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RELAXATION EFFECTS IN GRANULAR SUPERCONDUCTING THING FILMS

The studies on flux relaxation are important because one influences the current carrying ability and stability of type –II superconductors. Consequently, it limits the application of the superconductor. Attractive candidates for low power application are thin superconducting films, which apart from well controlled fabrication techniques, have the advantage of relatively high critical current density, as compared to bulk specimen [1]. The film thickness and grain anisotropy are the important parameters that can be controlled and varied over a wide range. The flux relaxation behavior is interpreted as resulting from surface-pinning effects and thickness dependent microstructure variations [2]. In general, for dc applications; thicker films are preferable due to their lower relaxation rates. The relaxation in a powdered sample must be dominated by processes within grains [3]. Clearly, an interpretation of magnetic relaxation data requires a well-defined and regular vortex distribution. From multiply mechanisms of pinning to consider the pinning at the surface of grains because as the thickness is decreased, domination of the surface pinning mechanism over the bulk pinning gives rise to increasing critical current density j_c [2], i. e. the vortex transport in thing films is dominated by the edge barrier rather than bulk pinning [4].

The time evolution of the local induction within the sample yields a detailed picture of the relaxation process within the superconductors, including data on the line current density, the flux line average velocity, and the activation energy for flux creep, as a function of position and time. The flux-line current density relaxation at the sample surface in determined by the Abrikosov vortices (AVs) penetration phenomenon. This time dependence implies that a vortex system is unstable during the vortex penetration process and a superconducting device may not work at this stage. Thus, such investigations yield information on the flux entry or flux exit process. It is thus important to gain knowledge regarding the effects of grain anisotropy and thickness variation on the various physical properties of thin films.

In this paper, we developed a theoretical model for persistent current in granular superconducting film based on modernized anisotropy equation. This approach is attractive since it allows analysis of surface effects, intragrain effects and thickness dependent variation. The model is similar to that of Hylton et al.[5] to calculate the the magnetic field penetration at grain boundaries (GBs) in superconductors, but with a single Abrikosov vortex (AV) in localized state. In Fig. 1. show the schematic figure of the weakly coupled grain model for a c-axis oriented high-T_c superconducting film, where the c-axis is perpendicular to the film surface. The average grain size is assumed to be a, and the film thickness is d. The field of the AV will satisfy an modernized anisotropic London equation [6] with $2(2L+1)$ sources (here L is the number of coordination zones considered, counted from the vortex to its images and the images of the images; Fig. 1(c) shows five superconducting laminae: $\{-2\},\{-1\},\{0\},\{1\}$ and $\{2\}$, which correspond to two coordinate zone $L=2$, while in the general case $L\to\infty$):

$$\lambda_x^2\frac{\partial^2 H_y}{\partial z^2}+\lambda_z^2\frac{\partial^2 H_y}{\partial x^2}-H_y=-\Phi_0\times\sum_{n=-L}^{L}\Big\{(-1)^n\cdot\delta[x-x_0]\cdot\delta\big[z-(-1)^n z_0-na\big]+ \\ +(-1)^{n+1}\cdot\delta[x+x_0]\cdot\delta\big[z-(-1)^n z_0-na\big]\Big\}+(-1)^{n+1}\cdot\delta[x-2d+x_0]\cdot\delta\big[z-(-1)^n\cdot z_0-na\big] \quad (1)$$

