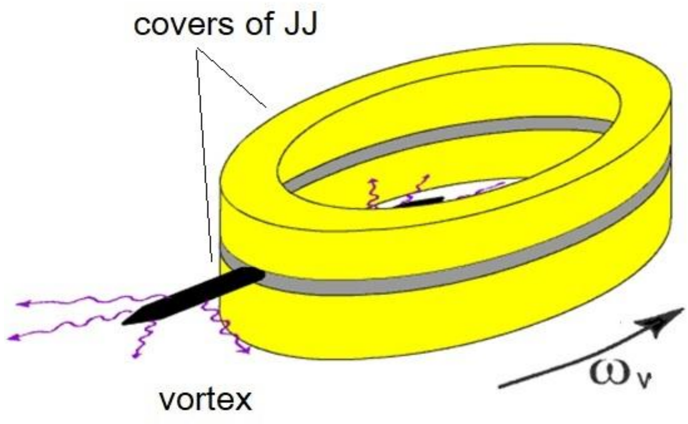

Figure 9. The annular Josephson's junction with penetrating it rotating magnetic vortex.

$\Delta\Phi$ in Eq. 6 is the phase difference on Josephson's junction covers, I_0 critical current of the junction, while α the material parameter. The symbol I denotes Josephson's current, while t is time, x is the position coordinate.

Because the present paper is intended to indicate the important meaning of the vortex dynamics effects in the superconducting electronic quantum devices and solving by the phenomenological approach arising problems, it should be relevant to extend the investigations on the joined superconducting – semiconducting devices. One of the possibilities is to use superconducting semiconductors at that aim. To this class of materials belongs lanthanum selenide $La_{3-x}Vac_xSe_4$, which characteristics measured by author [14] are shown in Figs. 10 and 11. Symbol Vac denotes here the vacancies of lanthanum atoms. In Fig. 10 is presented the influence of electrons concentration on the critical temperature of this compound, while in Fig. 11, on their magnetization, which for the fields higher than the first critical field smoothly decreases with a magnetic field, which is a characteristic effect for type II superconductors. In this Figure, small irregularities are also seen on the upper magnetization curve, connected probably with small flux jumps, also a specific effect for type II superconductors. The topic of superconducting semiconductors has found now again large scientific interest, especially because HTc superconductors are usually just low carrier concentration materials.

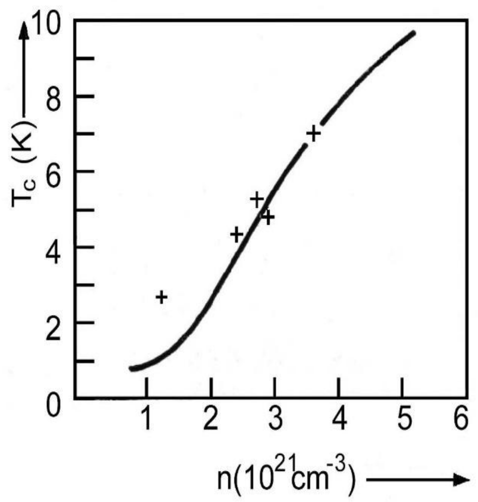

Figure 10. The critical temperature of the superconducting semiconductor $La_{3-x}Vac_xSe_4$ as a function of electron carrier concentration.

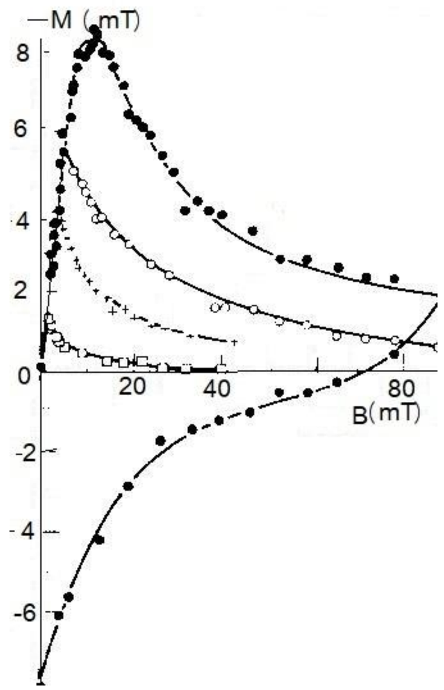

Figure 11. The magnetization curves of the superconducting semiconductor $La_{3-x}Vac_xSe_4$ for samples with increasing electron carrier concentration.

4. Conclusions

Superconducting quantum devices working in even small magnetic fields or with flowing current are exposed to the electromagnetic effects connected with the movement of the quantized magnetic vortices arising then. Therefore, model of the vortex dynamics in irradiated HTc multilayered superconductors based on the analysis of the capturing pancake vortices interaction with nano-sized defects was discussed, from the point of view of application it to the work condition of the superconducting electronic detectors. The comparison of the modeling calculations of pancake vortices movement in the flux creep processes with the experimental current-voltage characteristics in the stationary magnetic field has been presented, and the dynamically varying magnetic field was regarded. The dynamic case is especially interesting because it leads to creating dynamic anomalies of the current-voltage characteristics in a slowly varying magnetic field. It allows then to propose superconducting sensor construction, sensitive to the diffusion velocity of magnetic flux into a superconductor. Such sensors should help to determine the electromagnetic properties of superconductors. The influence of vortex dynamics on Josephson's junction based devices was discussed briefly too, as well as an example of the superconducting-semiconductor reminded, in which class of materials the joined superconducting-semiconducting electronic devices could be realized.

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