RF-dynamics of vortex kinks in the mixed state of nanostructured superconductors with columnar defects

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Introduction

We propose a theoretical model for the microwave response of Abrikosov vortices in nanostructured superconductors with columnar defects. The vortices are considered as the elastic strings while defects are the effective pinning sites [1]. It is supposed rigid pinning of vortex parts settled on columnar defects while vortex kinks can viscously move along the columnar defect axis due to the Lorentz force.

Artificial columnar defects

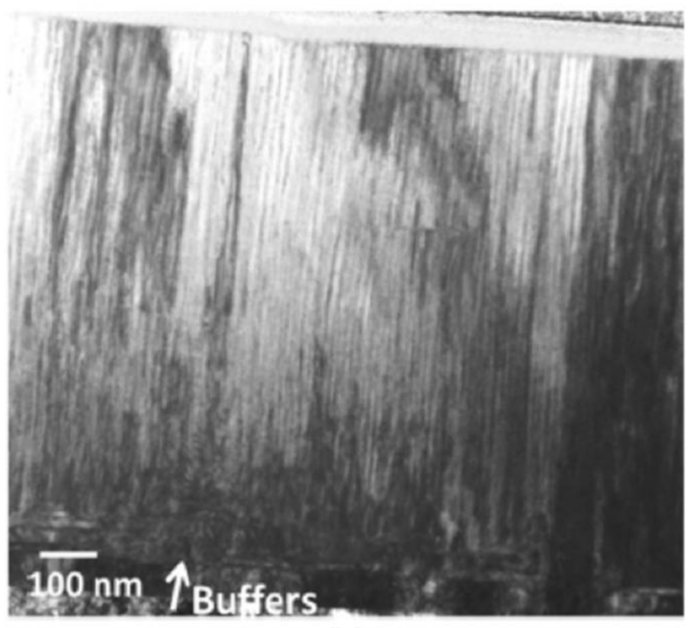
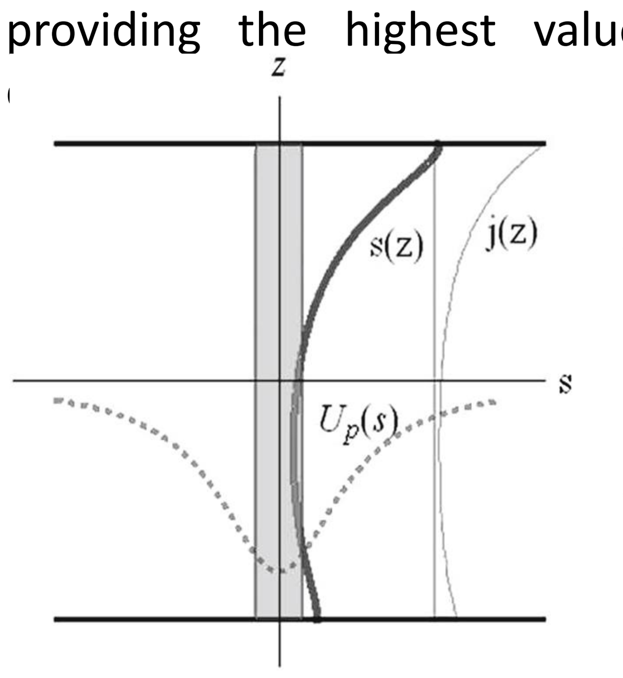


Fig.1 Transmission electron microscopy cross-section of REBCO superconductor containing $BaZrO_3$ nanorods (dark grey vertical lines) [2].

The formation of artificial columnar defects in high-Tc superconductors (HTS) (RE)-Ba-Cu-O (REBCO) could be: (i) due to the self-organization of implanted dielectric nanoparticles in form of so-called "nanorods" (Fig.1); (ii) due to irradiation of superconductor by high-energy heavy ions (radiation tracks).

The Mixed state in HTS with columnar defects

Columnar defects in high-Tc superconductors (HTS) are the most effective pinning sites for Abrikosov vortices thus providing the highest values of the depinning critical



Thermally activated vortex depinning leads to the formation of vortex kinks which can move along the columnar defect axis and provide vortex transfer from the columnar defect to the neighboring one due to the Lorentz force (see Fig.3).

Fig.2 Elastic Abrikosov vortex string in the potential well of a columnar defect in the presence of surface Meissner current.