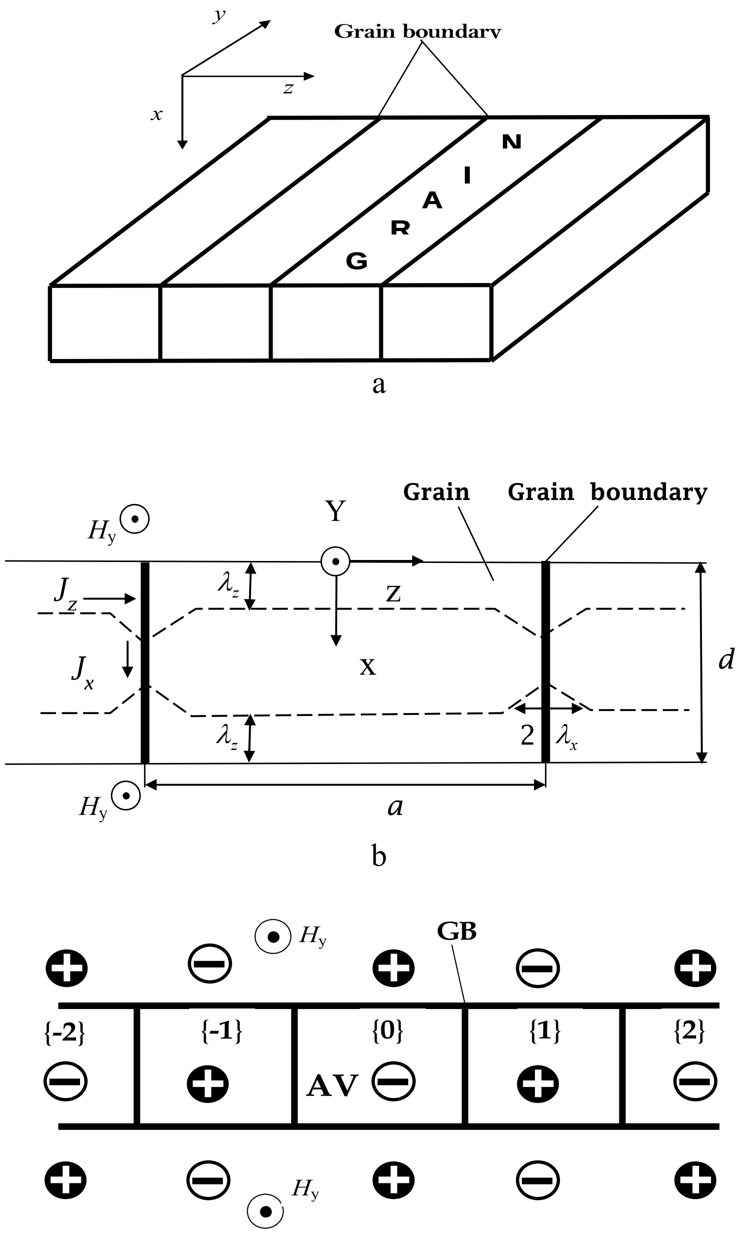

Fig.1. (a) Configuration of a superconducting film with laminar grain boundaries (GBs). The film thickness is a. (b) The cross section of the weakly coupled grain model. (c) The Abrikosov vortex (AV), its mirror images, and the images of images in an anisotropic superconducting grain in the limit of large grains, $a/2\lambda_x >> 1$.

With the boundary condition at the GB:

$$\frac{\partial^2 H_y}{\partial x^2} \mp \frac{\lambda_x}{\lambda_J^2} \cdot \frac{\partial H_y}{\partial z} = 0$$

with $\lambda_J = \sqrt{\dfrac{\Phi_0}{2\pi\mu_0 2\lambda_z \cdot J_c}}$,

where λ_x and λ_z are the magnetic field penetration depth in the x and z direction, respectively;

Φ_0 is flux quantum;

x_0 and z_0 are the position of the AV along x and z axis, respectively;

J_c is the critical current density for the Josephson junction and λ_J corresponds to the penetration depth for an isolated single Josephson junction. According to the symmetry and periodicity of the present problem, other boundary conditions for a single grain located in the region from $z=-a/2$ to $z=a/2$ can be expressed as:

$$H_y(x=0)=H_y^{app},$$

$$H_y(x=d)=H_y^{app},$$

By following the result [6], using Eq.1 can obtain the energy associated with AV as follows:

$$U_s(x_0,z_0,d)=\frac{\Phi_0}{4\pi}\left\{ H_y^{app}\cdot\frac{\cosh\left[\frac{1}{\lambda_z}\left(x-\frac{d}{2}\right)\right]}{\cosh\left(\frac{d}{2\lambda_z}\right)}-H_y^{app}+H_{c1}^{film}(\infty)+H_y^J(x_0,z_0,d)+\right.$$

$$\left.+\frac{\Phi_0}{4\pi\lambda_x\lambda_z}\left[\sum_{n=-L}^{L}P_n(0,z_0,0)-\sum_{\substack{n=-L\\(n\neq 0)}}^{L}P_n(x_0,z_0,0)-\sum_{n=-L}^{L}P_n(x_0,z_0,d)\right]\right\}, \tag{2}$$

