THEORETICAL DESCRIPTION OF SIS MULTILAYER FILMS FOR SRF CAVITIES*

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Abstract

The SIS structure—a thin superconducting film on a bulk superconductor separated by a thin insulating film—was propsed as a method to protect alternative SRF materials from flux penetration by enhancing the first critical field B_{c1}. In this work, we calculate the gibbs free energy of a vortex in a superconductor, and we show that an isolated thin film can enhance B_{c1}, but when it is placed in a SIS structure, due to the gradient in field across the film, we show that in fact $B_{c1} = 0$. We argue that the SIS structure is not beneficial for SRF cavities, but it may be useful in DC and low frequency applications. However, due to recent experiments showing low-surface-resistance performance above B_{c1} in cavities made of superconductors with small coherence lengths, we argue that enhancement of B_{c1} is not necessary, and that bulk films of alternative materials show great promise.

INTRODUCTION

SRF researchers have begun a significant effort to develop alternative materials to niobium, superconductors that could offer higher accelerating gradients E_{acc} and/or lower surface resistances R_s at a given temperature. There are several promising candidates, but most of them suffer from two potential liabilities. First, they have relatively small first critical fields B_{c1}, the magnetic field at which it becomes energetically favorable for a vortex to be inside the superconductor. Second, they have relatively small coherence lengths ξ. Vortex penetration is prevented at fields significantly above B_{c1} by an energy barrier, but surface defects on the order of ξ can reduce this barrier. These materials have ξ on the order of a few nm, compared to tens of nm for niobium, making even very small defects a potential vulnerability. As a result, there has been significant concern in the SRF community over whether vortex dissipation will occur if these materials are exposed to fields that bring them into the metastable state between B_{c1} and B_{sh}, the superheating field at which the energy barrier is reduced to zero for an ideal surface.

A. Gurevich proposed [1] a method to avoid the potentially vulnerable metastable state altogether. Pointing to the enhancement of parallel B_{c1} in films with thickness d smaller than the penetration depth λ, he suggested coating a niobium cavity with alternating layers of insulator (I) and thin film superconductor (S). With such a SIS structure, he proposed it might be possible to take advantage of the high B_{sh} and low R_s of the alternative superconductors used in the thin films without the disadvantage of their small B_{c1}. SRF researchers have been putting significant effort into developing SIS multilayers, and they are producing excellent work [2, 3, 4, 5, 6, 7, 8].

CALCULATING BC1

Tinkham [9] defines B_{c1} as the field at which "the Gibbs free energy [has] the same value whether the first vortex is in or out of the sample." For a SIS, the sample under consideration should be the full structure [10]. Stejic et al. [11] calculate the Gibbs free energy of a vortex in a thin film superconductor immersed in a parallel external field. They show that B_{c1} of the film is enhanced relative to the bulk value, according to

$$B_{c1} = \frac{2\phi_0}{\pi d^2}\left(\ln\frac{d}{\xi} + \gamma\right) \tag{1}$$

where ϕ_0 is the flux quantum, $\gamma = -0.07$ and $d << \lambda$. However, if a SIS structure is used to screen Nb SRF cavities, the geometry is quite different than that of an isolated film. How does Stejic's expression for B_{c1} change when the film is screening a bulk superconductor? In this case, it will have a B-field gradient across it, which will affect the free energy. We can use the same formalism as Stejic to calculate the Gibbs free energy for this case, and use it to find B_{c1} and B_{sh}[12].

Consider a single layer SIS structure, as shown in Fig. 1. A strongly type II superconducting film of thickness d, penetration depth λ_f, and coherence length ξ_f is separated from a bulk superconductor with with penetration depth λ_b by an insulating film of thickness δ. The superconducting film is screening the bulk from a parallel magnetic field with amplitude B_0. The screened field inside the bulk region has amplitude B_i. In our geometry, the x-axis is perpendicular to the film, pointing into it, with origin at the interface with the exterior. The z-axis is aligned with the magnetic field.

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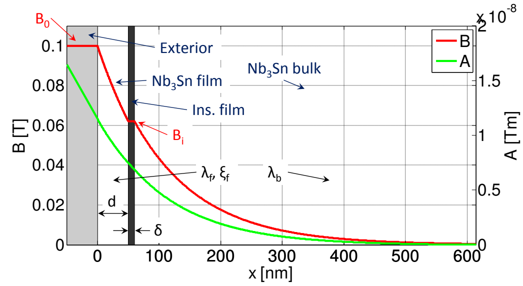

Figure 1: Geometry of the structure under consideration. The amplitudes of the magnetic field and the vector potential are plotted as a function of distance into the structure.

