FLUX PINNING MECHANISM OF ARTIFICIALLY INTRODUCED Nb INTO SUPERCONDUCTING Nb-Ti

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ABSTRACT

The elementary pinning force of a thin Nb layer introduced as an artificial pinning centers in Nb-Ti is theoretically calculated at relatively low fields using the Ginzburg-Landau theory. The pinning interaction originates from the kinetic energy due to the induced superconductivity in the Nb layer by the proximity effect and the layer acts as a repulsive pinning center. This is different from the α-Ti layer acting as an attractive one through the condensation energy interaction. The elementary pinning force depends sensitively on the coherence length in the Nb layer. It turns out that this elementary pinning force is stronger in usual cases than that of the α-Ti layer in commercial Nb-Ti wires.

1. Introduction

Improvement of the critical current density, J_c, especially at high fields is desired for application of superconducting materials. For this purpose introduction of artificial pinning centers has been tried into Nb-Ti superconducting wires.[1–3] The critical current density of 4.25×10^9 A/m^2 was achieved at 5 T by introduction of Nb of a laminar structure.[3] The higher critical current density in this Nb-Ti wire than usual Nb-Ti with α-Ti precipitates was partly attributed to the higher volume fraction of pinning material. On the other hand, the critical current density in the Nb-Ti with laminar Ti as an artificial pinning material was lower than that with Nb. This suggests that the pinning mechanism of superconducting Nb is different from the usual one of normal materials, i.e., the condensation energy interaction.

It is necessary, therefore, to understand exactly the flux pinning mechanism of Nb in Nb-Ti for the investigation of the possibility of further improvement of the critical current density in Nb-Ti. In this paper this problem is investigated using the Ginzburg-Landau theory. Discussions are given on the theoretical result and the possibility of further improvement.

2. Theory

The superconducting property under the magnetic field is exactly described by the G-L theory. According to this theory the free energy density is expressed as

$$F_s(B) = F_n(0) + \alpha|\Psi|^2 + \frac{\beta}{2}|\Psi|^4 + \frac{B^2}{2\mu_0} + \frac{\hbar^2}{2m^*}(\nabla|\Psi|)^2 + \frac{\mu_0}{2}\lambda^2\left(\frac{|\Psi_\infty|}{|\Psi|}\right)^2 \boldsymbol{J}^2. \quad (1)$$

In the above $F_n(0)$ is the free energy in the normal state in the absence of magnetic

field, Ψ is the order parameter, Ψ_∞ is its equilibrium value, m^* is the mass of superconducting electron, λ is the penetration depth, $\boldsymbol{J}$ is the current density, and α and β are the coefficients. In the case of usual condensation energy interaction by a normal precipitates, the energies of the magnetic field and the current are disregarded because of less importance and the second and third terms in Eq. (1) contribute to the pinning. It is to be noted that the superconductivity is also induced in thin precipitates of α-Ti due to the proximity effect. The important point in this case is that α is positive in the normal material, while it is negative in the surrounding superconducting region. Hence, if the normal core of the fluxoid comes out of the normal material, the energy increases because of the variation in the second term in Eq. (1). It means that such a normal material works as an attractive pinning center.

On the other hand, Nb is superconducting at 4.2 K at low fields. Hence, α depending only on temperature is negative in Nb. This is the most different point from the usual pinning by normal materials. That is, even if the core of fluxoid is inside Nb, there is no gain in the free energy. Then, the question arises. Why is the superconductivity in Nb broken by the magnetic field? Although the upper critical field is derived mathematically from the theory, the explanation is not given from the viewpoint of energy. According to the theory, the approximate expression of the order parameter in the vicinity of upper critical field is given by[4]

$$|\Psi|^2 = \langle|\Psi|^2\rangle \left\{1 - \frac{1}{3}\left[\cos\frac{2\pi}{a_\mathrm{f}}\left(\frac{2}{\sqrt{3}}x\right) + \cos\frac{2\pi}{a_\mathrm{f}}\left(\frac{x}{\sqrt{3}} + y\right) + \cos\frac{2\pi}{a_\mathrm{f}}\left(\frac{x}{\sqrt{3}} - y\right)\right]\right\}, \tag{2}$$