where

$$P_n(x,z_0,d)=(-1)^n\cdot K_0\left(\sqrt{\frac{(2x_0-2d)^2+\left[z_0-(-1)^n z_0-na\right]^2}{\lambda_x\lambda_z}}\right),$$

here K_0 is the modified Bessel function of order zero [7],

$$\frac{H_y^J(x_0,z_0,d)}{H_y^{app}}=$$

$$=-\sum_{n=1}^{\infty}\frac{8n\pi}{d^2}\cdot\frac{\cos\left(\frac{2n\pi}{d}\cdot x\right)\cdot\cosh\left(\frac{1+\lambda_z^2\left(\frac{2n\pi}{d}\right)^2}{\lambda_x}\cdot z\right)}{\left[\left(\frac{2n\pi}{d}\right)^2\cdot\cosh\left(\frac{a}{2\lambda_x}\sqrt{1+\lambda_z^2\left(\frac{2n\pi}{d}\right)^2}\right)+\frac{\sqrt{1+\lambda_z^2\left(\frac{2n\pi}{d}\right)^2}}{\lambda_J^2}\cdot\sinh\left(\frac{a}{2\lambda_x}\sqrt{1+\lambda_z^2\left(\frac{2n\pi}{d}\right)^2}\right)\right]}$$

We focus our attention initially on the higher temperature thin films, where the flux relaxation phenomena usually exhibit strongly non-logarithmic behavior. The experimental data usually cannot be well fitted by the theoretical models. In this case, one may consider using the infinite series model [8, 9], which gives the information about the elastic and non-elastic deformation of the AVs. Equation (2) shows that surface barrier affect AV penetration. That is naturally because this SB also affects flux relaxation. In flux relaxation the external field is usually zero and the other, and forties terms in Eq. (2)