Stejic shows that the Gibbs free energy of a vortex in a superconductor can be determined from the value of two magnetic fields evaluated at the vortex location r_0: the Meissner-screened external field B_M and the field generated by the vortex in the film B_V.

$$\mathcal{G} = \frac{\phi_0}{\mu_0}\left(B_V(r_0)/2 + B_M(r_0)\right) \tag{2}$$

B_M can be found by minimizing the free energy in the structure when no vortex is present. This procedure gives:

$$B_M = \frac{B_0 + B_i}{2}\frac{\cosh\frac{x}{\lambda_f}}{\cosh\frac{d}{2\lambda_f}} - \frac{B_0 - B_i}{2}\frac{\sinh\frac{x}{\lambda_f}}{\sinh\frac{d}{2\lambda_f}} \tag{3}$$

where B_i is given by

$$B_i = B_0\left[\frac{\delta + \lambda_b}{\lambda_f}\sinh\frac{d}{\lambda_f} + \cosh\frac{d}{\lambda_f}\right]^{-1} \tag{4}$$

Stejic gives a relatively simple expression for B_V for the case when $d << \lambda$, but this would restrict us to very thin films. To study the full range of thicknesses, we turn to the more general expression from Shmidt [13] (this expression assumes $r_0 = (x_0, 0)$), which agrees with Stejic's expression for very small films:

$$B_V = \frac{2\phi_0}{\lambda^2 d}\sum_{n=1}^{\infty}\int_{-\infty}^{\infty}\frac{dk}{2\pi}e^{iky}\frac{\sin(\pi n x/d)\sin(\pi n x_0/d)}{k^2 + (\pi n x_0/d)^2 + 1/\lambda^2} \tag{5}$$

We can check our procedure by choosing $d >> \lambda$, such that the film behaves as a bulk superconductor. This calculation is shown in the top plot of Fig. 2. $B = B_{c1}$ when the free energy outside the superconductor is equal to that when a vortex is deep in the bulk. $B = B_{sh}$ when the barrier to flux penetration is reduced to zero (this plot is very similar to the one from Bean and Livingston's 1963 paper [14]).

We can study a single thin film (not in a SIS structure) by setting $B_i = 0$ in Eq. 3. This calculation is shown in the center plot of Fig. 2 (the free energy outside the film is

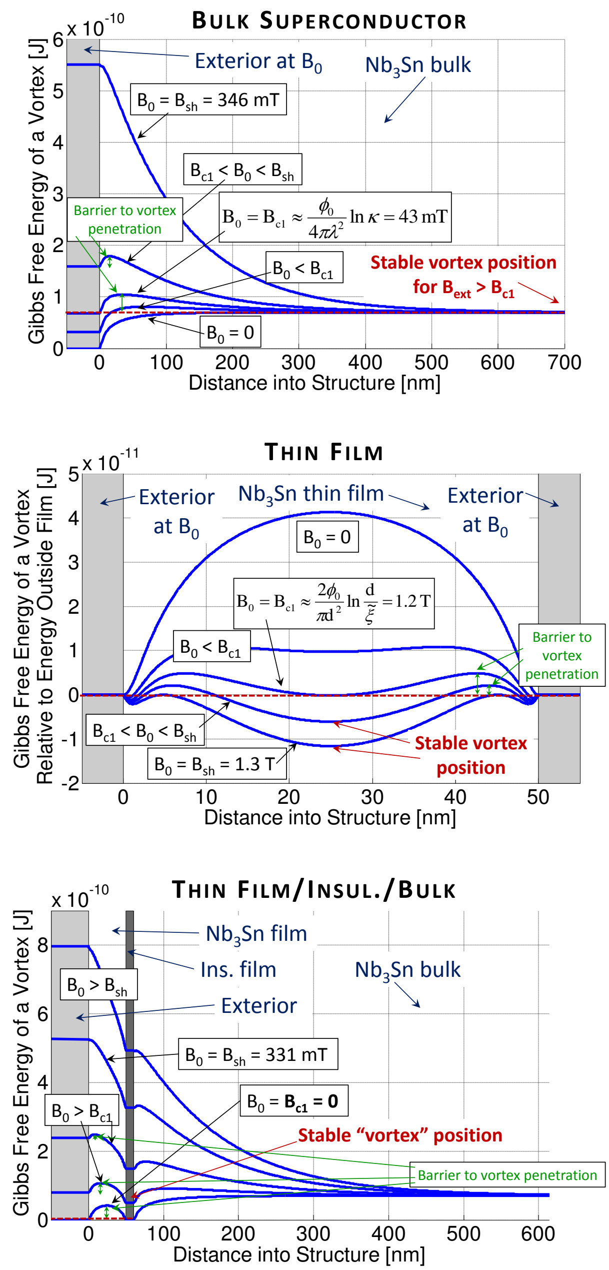

Figure 2: Gibbs free energy at various fields for a single vortex in (top) bulk Nb_3Sn, (center) a 50 nm Nb_3Sn thin film, and (bottom) a SIS structure with a 50 nm Nb_3Sn film on a Nb_3Sn bulk. B_{c1} is the smallest field at which there is a position inside the structure where the free energy for a vortex is smaller than the value outside. B_{sh} is the field at which the energy barrier to vortex penetration disappears. The top and center plots show the B_{c1} enhancement for a thin film compared to a bulk. The bottom plot shows that for a SIS structure $B_{c1} = 0$. The expression for the thin film B_{c1} is not valid for the SIS structure because it assumes that the first stable vortex position will be at the center of the film. However, for the SIS structure, the first stable vortex position occurs on the side of the film adjacent to the insulating layer.