where $\langle\ \rangle$ represents the spatial average and $a_\mathrm{f} = (2\phi_0/\sqrt{3}B)^{1/2}$ is the fluxoid spacing with ϕ_0 denoting the flux quantum. Using Eq. (2), both the fifth and sixth terms in Eq. (1) are reduced to $(B_\mathrm{c}^2\xi^2/\mu_0)(\nabla|\psi|)^2$, where B_c is the thermodynamic critical field, ξ is the coherence length and $\psi = \Psi/|\Psi_\infty|$ is the normalized order parameter. Hence, if we neglect the small term proportional to $|\Psi|^4$, we have

$$F_\mathrm{s}(B) - F_\mathrm{n}(B) \simeq \frac{B_\mathrm{c}^2}{\mu_0}[-|\psi|^2 + 2\xi^2(\nabla|\psi|)^2]. \tag{3}$$

With increasing magnetic field the spacing of zero points of $|\psi|^2$ decreases, resulting in a relative increase in the kinetic energy. That is, if we use Eq. (2) for the approximate solution of $|\psi|^2$, we have

$$\langle(\nabla|\psi|)^2\rangle = \frac{3.71}{a_\mathrm{f}^2}\langle|\psi|^2\rangle. \tag{4}$$

Hence, the superconductivity predicted to be broken at $a_\mathrm{f}^2 = 7.42\xi^2$, i.e., the external magnetic field of $0.98H_{\mathrm{c}2}$. The error comes from the approximation by Eq. (2). It is found, therefore, that the increase in the kinetic energy determines the phase transition.

This can also be expected for the flux pinning by thin Nb layers in Nb-Ti. That is, if the structure of the order parameter with a short periodicity is induced in Nb due to the proximity effect, a significant increase in the kinetic energy will be resulted. In fact, a clear evidence of the proximity effect can be seen in the degradation of the upper critical field.[5] This is a large difference from the proximity effect by α-Ti

Figure 1: Multilayers of Nb-Ti and Nb.

precipitates where the critical temperature is degraded. Thus, the kinetic energy increases when the fluxoid meets the Nb layer. It means that the pinning interaction by Nb layer is repulsive, while the interaction by usual normal precipitates is attractive. It is to be noted that the above phenomenon is unchanged even if the magnetic field is lower or higher than the upper critical field of Nb. The magnetic field dependence of the pinning property is predicted to be monotonic even at this field as observed usually. This supports the above conclusion that the pinning mechanism comes from the kinetic energy. If the condensation energy interaction is responsible, the interaction of Nb layer will change from repulsive to attractive with increasing magnetic field, resulting in a minimum pinning force near its upper critical field.

We assume a multilayered structure as shown in Fig. 1. If the thickness of Nb layers, d_{N}, is sufficiently small, the order parameter will be easily induced in them by the proximity effect. For simplicity the case is treated where the magnetic field is normal to the layers and the distance between fluxoids is sufficiently large. Thus, the present analysis is applicable to the relatively low field region.

Under the present geometry we assume that $|\Psi_\infty|$ and the structure of the order parameter of the fluxoid are approximately the same as those in a bulk Nb-Ti, since the thickness of Nb-Ti layers, d_{NT}, is usually much thicker than that of Nb, d_{N}. As an analytic expression of the structure of the order parameter, we use

$$|\psi| = \tanh(ar) \tag{5}$$

where a takes $1.8\xi_{\mathrm{NT}}$.[6]

Since the critical temperature and the thermodynamic critical field are approximately the same for Nb-Ti and Nb, the coefficients, α and β, are speculated to be approximately the same. As it is assumed in the above that the magnetic structure of fluxoid is approximately the same between the two layers because of thin thickness of the Nb layer, the magnetic energy and the energy of the current are not involved in the pinning mechanism. Thus, the associated energy is only the kinetic energy owing to the spatial variation in the order parameter.