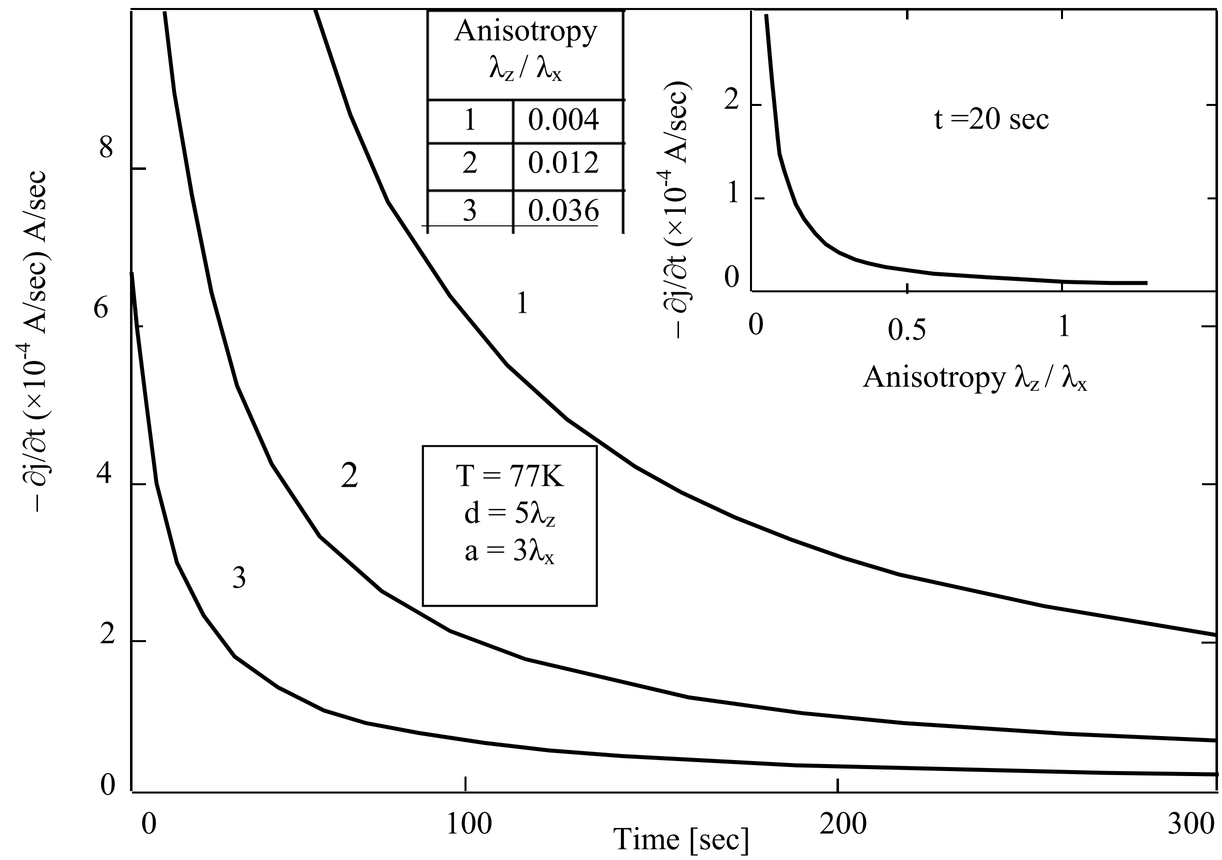

Fig. 2. Relaxation rate $\partial j/\partial t$ as a function of time, calculated at $T = 77K$ and $d = 5\lambda_z$ at different grain anisotropy parameters λ_z / λ_x: 0.004(*1*), 0.012 (*2*) and 0.036 (*3*). Inset: relaxation rate of current as function of grain anisotropy λ_z / λ_x.

vanishes. The last term is caused by the surface imagine force (attractive), which helps to draw the AVs out of the superconductor and reduced the activation energy of the AVs. As was shown by Ma [9], in flux relaxation the time dependence of current density is:

$$j(t) = \sum_{l=1}^{n} b_l w^l(t), \tag{3}$$

where $w(t) = U_p - k_B T \ln\left(1 + \frac{t}{\tau}\right)$ and b_l are constants. We will consider the surface imaging force, $w(t)$ as

$$w(t) = U_p - \frac{\Phi_0^2}{16\pi^2 \lambda_x \lambda_z}\left[\sum_{n=-L}^{L} P_n(0, z_0, 0) - \sum_{\substack{n=-L \\ (n\neq 0)}}^{L} P_n(x_0, z_0, 0) - \sum_{n=-L}^{L} P_n(x_0, z_0, d)\right] - k_B T \cdot \ln\left(1 + \frac{t}{\tau}\right), \tag{4}$$

where U_p is the effective pinning energy of AVs at the edge of granule, k_B is the Boltzmann constant, τ is a characteristic time which depends on the temperature (with typical values in the range $10^{-12} - 10^{-6}$ sec). By following [10], we assume that $\tau = 3 \cdot 10^{-5}$. The last parameter is a macroscopic quantity depending on the sample size. Also in the further calculations we take $x_0 = 0.2\lambda_z$ and $z_0 = 0$, i. e. the AV is at the surface and the centre of grain.

In flux relaxation process, the current density j can reduce the vortex activation energy U_a by its Lorentz force and therefore increase the vortex hopping rate. This indicates that U_a is a decreasing function of j. Because j is a decreasing function of the time t, U_a is an increasing function of t. We are interested to consider the rate of change of the current density, dj/dt, is proportional to the vortex hopping rate. Furthermore, the current density in a flux relaxation process is a decreasing function of the time t, i. e., $dj/dt < 0$. According to the Arrhenius equation, therefore, we have the following equation [9] $dj/dt = -Ce^{-U_a/k_B T}$, where C is a positive proportional constant.

