COMMENTS

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Comment on ''Magnetic-coherence-length scaling in metallic multilayers''

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In a recent paper [Phys. Rev. B **54**, 515 (1996)], Koperdraad and Lodder compare calculations of the parallel critical field $H_{c2}^{\parallel}$ in superconductor–normal-metal multilayers with experimental data taken from the literature. The poor agreement leads them to introduce a scaling factor α in the superconducting coherence length. The aim of this Comment is to point out the importance of the boundary conditions of the problem. Free sample surfaces will yield different results than an infinite stack of layers. The effect of free surfaces on the temperature of the dimensional crossover in $H_{c2}^{\parallel}$ is shown to be similar to the effect of α, making the need for the latter parameter questionable. [S0163-1829(97)01037-0]

In a recent publication,[1] Koperdraad and Lodder addressed the issue of the behavior of the parallel and perpendicular critical fields in superconductor–normal-metal (S/N) multilayers. Starting from the Takahashi-Tachiki theory,[2] but going beyond the diagonal approximation used in that work (see Ref. 3), the authors try to fit computed critical-field curves to a number of published experimental results, notably on Nb/Cu, V/Ag, V/Cu, and Nb/Ag. The free parameters in their fitting procedure are the diffusion coefficients of both metals D_N and D_S, as well as N_S, the density of states of the superconductor. The calculation is for an infinite stack of layers. They come to the conclusion that generally the agreement is poor, which is most clearly manifested in the inability of the calculations to reproduce the temperature of the dimensional crossover (DCO), present in the parallel critical-field behavior of all these systems. In order to circumvent this problem, the authors introduce the concept of a coherence length scaling factor α, to be used in the relation [their Eq. (20)]:

$$\xi = \sqrt{\frac{\alpha \hbar c}{2eH}}, \tag{1}$$

with $e,\hbar,c$ having their usual meaning. For $\alpha=1$, this is the equation for the Ginzburg-Landau coherence length ξ, provided it is calculated at the magnetic field $H=H_{c2}$, which is implicit in critical-field calculations. The role of α is to decouple the magnitude of the calculated critical field from the crossover temperature, using α as a fourth parameter. In this way, much better agreement is reached. The authors conclude that, since the introduction of scaling lacks external justification, the fact that it works signals the need for a modification of the Takahashi-Tachiki theory in order to obtain realistic quantitative descriptions for the critical fields of S/N multilayers. The purpose of this Comment is to point out that the most serious modification needed is the use of boundary conditions which take into account that all samples in experimental measurements have two free surfaces. An unphysical scaling parameter in the Ginzburg-Landau coherence length may then well prove unnecessary.

As a matter of fact, the influence of free surfaces on the parallel critical fields in multilayers with two different superconducting components (S/S'), having the same T_c but different diffusion constants, was investigated both experimentally[4] and theoretically[5] some time ago. In such systems there are two DCO's rather than one, from ''sample averaged three-dimensional (3D)'', to 2D, to ''single film 3D.'' When the outer layer has the smaller diffusion constant of the two, and therefore will carry surface superconductivity at low temperatures, it was shown that the low-temperature DCO (2D-3D) strongly depends on the thickness of this layer. The transition is governed by the condition that the film-averaged and temperature-dependent coherence length $\xi_{av}(T)$ becomes less than some large fraction c_f of the multilayer periodicity Λ:

$$\frac{\xi_{av}(T)}{\Lambda} \leqslant c_f, \quad c_f \leqslant 1, \tag{2}$$

where $\xi_{av}(T)$ follows the usual inverse square root behavior, $\xi_{av}(T) = \xi_{av}(0)(\sqrt{1-T/T_c})^{-1}$, with T_c the zero-field critical temperature of the system. If the outer layer is thinner than the inside layers of the same type, Λ will be effectively smaller, and condition (2) will be met at a lower temperature. This results in considerable shifts of the second DCO.

The principle for the higher-temperature 3D-2D DCO (usually the only one encountered in N/S multilayers) is similar. Quoting from Ref. 1, ''ξ is the length scale that controls the position of the DCO . . . .'' According to Eq. (2), this is not entirely accurate: the length scale is set by Λ. Now consider the experiments. All were performed on samples with the N layer as the outer layer, with a thickness d_N the same as or larger than the inside N layers. From the symmetry condition for the order parameter at the free surface, this means that the outer layer behaves as one twice as thick. In other words, near the free surface, Λ is effectively larger, and condition (2) will be met at a higher value for ξ and therefore at a higher temperature. This is what is mimicked by the scaling parameter α in Ref. 1. For all systems where experiments were compared to the infinite layer calculation, a shift to higher temperature is needed, meaning values for α smaller than 1.

The one exception appears to be the case of V/Cu (25 nm/15 nm), where a value $\alpha = 1.65$ is necessary. That can be explained by inspecting the original data of Dediu *et al.*[6] The temperature dependence of the parallel critical field $H_{c2}^{\parallel}$ actually shows two DCO's, not one, which is quite unusual for S/N systems. The behavior is linear near T_c, square-root-like below a crossover temperature T^+, but then again linear below a second crossover temperature T^*. The higher point density in the actual measurement clearly shows (as also remarked in Ref. 1) that the two linear regimes are in line. Given also the fact that the perpendicular critical field is linear in the whole range of measured temperatures, with a slope which is a factor 1.4 times smaller than that of $H_{c2}^{\parallel}$, it appears that the linear $H_{c2}^{\parallel}(T)$ near T_c is the result of surface superconductivity, that the high-temperature DCO is a crossover from the surface superconducting state to bulk nucleation in the thin V layer, and that the low-temperature DCO is a crossover back to surface superconductivity. This reappearance of surface superconductivity at lower temperatures is a quite uncommon experimental finding, and apparently due to both the small thickness of the Cu layers and the rather large thickness (only just 2D) of the V. The low-temperature DCO at T^* then should not be used to fit the calculations (or to determine a value for α), since the physics is slightly different. Although it concerns a shift of nucleation point (from a bulklike V layer back to somewhere near the free surface), the special surface solutions which result in a critical field of maximally 1.7 times higher than the bulk critical field cannot be reproduced by the infinite layer calculations, nor can the DCO. However, that is not needed anyway. The DCO equivalent to the ones seen in the other systems is the high-temperature DCO around $T^+ = 3.83$ K. The difference between the surface critical field and the equivalent bulk critical field is quite small near T_c and indeed, that DCO is quite well reproduced without a scaling factor (see Fig. 6 in Ref. 1). The surface superconductivity also explains why the calculation underestimates $H_{c2}^{\parallel}$ near T_c. On the other hand, using $\alpha = 1.65$ simply forces the calculation to the wrong crossover. Finally, it is worth noting that the problem of surface superconductivity will dominate $H_{c2}^{\parallel}$ near T_c in most of the experiments used for the comparison, the case of Nb/Cu being the only one where samples were covered with a very thick Cu layer in order to suppress this effect.[7] The comparison in the other cases is therefore approximate rather than exact.

In conclusion, I have argued that infinite layer calculations should not be used in comparison with finite layer experiments. The introduction of a scaling parameter α is premature, as long as this point is not taken into account. It is interesting to note that no experiment can be devised which circumvents this problem: if very thick N layers are used to suppress surface superconductivity, the S layer next to these N layers will be in a situation of different symmetry; if the N layers are chosen thin, especially of half the thickness of the inside N layers (for conservation of symmetry), then surface superconductivity as another manifestation of the free surface problem cannot be avoided.

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