We consider the two cases shown in Fig. 2(a) and 2(b). To discuss the difference of the energy between the two cases, we have only to compare the sum of the energies in the regions of V_1 and V_2. In the condition shown in Fig. 2(a) where the normal

Figure 2: Arrangements of pinning layers and core of fluxoid.

core occupies V_1, the energy in V_1 increases from the situation where the normal core is absent as in Fig. 2(b). The increase in the kinetic energy is estimated as

$$\frac{B_{\rm c}^2\xi_{\rm N}^2 d_{\rm N}}{\mu_0}\int_0^\infty\left(\frac{{\rm d}|\psi|}{{\rm d}r}\right)^2 2\pi r{\rm d}r=\frac{4\pi B_{\rm c}^2\xi_{\rm N}^2 d_{\rm N}}{3\mu_0}\left(\ln 2-\frac{1}{4}\right). \tag{6}$$

On the other hand, in the case of Fig. 2(b) the increase in the kinetic energy in V_2 is similarly given by $(4\pi B_{\rm c}^2\xi_{\rm NT}^2 d_{\rm N}/3\mu_0)(\ln 2-1/4)$. As a result the difference of the energy between (a) and (b) in Fig. 2 is obtained as

$$\Delta U_{\rm N}=U_{\rm a}-U_{\rm b}=\frac{4\pi B_{\rm c}^2 d_{\rm N}}{3\mu_0}(\xi_{\rm N}^2-\xi_{\rm NT}^2)\left(\ln 2-\frac{1}{4}\right)=0.591\pi\frac{B_{\rm c}^2 d_{\rm N}}{\mu_0}(\xi_{\rm N}^2-\xi_{\rm NT}^2). \tag{7}$$

It is found that $\Delta U_{\rm N}>0$ since $\xi_{\rm N}>\xi_{\rm NT}$. Therefore, Nb layers work as repulsive pinning centers. The elementary pinning force of an edge of Nb layer is

$$f_{\rm pN}\simeq\frac{\Delta U_{\rm N}}{2\xi_{\rm N}}=0.296\pi\frac{B_{\rm c}^2 d_{\rm N}}{\mu_0\xi_{\rm NT}}(\xi_{\rm N}^2-\xi_{\rm NT}^2). \tag{8}$$

3. Discussion

Here we compare the above result with the elementary pinning force of a thin α-Ti layer with the same thickness, $d_{\rm N}$. From a similar calculation in Ref. 7 we have

$$f_{\rm p}\simeq\frac{\pi B_{\rm c}^2 d_{\rm N}}{\mu_0 a^2\xi_{\rm NT}}(1-c)\left[(1+\theta)\ln 2-\frac{1-c}{12}(8\ln 2+1)\right]. \tag{9}$$

In the above θ is the ratio of the coefficient, α, between α-Ti and Nb-Ti, i.e., $\theta=\alpha_{\rm T}/|\alpha_{\rm NT}|$ and $c=(d_{\rm N}/d_{\rm NT})\theta$. In the case of α-Ti we have[8] $\theta\simeq 1.4$. The high critical

current density was attained for the case of $d_{\rm N}/d_{\rm NT} = 0.25$. If we discuss this case, we have $c = 0.35$. Thus the elementary pinning force is estimated as

$$f_{\rm pT} = 2.76\pi \frac{B_{\rm c}^2 \xi_{\rm NT} d_{\rm N}}{\mu_0}. \tag{10}$$

From Eqs. (8) and (10) we have

$$\frac{f_{\rm pN}}{f_{\rm pT}} = 0.107 \left[\left(\frac{\xi_{\rm N}}{\xi_{\rm NT}} \right)^2 - 1 \right]. \tag{11}$$

It is seen from Eq. (11) that $f_{\rm pN}$ depends sensitively on $\xi_{\rm N}$ of Nb layers. The coherence length of Nb-Ti, $\xi_{\rm NT}$, amounts to 5.33 nm ($B_{\rm c2} = 11.6$ T). In Nb in the clean limit $\xi_{\rm N}$ is 32.1 nm ($B_{\rm c2} = 0.32$ T) and the ratio of the elementary pinning force is $f_{\rm pN}/f_{\rm pT} = 3.77$. Thus, $f_{\rm pN}$ in this limit is quite strong. However, the practical Nb layer is heavily cold worked and the electron mean free path will be very short. The thin layer thickness will also make $\xi_{\rm N}$ short, since the interfaces between Nb and Nb-Ti scatter electrons. The upper critical field of heavily cold worked Nb is reported to be saturated at about 1.10T.[9] It means $\xi_{\rm N}$=17.3 nm and we have $f_{\rm pN}/f_{\rm pT} = 1.02$ in this case. Thus, the elementary pinning force of Nb layers is not weaker than that of α-Ti layers even in the case of short $\xi_{\rm N}$. This result seems to be consistent with the very high critical current density attained in Nb-Ti wires with artificially introduced Nb pins.