Using the fitting of the experimental data with Eq.(3) we obtain the fitting parameters b_l to available superconducting $YBa_2Cu_3O_{7-\delta}$ films of thickness 350–3000 Å, that of Sheriff et al.[2]. The fitting result are: $j(t) = b_1 w(t) + b_2 w^2(t) + b_3 w^3(t)$ where $b_1 = 4.964 \times 10^{11}$, $b_2 = 5.833 \times 10^5$, $b_3 = 0.685$, $U(x_0, z_0, d) = U(\xi, 0, d)$. We can see that $b_1 >> b_2, b_3$. Hence Eq.(3) is equal to assuming that the vortices have very large elastic modulus and the elastic deformation can be ignored [9]. The current relaxation rate (CRR) is a very strong function of time as shown in Fig. 2. Here we have plotted $\partial j/\partial t$ at $T = 77K$ and $d = 5\lambda_z$ as function of t for the grain anisotropy $\nu = \lambda_z/\lambda_x = 0.004$, 0.012 and 0.036. From the data we clearly see that $\partial j/\partial t \propto t^{\mathrm{A}(\nu)}$, where $\mathrm{A}(\nu)$ is the same function of anisotropy at initial times. Thus, the highly nonlinear decay rate $\partial j/\partial t$ is also a function of anisotropy. It decreases as the anisotropy increases (inset). What is intriguing here is that the fast relaxation that takes place over about a minute of time seems to be understood as a fast relaxation mode shown by Levin et al. [11]. It is that over the first 40–50 sec, immediately after the peak currents was reached and before the relaxation settled into the flux creep mode, the decay of the induced current is much faster than the thermally activated creep. According to above results, Fig. 2, this leaves a possibility that the initial phase of the relaxation evident is due to the same effect of GB (the grain anisotropy) as well as the topology (the film thickness).

According to the collective creep theory [12] the activation barrier for $j << j_c$ can be written as

$$U_a(H, j) = \frac{U_0(H)}{\mu}\left[\left(\frac{j_c}{j}\right)^{\mu} - 1\right] \propto H^{\alpha} j^{-\mu}, \quad (5)$$

where $U_0(H)$, in our case, is reasonable to rewrite as $U_0(r_0,d) = U_s(r_0,d) + U_p$ [here $r_0 = (x_0,z_0)$]; μ is a critical exponent related the vortex structure in the superconductor. The number 1 on the right site is introduced to ensure that $U_a(j_c) = 0$. Using Eq. (5), we calculate the local activation energy $U(r_0,d)$ as a function of normalized film thickness, $d/2\lambda_z$, at various magnetic fields, Fig. 3. For numerical calculations we took $t = 50\,\mathrm{sec}$, $j_c = 10^6\,A/cm^2$, the grain anisotropy $\lambda_z/\lambda_x = 0.4$ and assume a small critical exponent $\mu = 0.5692$. Then is, Fig. 3 show that the applied field intensity have but a minor effect on the shape of U_a versus a film thickness. This is in accordance with the general solution of the equation (6); i. e. the activation energy $U_0(H)$ must increase with H, which means that the exponent α must be positive[13]. Also, it is with accordance of the results by Zeldov et al. [14] that is in the limit $U_a >> kT$, the activation energy should be almost constant over the sample volume (the film area A). However, in a presence of surface barrier [15] the value of U_a at the surface and in the bulk may be different (the film and massive areas A and C, respectively). In the middle zone (the area B is the transition "*film – massive*") of Fig. 3, the lines are a fit to the power law $U(d,H_{c1}) \propto d^{-4.1034}$, $U(d,2H_{c1}) \propto d^{-4.1033}$ and $U(d,3H_{c1}) \propto d^{-4.1026}$. Such behavior of U_a means that the current instability effect in the films with same thickness must occurs at very high magnetic fields.

