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Vortex relaxation for the surface barrier in 3D type-II superconductor

3차원 제2종 초전도체의 표면장벽에 대한 자속의 이완

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We report the activation energies which is calculated by adding a term being neglected usually, and magnetic relaxation effects for the surface barrier. The activation energies U at initial magnetization m (m_{en} and m_{ex}) and equilibrium magnetization m_{eq} are nearly similar to those of Burlachkov, but the m dependence of the activation energy U is remarkably different. The relaxation effects, which were determined by the m dependence of the activation energies U, are nonlinear for vortex entry, but linear at the initial stage and nonlinear at m(lnt) $\simeq$ m_{eq} for vortex exit. During relaxation process, the vortex entry at m = m_{en} is faster than the vortex exit at m = m_{ex} by about factor 90. The vortex exit at m = m_{eq} is faster than one at m = m_{ex} by about factor 1.3

1. Introduction

Vortex can't enter freely type-II superconductor because of the Bean-Livingston surface barrier (SB) [1] caused by the competition between the interaction of a vortex line with its mirror image and the interaction with the surface shielding current. The SB inhibits vortex penetration inside the superconductor at the lower critical field H_{c1}. Therefore the vortex penetration starts at the H_p ($\simeq$ H_c $\simeq$ $\kappa H_{c1}/\ln\kappa \gg H_{c1}$), at which the SB disappears. The SB should be very remarkable in the high temperature superconductors having the large value of κ (= λ/ξ), as has already been discussed [2,3].

In the case of negligible bulk pinning, Clem [4] showed the magnetization curve in the ascending branch is

$$-4\pi M_{en} = H - \sqrt{H^2 - H_p^2}. \tag{1}$$

and the magnetization curve in the descending branch is $-4\pi M \simeq 0$.

The equilibrium magnetization $-4\pi M_{eq}$ (= H - B_{eq}) was discussed by Hao and Clem [5] in detail and is given by as follows:

$$-4\pi M_{eq} \simeq \frac{\varphi_0}{8\pi\lambda^2}\ln\left(\frac{\eta H_{c2}}{H}\right), \tag{2}$$

where η is the constant of order of unity.

In this paper, we report on detailed results of the activation energies for the surface barrier in 3D type-II superconductor. We analyzed the relaxation effect based on our results of the activation energies of the surface barrier. We considered only 3D case and used m = H - B = -4πM, m_{en} for vortex entry, m_{ex} for vortex exit, and m_{eq} = H - B_{eq}.

2. Calculation of surface activation energies and relaxation rate

2-1. vortex entry

Consider the penetration of vortex through the ideal plane surface parallel to the c-axis of the superconductor. Penetration of the vortex through the SB takes place as a result of fluctuations. The magnetic field H is directed along the surface on the y-axis. There is a critical point which corresponds to a critical configuration of the vortex $x_0(y)$. The activation energy U at the critical configuration $x_0(y)$ is given by [6-8]

$$U_0=\frac{2}{\sqrt{\gamma}}\int_{x_1}^{x_2}\sqrt{V(x)\left(\frac{\varphi_0 H_{c1}}{4\pi}-V(x)\right)}dx \quad (3)$$

where γ is the effective mass anisotropy(= m_c/m_{ab}), and for vortex entry $x_1 = 0$ and x_2 is determined from the equation $V(x_2) = 0$; for vortex exit $x_2 = x_f$. where x_f is the width a vortex-free region.

In $0 < x < x_f$ region, V(x) has the form

$$V_{en}(x)=\frac{\varphi_0}{4\pi}\left[\frac{B}{2}\left(\frac{x_f-x}{\lambda}\right)^2+m_{eq-m}\right] \quad (4)$$

for vortex entry. We neglected the mirror image term for the case of vortex nucleus. However, contrary to the 3D case, the mirror image term cannot neglected in the 2D case [9].

Using Eqs. (3) and (4) and the condition $B \simeq H$, we calculated the activation energy U

$$U_{en}(m)=\frac{\varphi_0\lambda}{2\pi\sqrt{\gamma H}}\left[\sqrt{\frac{m^3+mm_{eq}(2H_{c1}-m_{eq})}{2}}-\sqrt{\frac{(m-m_{eq})^3}{2}}+\frac{1}{2}(m_{eq}-m)\frac{m+2H_{c1}-m_{eq}}{\sqrt{m+H_{c1}-m_{eq}}}\times\ln\frac{\sqrt{2m^2-m(H_{c1}-m_{eq})}+\sqrt{m^2+m_{eq}(2H_{c1}-m_{eq})}}{\sqrt{2(m-m_{eq})(m+H_{c1}-m_{eq})}+(m-m_{eq})}\right] \quad (5)$$