The above result suggests that, if $\xi_{\rm N}$ is enlarged, the higher critical current density will be obtained. Some heat treatment may be useful for reduction in the density of defects remained in Nb. However, the thickness of Nb layer is required to be reduced below a certain level to make the effective pin concentration high. Then, it is speculated that the very thin thickness of the layer determines mainly $\xi_{\rm N}$ through the limitation of the electron mean free path. In addition, the degradation of $B_{\rm c2}$ seems to be significant for extremely thin layers. In the thin limit the energy density in each layer is given by Eqs. (3) and (4). Thus, the total energy in a couple of layers is

$$\frac{B_{\rm c}^2 |\psi|^2}{\mu_0} \left[d_{\rm N} \left(-1 + \frac{7.26 \xi_{\rm N}^2}{a_{\rm f}^2} \right) + d_{\rm NT} \left(-1 + \frac{7.26 \xi_{\rm NT}^2}{a_{\rm f}^2} \right) \right], \tag{12}$$

where the factor 7.42 was corrected to 7.26 so that the estimation gives a correct value of $B_{\rm c2}$. From the condition that $B_{\rm c2}$ is given by the field at which the above energy goes to zero, we have

$$B_{\rm c2} = B_{\rm c2}^{\rm NT} \cdot \frac{1 + d_{\rm N}/d_{\rm NT}}{1 + d_{\rm N}\xi_{\rm N}^2/d_{\rm NT}\xi_{\rm NT}^2}. \tag{13}$$

In the present case of $d_{\rm N}/d_{\rm NT} = 0.25$ and $\xi_{\rm N}^2/\xi_{\rm NT}^2 = 10.5$, $B_{\rm c2}$ is estimated as 4.0 T. The upper critical field of multilayer was calculated using the microscopic theory by Takahashi and Tachiki.[10] They calculated the case of $d_{\rm N} = d_{\rm NT} = 0.75\xi_{\rm NT}(0)$ for various values of the ratio of diffusion coefficient, $D_{\rm N}/D_{\rm NT}$. Since this ratio is equal to $\xi_{\rm N}^2/\xi_{\rm NT}^2 = 10.5$, their result for $D_{\rm N}/D_{\rm NT} = 10$ can be approximately compared with

the present multilayer of Nb-Ti and Nb. In this case it is predicted that $B_{c2}(T/T_c = 0.5) \simeq 1.3B_{c2}^{N}(0)$. Assuming a parabolic temperature dependence for $B_{c2}(T)$, we have $B_{c2}/B_{c2}^{N} = 1.79$ at high temperature region. That is, B_{c2} is estimated as 1.97 T, while the above estimation leads to 2.01 T. Thus, the agreement is rather good and the present simple analysis using the G-L theory explains the phenomenon well.

It is concluded from the above argument that the drastic improvement of the elementary pinning force seems to be difficult. The optimum conditions should be sought out with respect to the volume fraction and the geometry for further improvement of the critical current density.

4. Summary

The flux pinning mechanism of thin Nb layers introduced in Nb-Ti as artificial pinning centers was investigated using the Ginzburg-Landau theory and the elementary pinning force was estimated. The following results are obtained.
(i) The energy associated with the pinning is the kinetic energy owing to the spatial variation in the order parameter induced in the Nb layers by the proximity and these layers work as repulsive pinning centers.
(ii) The elementary pinning force depends sensitively on the coherence length of the Nb layers and is stronger for the longer coherence length.
(iii) Even in the case of short coherence length the elementary pinning force of the Nb layers is comparable to or stronger than that of the α-Ti layers in commercial Nb-Ti wires.

5. References

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