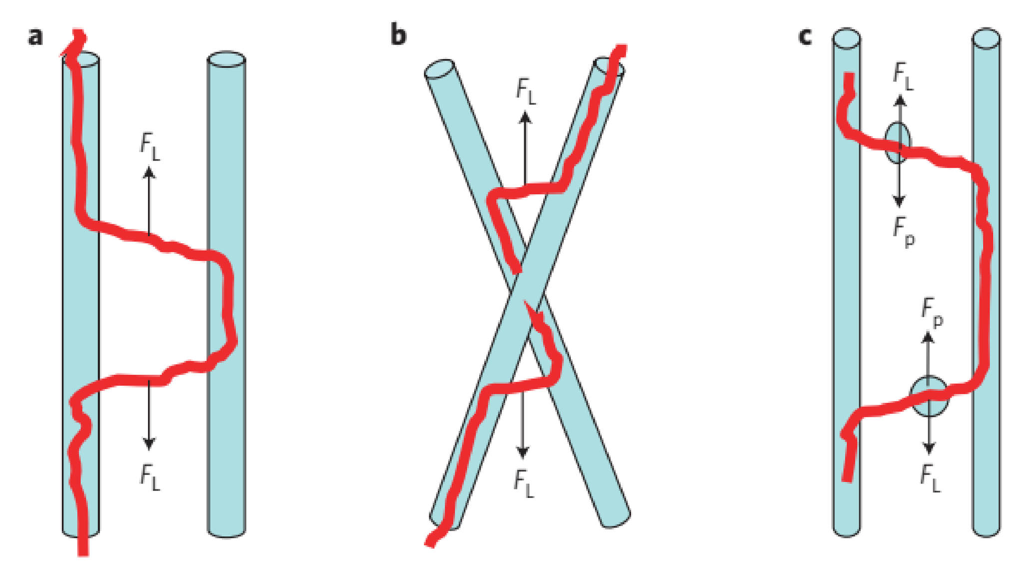


Fig.3 (a) Diagram of two parallel correlated columnar defects with a vortex depinning through the double-kink excitation mechanism. (b) Diagram of a vortex and two splayed correlated defects, showing how splay prevents the expansion of double kinks. (c) Diagram of a vortex and two parallel correlated defects plus dielectric nanoparticles, showing how the double-kink mechanism is arrested by the nanoparticles [3]

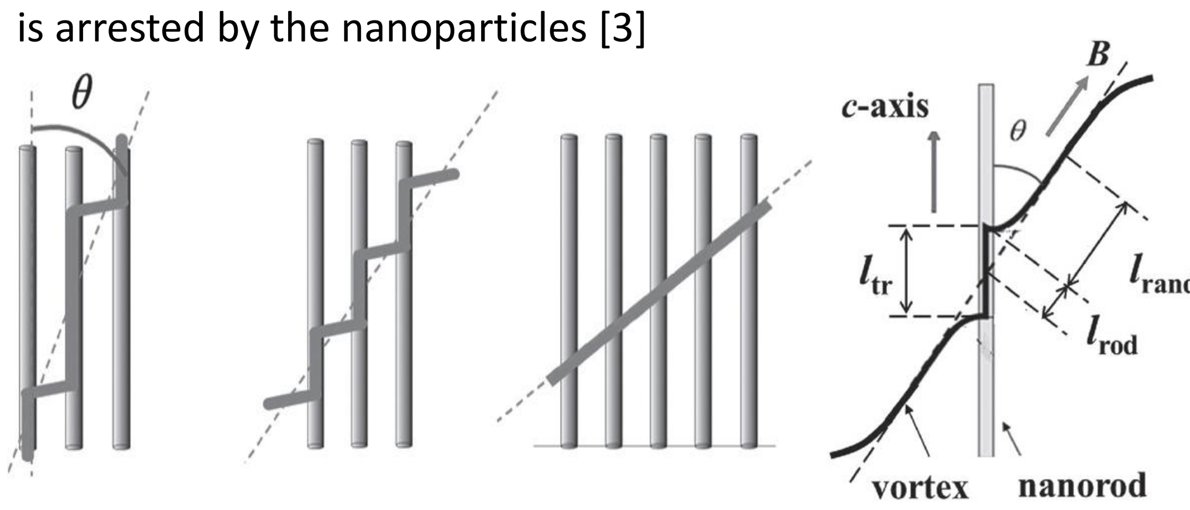


Fig.4 Vortex staircase in a superconductor with columnar defects in a tilted magnetic field [4].

Columnar defects strongly increase the critical current value for magnetic field (vortices) oriented along the columnar defect axis (c-axis). The existence of additional point-like defects in form of dielectric nanoparticles supports this critical current growth and spreads it to a wide range of magnetic field orientations, as it is demonstrated in Fig. 5.

