PHYSICAL REVIEW B **66**, 136502 (2002)

Reply to "Comment on 'Ferromagnetic film on a superconducting substrate' "

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(Received 14 May 2002; published 31 October 2002)

The energy of the magnetic field has been overestimated in our original paper but the paper did not say that domains could shrink drastically due to the substrate. The maximal shrinkage of domains is by 18.35%, which is sufficiently large to be easily observed in experiment.

DOI: 10.1103/PhysRevB.66.136502 PACS number(s): 74.60.Ge, 74.50.+r, 75.70.Cn

We thank Sonin[1] for noticing that the model of Ref. 2, overestimates the energy of the magnetic field. Reference 2, however, did not contain the statement, attributed to it by the Comment, namely, that the ferromagnetic domains in a ferromagnetic film "drastically" shrink when the film is placed on a superconducting substrate.

The paper said only that in the presence of the superconducting substrate "the balance of the magnetic energy changes drastically" and that this causes domains to "shrink by an appreciable factor."

Sonin solves the problem in the limit of $\lambda_L \to 0$, where λ_L is London penetration depth. The exact free energy $\mathcal{F}$ for any λ_L, which corrects the formula of Ref. 2, is given by

$$\frac{\pi\mathcal{F}}{28\zeta(3)M_0^2\lambda_L} = 3\bar{l} + \frac{2\bar{l}_N^2}{\bar{l}} - \frac{16\bar{l}}{7\zeta(3)}\sum_{k\geqslant 0}\{(2k+1)^2 [2k+1+\sqrt{(2k+1)^2+16\bar{l}^2}]\}^{-1}. \qquad (1)$$

Here $\bar{l}=l/4\pi\lambda_L$ and $\bar{l}_N=l_N/4\pi\lambda_L$ are the reduced widths of domains on a superconducting and normal substrate, respectively, and M_0 is the saturation magnetization of the ferromagnetic film.

In the limit of $\lambda_L \to 0$, that is, for large $\bar{l}_N$, the last term in Eq. (1) tends to a constant and the minimization of the free energy yields $\bar{l}=(2/3)^{1/2}\bar{l}_N$, in accordance with Sonin.[1]

For arbitrary $\bar{l}_N$, the dependence of $\bar{l}$ on $\bar{l}_N$ should be obtained by the minimization of the total free energy, Eq. (1). This dependence is provided by a solid line in Figs. 1 and 2. The thin dashed line, $\bar{l}=\bar{l}_N$, corresponds to the normal substrate. The thick dashed line, $\bar{l}=(2/3)^{1/2}\bar{l}_N$, gives the maxi-

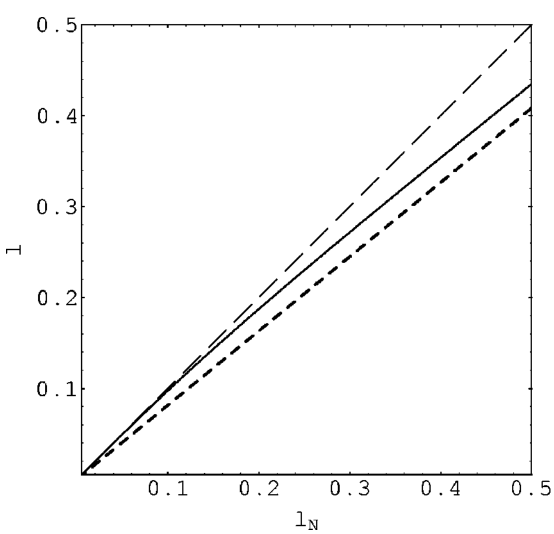

FIG. 1. Shrinkage of small domains in a ferromagnetic film on a superconducting substrate in terms of reduced variables; see text for explanation.

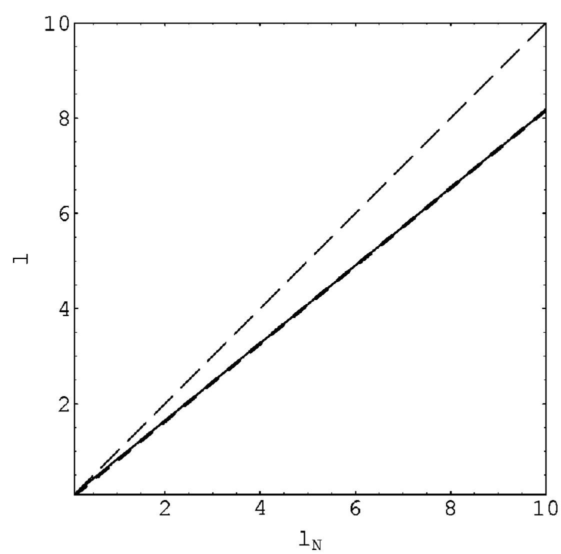

FIG. 2. Shrinkage of large domains in a ferromagnetic film on a superconducting substrate in terms of reduced variables; see text for explanation.

mal possible shrinkage of domains. The effect of the superconductor becomes noticeable at $\overline{l}_N \gtrsim 0.1$ (see Fig. 1). At $\overline{l}_N > 1$ the limiting formula $\overline{l} = (2/3)^{1/2} \overline{l}_N$ provides a rather good approximation (see Fig. 2). The maximal shrinkage of the domains is by 18.35%, that is, sufficiently large to be easily observed in experiment.

This work has been supported by the U.S. Department of Energy through Grant No. DE-FG02-93ER45487.

[1] E. B. Sonin, preceding Comment, Phys. Rev. B **66**, 136501 (2002).

[2] L. N. Bulaevskii and E. M. Chudnovsky, Phys. Rev. B **63**, 012502 (2001).