We first considered the activation energy U when $m = m_{eq}$, which is given by Eq. (2). $U_{en}(m_{eq})$ is immediately given from Eqs. (5) as follows;

$$U_{en}(m_{eq}) = \left(\frac{\varphi_0\lambda m_{eq}}{2\pi}\right)\sqrt{\left(\frac{H_{c1}}{\gamma H}\right)} \quad (6)$$

By considering initial stage i.e., $m \gg m_{eq}$ for flux entry, we obtained the activation energy

$$U_{en}(m)\approx\left(\frac{\varphi_0\lambda m_{eq}}{2\pi}\right)\sqrt{\left(\frac{H_{c1}}{2\gamma H}\right)\left(\frac{m_{eq}}{m}\right)} \quad (7)$$

at around the initial stage of relaxation process.

On increasing (decreasing) of H, m within the sample is determined by the rate of vortex entry (exit). When m varies with time, the rate of vortex entry or exit is given from the activation energies U,

$$\frac{dm}{dt} \sim \exp\left(-\frac{U}{kT}\right) \quad (8)$$

From Eq. (8), relaxation rate R for vortex entry or exit is approximately given by

$$R = \frac{dm}{d\ln t} \simeq kT\left(\frac{dU}{dm}\right)^{-1}. \quad (9)$$

From Eq. (9), we can get the relationship as follows;

$$\ln\left(\frac{t}{t_0}\right) = \frac{U(m(t))-U(m(t_0))}{kT} \quad (10)$$

where U(m) is determined by Eq. (5) for vortex entry and t_0 is the initial time. For vortex entry, the dependence m(lnt) is expected to be a strongly nonlinear function of lnt, specially at initial state.

At the initial stage ($m = m_{en}$) of the relaxation process, the relaxation rates R are estimated to be

$$R_{en}=\left(\frac{dm}{d\ln t}\right)_{m=m_{en}} =-\left(\frac{4\pi}{\varphi_0\lambda}\right)\left(\frac{m_{en}}{m_{eq}}\right)^{3/2}\left(\frac{2\gamma H}{H_{c1}}\right)^{1/2}kT \quad (11)$$

In the region $m \simeq m_{eq}$, the relaxation rate R are estimated to be

$$R_{eq}=\left(\frac{dm}{d\ln t}\right)_{m=m_{eq}} =-\left(\frac{2\pi}{\varphi_0\lambda}\right)\left(\frac{\gamma H}{H_{c1}}\right)^{1/2}kT \quad (12)$$

for vortex entry.

2-2 vortex exit

The procedure of calculation of the activation energy for vortex exit is similar to that for vortex entry. V(x) has the form

$$V_{ex}(x) = \frac{\varphi_0}{4\pi}\left[\frac{B}{2}\left(\frac{x_f - x}{\lambda}\right)^2\right] \quad (13)$$

The activation energy U for flux exit is given by

$$U_{ex}(m) = \frac{\varphi_0 \lambda}{3\pi\sqrt{\gamma}} H\sqrt{\left(\frac{H_{c1}}{H}\right)^3} \cdot \times\left[1 - \sqrt{\left(1 - \frac{m}{2H_{c1}}\right)^3}\right] \quad (14)$$

We first considered $H_p < H < H_c$ in order to calculate $U_{ex}(m_{eq})$. As we mentioned above, we have already know $m_{eq} \simeq H_{c1}/2$ in this field range, so we obtained $U_{ex}(m_{eq})$ as follows;

$$U_{ex}(m_{eq}) \approx \left(\frac{\varphi_0 \lambda m_{eq}}{3\pi}\right)\sqrt{\left(\frac{H_{c1}}{\gamma H}\right)} \quad (15)$$

We believe that these results are reasonable for entire field $H > H_p$. Also, we found that $U_{en}(m_{eq}) \approx U_{ex}(m_{eq})$ is given by several constants.

For initial stage of relaxation out i.e. $m \ll m_{eq}$, we obtained the activation energy

$$U_{ex}(m) \approx \left(\frac{\varphi_0 \lambda m}{2\pi}\right)\sqrt{\left(\frac{H_{c1}}{\gamma H}\right)}. \quad (16)$$

By using Eqs. (10) and (14), we can know immediately the relation

$$\sqrt{\left(1-\frac{m(t_0)}{2H_{c1}}\right)^3} - \sqrt{\left(1-\frac{m(t)}{2H_{c1}}\right)^3} \propto \ln\left(\frac{t}{t_0}\right) \quad (17)$$

for vortex exit. Because $m \ll H_{c1}$ at the initial stage of relaxation out, Eq. (15) is approximated to $m(t)-m(t_0) \propto \ln(t/t_0)$. According to our results, we found that the dependence m(lnt) for vortex exit should be nonlinear for m near m_{eq}, and relaxation rate at $m = m_{eq}$ would be larger than one at $m = m_{en}$.