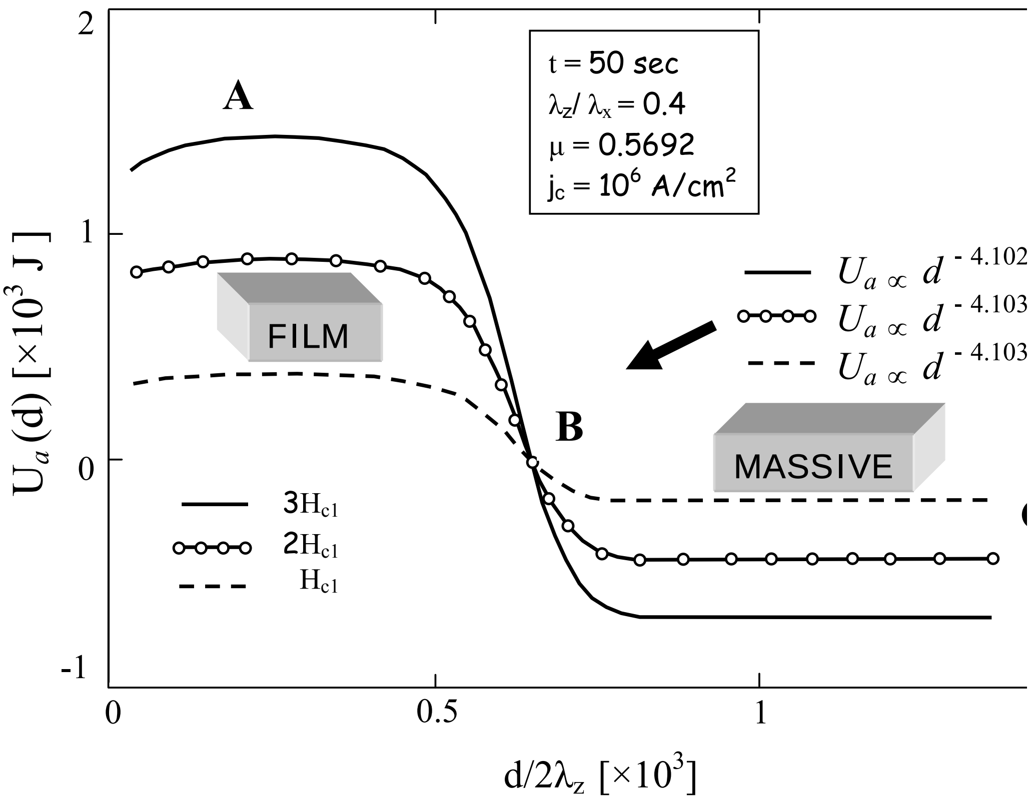

Fig. 3. Activation energy U_a as a function of the normalized film thickness $d/2\lambda_z$ at various magnetic fields

With above model it is not possible to find the grain-size-dependent activation energy. Incidentally this indicates the fact that the film thickness d rather than the grain size a influence on the state of U_a. It is because the polycrystalline superconductor is strongly linked. There may be a point that the activation barriers relevant for a surface are not related to the size of grains but to the internal structure of grains [19].

Fig. 4 (a) – 4 (b) show the rate of change of the current density, $\partial j/\partial t$, at different times for two film thickness with $d = 5\lambda_z$ (blue curve) and $d = 10\lambda_z$ (red curve) for grain anisotropy $\lambda_z/\lambda_x = 0.4$ (main fragment). Before all we can see that the red curve oscillating around the blue curve. Understanding of such behavior is clearly observed from the inset of Fig. 4(b), i. e. the rate of change of the current density, $\partial j/\partial t$, versus a normalized film thickness $d/2\lambda_z$ shown at different times: $t = 80$, 300 , 400 and 3900 sec. We can see that at $d = 5\lambda_z$ exist the oscillations of the relaxation rate peak. Whereas for $d \le 4\lambda_z$ and $d \ge 6\lambda_z$ the rate $\partial j/\partial t$ is a constant during over the time. It is our opinion that existence of a maximum in the CRR is a result of magnetic fields overlapping from both surfaces of a film. Then, the same maxima in the relaxation of magnetic moment have been reported by Norling et at. [17] for YBCO polycrystals and by Blinov et al. [18] for YBCO films as well as by Altshuler et al. [19] in the absolute relaxation rate of transport critical current for HBCCO and YBCO polycrystalline samples. With a practical point of view the above results can be used to obtain the absolute values of penetration depth λ_z of a magnetic field into a superconducting film at different fields and temperatures. For instance, it can be used the magnetostriction superconducting materials with variable thickness $d(H)$ which is strongly dependent of applied magnetic field. More work is needed, however, to clarify this issue.