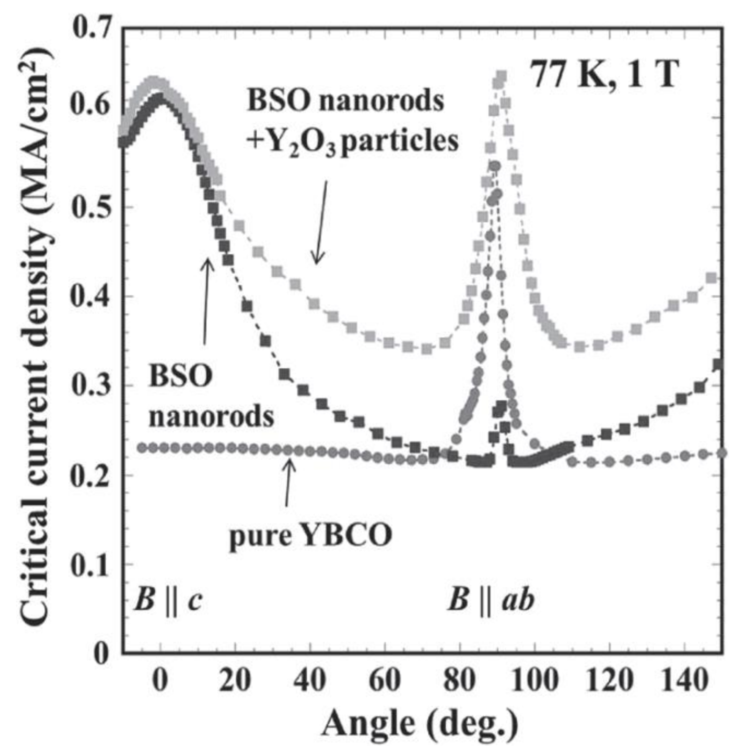


Fig.5. Angular dependent $J_c(\theta)$ for $YBa_2Cu_3O_{7-x}$ (YBCO), YBCO + $BaSnO_3$ (BSO) and YBCO +BSO + Y_2O_3 films measured at 77 K, 1 T. [4].

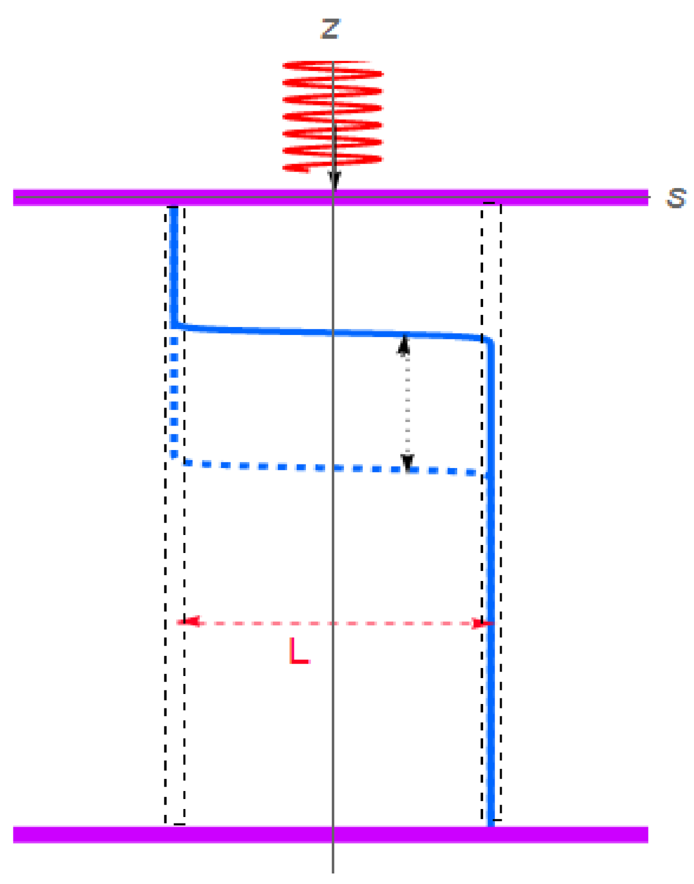


Fig. 6. Microwave-induced oscillations of vortex kinks in a superconductor with columnar defects.