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subracted from each of the plots for clarity). In this case, there is no bulk, so the first location at which the free energy drops below the external value at high fields is in the center of the film. This would be the stable position for a single vortex above B_{c1}. Both B_{c1} and B_{sh} are much higher for the film than the bulk.

Finally, we plot the free energy of vortex in a single SIS structure in the bottom plot of Fig. 2. In contrast to the previous case, only one side of the thin film is exposed to the external magnetic field. The field at the other side is smaller due to screening by film. Since $B_V = 0$ at the edges of the film, Eq. 2 shows that the free energy in the insulating layer is lower than the free energy outside. The film provides screening at any finite B_0 below the second critical field, so for $B_0 > 0$, the energetically favorable configuration is for flux to be trapped in the insulating layer. As we explain below, this implies that in practice for the SIS structure, B_{c1} is zero.

Why is Eq. 1 describing the enhancement of B_{c1} in a lone thin film not applicable for the SIS structure? This expression assumes that the first stable vortex position will occur in the center of the film. It predicts when the free energy at the center of the film will dip below the value of the free energy in the exterior. However, for the SIS structure, the free energy at the insulator side of the film will dip below the exterior value at fields much smaller than this.

DISCUSSION AND CONCLUSIONS

In this paper, we have shown that contrary to suggestions that SIS structures enhance B_{c1}, in fact they reduce it to zero. In [15], it is also shown that the B_{sh} of an SIS structure is only marginally larger than the bulk value and only for a small parameter space, and that using a multilayer only decreases B_{sh} of the film. In addition, [15] shows that SIS structures exhibit unmanageable levels of heating above B_{sh} at high frequencies. Therefore, it seems that SIS structures are not beneficial for SRF applications. However, they may be useful in DC and low frequency applications, where it should be possible to set up a gradient in the phase of the order parameter in the thin films, allowing them to screen very large fields.

Based on the results of this study, the authors of this paper recommend that SRF researchers developing alternative materials concentrate their efforts on bulk films. Bulk films are quite simple to fabricate compared to SIS films, but they offer a similar ideal SRF performance. And although we have shown that it is not possible to augment B_{c1} with SIS structures, there is still great promise for alternative materials. Because of recent experiments showing that low-surface-resistance operation above B_{c1} is possible with cavities made from short coherence lengths superconductors [16] [17], we now know that the potential of bulk films has not yet been realized.

REFERENCES

[1] A. Gurevich, App. Phys. Lett. 88, 012511 (2006).

[2] C. Antoine, Phys. Rev. ST-AB 13, 12 (2010).

[3] T. Tajima et al., AIP Conf. Proc. 1435, 297 (2012).

[4] D. Beringer et al., IEEE Trans. App. Superc. 23, 3 (2013).

[5] A.-M. Valente-Feliciano et al., Proc. of SRF2011, THPO074, (2011).

[6] X. Xi, Supercond. Sci. Technol. 22 (2009) 043001.

[7] T. Proslier et al., WEIOC03, SRF2013.

[8] D. Oates et al., (Presented at the Thin Films SRF Workshop, Newport News, USA, 2012).

[9] M. Tinkham, *Introduction to Superconductivity* (New York: Dover, 1996).

[10] This definition is chosen because if vortices move from the external region across the superconductor to become trapped flux in the insulating region, a very large amount of heating will occur. In other words, above B_{c1} as we have defined it, the film is in a metastable state, and only an energy barrier prevents strongly dissipative flux penetration.

[11] G. Stejic et al., Phys. Rev. B 49 (1994) 1274.

[12] These calculations use the London model, valid only for strongly type II materials. It neglects non-linearity, and likely overestimates B_{sh}.

[13] V. Shmidt and G. Mkrtchyan, Soviet Physics Uspekhi 17, (1974) 170.

[14] C. Bean and J. Livingston, Phys. Rev. Lett. 12 (1964).

[15] S. Posen and M. Liepe, WEIOC04, SRF2013.

[16] S. Posen and M. Liepe, TUP087, SRF2013.

[17] D. Gonnella and M. Liepe, TUP027, SRF2013.