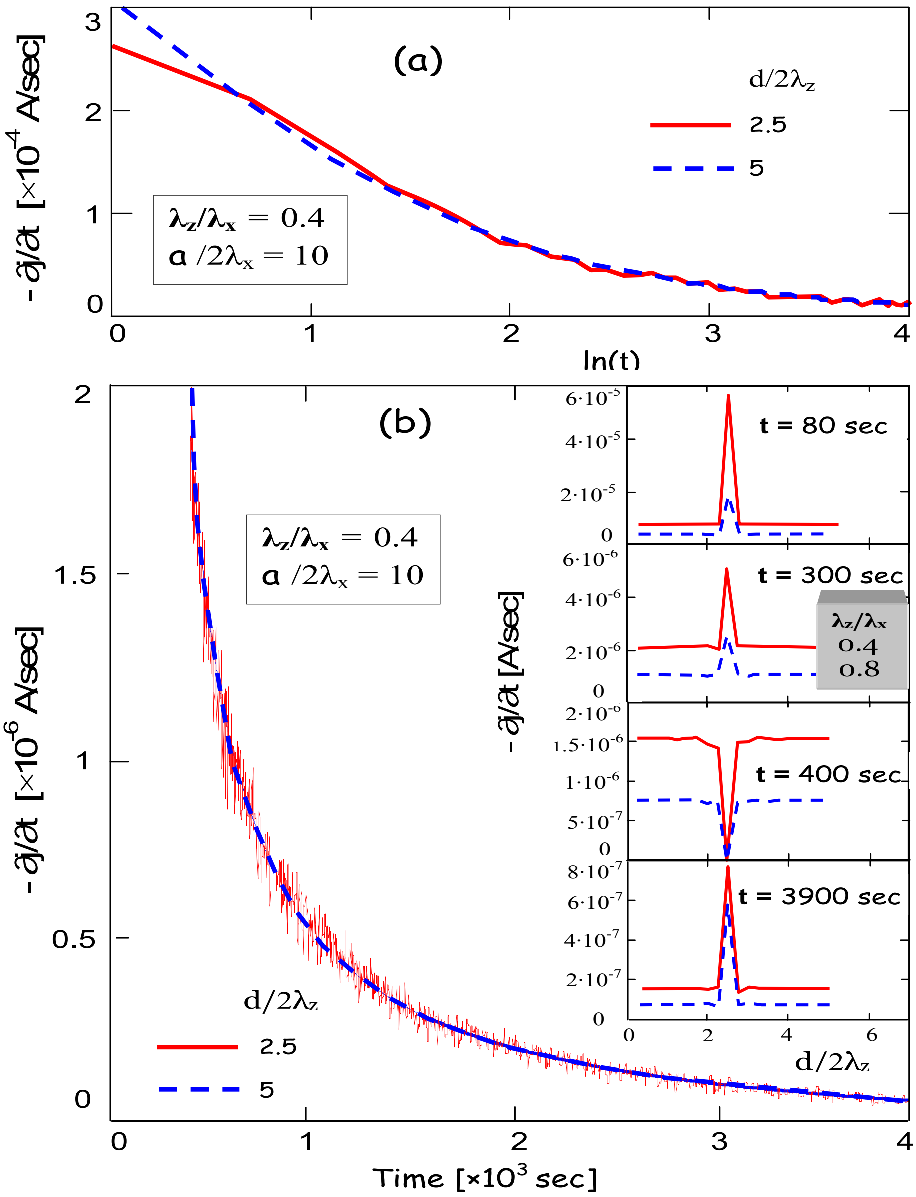

Fig. 4. Relaxation rate $\partial j / \partial t$ as a function of time at different normalized film thickness $d / 2\lambda_z$: 2.5 (solid line) and 5 (dashed line) – main fragment of (a) and (b). Inset in (b): relaxation rate $\partial j / \partial t$ at $\Gamma = 0.4$ (solid line) and $\Gamma = 0.4$ (dashed line) as a function of the normalized film thickness $d / 2\lambda_z$ at different times: t= 80, 300, 400 and 3900 sec.

CONCLUSION

In conclusion, we have out detailed numerical study of the current relaxation rate and the activation energy in granular films. Our results show that the CRR is strongly dependent no only the external magnetic field H and the temperature T but also the grain anisotropy λ_c / λ_{ab}. Like enough with this effect can arise the relaxation mode that is much faster of the flux-creep mode observed in experiments[11]. The results are clearly show that the film-thickness dependence of activation energy $U_a(d)$ disunited by three zones: (1) the film area; (2) the transition area "*film – massive*", and (3) the massive area. The transition wide $\delta(H)$ depends on the value of magnetic field H. In the superconducting magnetostriction samples with a thickness $d \in \delta(H)$ the current state to be unstable. Our theory predicts the film–thickness–dependente maxima in CRR, $\partial j / \partial t$, that is like to one dependence on an external magnetic field H [16-18]. Based on this effect, we have demonstrated the possibility a next technique for determination the magnetic penetration depth λ_c into a film.

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