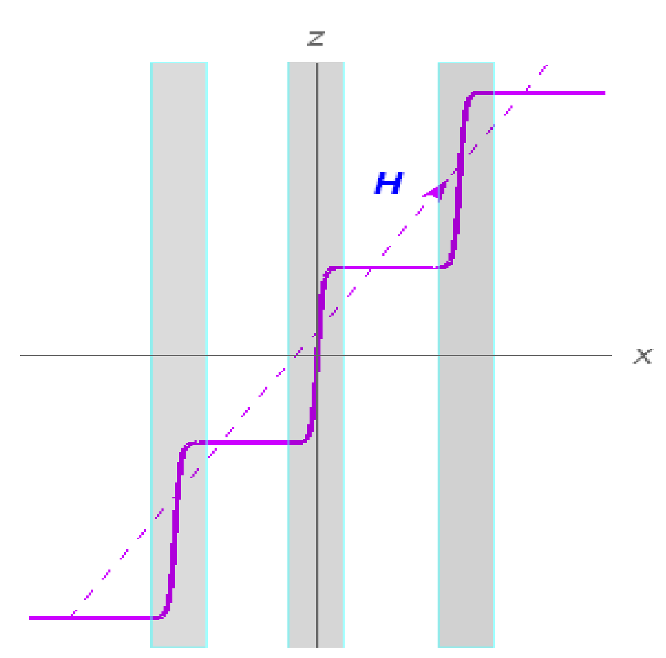


Fig.7. The vortex kinks formation in a tilted magnetic field – vortex staircase.

Vortex oscillations in a microwave field

When the major type of vortex pinning sites is columnar defects, we suppose that microwave losses related to the vortex oscillations in a microwave field arise caused by viscous oscillations of vortex kinks, which connect parts of the vortex line pinned on adjacent columnar defects.

At high enough temperatures vortex kinks arise as thermal excitations of the whole vortex lines settled in potential wells produced by columnar defects. In this case, the kinks concentration inside the superconductor should obey the barometric law:

$$n_k(z,T)=\frac{B}{\phi_0}P(z,T)=\frac{B}{\phi_0}P_0\exp\left(-\frac{E_k(z)}{kT}\right)$$

$$E_k=\left(\varepsilon_\phi-U_p(z)\right)L\,;$$

$$U_p(z)\approx\frac{\phi_0^2}{8\pi^2\lambda^2}K_0\left(\frac{2z}{\lambda}\right),\ (z>\xi);$$

Here $E_k(z)$ – is the kink's energy, ε_ϕ - is the vortex self-energy, and $Up(z)$ – is the vortex potential energy for its interaction with the specimen surface, which is evaluated per unit length of the vortex line. Calculation of the viscous losses, W, for vortex kinks motion, driven by a microwave current, can be produced as follows:

$$W=\int_{-\infty}^{0}n_k(z,T)\eta\frac{\langle v_\phi^2\rangle_{t,\phi}}{2}dz=\int_{-\infty}^{0}n_k(z,T)\frac{\langle F_L^2(z,\phi,t)\rangle_{t,\phi}}{2\eta}dz$$

Averaging $\langle\ldots\rangle_{t,\phi}$ in (3) means a time and orientation averaging for vortex kinks dynamics, φ - is an angle between the local kink and microwave current directions, v_ϕ - is velocity of the kink which moves viscously due to the *rf* Lorenz force $F_L(z,t)$ = $[j(z,t)\times\phi_0]$. Equating the calculated losses in (3) to the well-known expression for *rf*-losses: $W=R_sI^2/2$ (I – is a sheet current amplitude), one gets a result for the surface resistance due to vortex kinks motion:

$$R_{s,v}(B,\omega,T)=C\frac{B}{\eta\omega}\exp\left[-\frac{\varepsilon_\phi L}{kT}\right]$$

For the case of inclined magnetic field H, schematically shown in Fig.8, rf losses due to viscous kinks oscillations under the microwave current action arise even at $T=0$ if the inclination angle θ_H concerning the columnar pinning site axis (z-axis) exceeds some locking angle value θ_L [2]. For this case the contribution to the surface resistance $R_{s,v}$ due to kinks oscillations can be approximately written as follows:

$$R_{sv}=C_1\frac{B}{\eta\omega}\tan\left(\frac{\theta_H-\theta_L}{1-\frac{H_{c1}}{\Gamma H}}\right)+C_2\frac{B}{\eta\omega}\exp\left[-\frac{\varepsilon_\phi L}{kT}\right]$$

Here H_{c1}– is the lower critical magnetic field (for z-orientation of the field), Γ- is the anisotropy coefficient (for moderately anisotropic layered superconductors, e.g. REBCO). It should be noticed that in the case of columnar pinning sites for vortices the frequency and temperature dependencies of $R_{s,v}$, caused by vortex oscillations, are essentially different from those, obtained for point-like pinning sites.

Conclusion

Obtained results indicate that implantation of dielectric columnar defects in the interior of superconductor can significantly eliminate Abrikosov vortices oscillations and related microwave energy losses, thus decreasing the Abrikosov vortices contribution to the R_s value in the mixed state of HTS film. Such kind of nanoparticle`s influence on the microwave response of HTS films was observed in some recent experiments.

References

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