At the initial stage ($m = m_{ex}$) of the relaxation process, the relaxation rates R are estimated to be

$$R_{ex} = \left(\frac{dm}{d\ln t}\right)_{m=m_{ex}} = \left(\frac{2\pi}{\varphi_0\lambda}\right)\left(\frac{\gamma H}{H_{c1}}\right)^{1/2} kT \quad (18)$$

In the region $m(\ln t) \simeq m_{eq}$, the relaxation rate R are estimated to be

$$R'_{eq} = \left(\frac{dm}{d\ln t}\right)_{m=m_{eq}} = \left(\frac{2\pi}{\varphi_0\lambda}\right)\left(\frac{\gamma H}{H_{c1}}\right)^{1/2}\left(1-\frac{m_{eq}}{2H_{c1}}\right)^{-1} kT \quad (19)$$

for vortex exit.

3. Discussion

As we can know from Eqs. (5) and (14), the dependences of U_{en} and U_{ex} on m are quite different, which will result in the different relaxation rates for vortex entry and exit. Because $m_{en} \gg m_{eq}$ and $m_{ex} \ll m_{eq}$, $U_{en}(m_{en}) \approx U_{ex}(m_{ex}) \approx 0$, which are given by Eqs. (7) and (16). Therefore, the activation energy for vortex entry increases from $U_{en}(m_{en}) \approx 0$ to $U_{en}(m_{eq})$ as m decreases and the activation energy for vortex exit increases from $U_{ex}(m_{ex}) \approx 0$ to $U_{ex}(m_{eq})$ as m increases. By the reason mentioned just above, we can predict that relaxation in (vortex entry) from m_{en} to m_{eq} should take approximately the same time as relaxation out (vortex exit) from $m_{ex} \approx 0$ to m_{eq}.

From our results, we found that R_{eq} for vortex entry in the region $m(\ln t) \simeq m_{eq}$ is approximately the same as R_{ex} for vortex exit in the region $m(\ln t) \simeq m_{ex}$, and R'_{eq} for vortex exit is approximately larger than R_{ex} by a factor by the reason mentioned above. So, we can write the relation of R_{en} (R_{ex}) and R_{eq} (R'_{eq}) as follows:

$$\frac{R_{eq}}{R_{en}} = \left|\frac{R_{ex}}{R_{en}}\right| = \left(\frac{m_{eq}}{2m_{en}}\right)^{3/2} \quad (20)$$

for vortex entry (or vortex exit), and

$$\frac{R'_{eq}}{R_{ex}} \simeq \left(1 + \frac{m_{eq}}{2H_{c1}}\right) \quad (21)$$

for vortex exit. The vortex entry at $m(\ln t) = m_{en}$ is faster than one at $m(\ln t) = m_{eq}$ or the vortex exit at $m(\ln t) = m_{ex}$ by factor $(2m_{en}/m_{eq})^{3/2} \simeq (2\kappa H_p/H)^{3/2} \approx 90$ for reasonable values such as $\kappa \simeq 100$ and $H/H_p \simeq 10$. The vortex exit at $m(\ln t) = m_{eq}$ is faster than one at $m(\ln t) = m_{ex}$ by factor $(1 + m_{eq}/2H_{c1}) \approx 1.3$ due to the fact that $m_{eq} \approx H_{c1}/2$ at $H = H_p$. For vortex exit, as m_{eq} decreases with field H, we expect that the nonlinearity of relaxation process will become disappeared at the region $H \gg H_p$ ($m_{eq} \ll H_{c1}$). If m is not too close to m_{eq} then the critical nucleus consists of one vortex loop, i.e. vortices enter (exit) through SB independently. In the vicinity of m_{eq}, vortex entry (exit) becomes collective, i.e. includes the motion of a large number of vortex lines [7,10].

4. Conclusion

We have calculated the activation energies U and the relaxation rates R = dm/dlnt for the vortex relaxation over the Bean-Livingston surface barrier. As m increases from m_{en} to m_{eq} for relaxation in (vortex entry) or increases from m_{ex} to m_{eq} for relaxation out (vortex exit), the activation energies are represented by Eqs. (5) and (14) for vortex entry and exit, respectively. The relaxation effects, which were determined by the m dependence of the activation energies U, are nonlinear for vortex entry, and linear at the initial stage but nonlinear at $m(\ln t) \simeq m_{eq}$ for vortex exit. The vortex entry at $m = m_{en}$ is faster than the vortex exit at $m = m_{ex}$ by about factor $(2m_{en}/m_{eq})^{3/2}$. The vortex exit at $m(\ln t) = m_{eq}$ is faster than one at $m = m_{ex}$ by about factor $(1 + m_{eq}/2H_{c1})$.

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