Thermoelectric Generation of Magnetic Flux in Thin-Film Superconductors

In a recent Letter, Garland and VanHarlingen[1] (GV) propose a theory to explain the experimental results of Lee, Rudman, and Garland[2] (LRG) related to thermoelectric generation of net magnetic flux in very thin high-resistivity superconducting films. However, it should be noted that the *ad hoc* assumption of GV about the relaxation of the nonequilibrium state caused by the electric field and thermal gradient violates flux conservation. The only processes which can change the flux density in the interior of a two-dimensional film, as contrasted to its edges, are diffusion which depends on the gradient of the vortex areal density n_f, and recombination (or thermal generation, if any) of vortices with antivortices which have the opposite direction of field and angular momentum (i.e., current circulation) to vortices. (This situation is analogous to charge conservation of electrons and holes in semiconductors.) Only at the edges (e.g., the boundaries in the plane of the film) can vortices and antivortices be injected asymmetrically, as a result of applied currents or fields. In Eq. (2) of Ref. 1,

$$\frac{dn_f}{dt}=\frac{\partial n_f^{\pm}}{\partial T}\mathbf{v}_d^{\pm}\cdot\nabla T-\frac{(n_f^{\pm}-n_{f0}^{\pm})}{\tau_f}=0, \qquad (1)$$

the first term represents flux flow of vortices driven by the transport current at a drift velocity $\mathbf{v}_d^{\pm}$, and the final term represents their *ad hoc* relaxation process, with τ_f the relaxation time. Note that since $n_f^+ > n_{f0}^+ = n_{f0}^- > n_f^-$ in Fig. 1 of Ref. 1, these two relaxation terms (for $\pm$ vortices) are not equal and represent a net depletion (sink) of (+) vortices and creation (source) of (−) antivortices at every point in the interior of the film. Thus this *ad hoc* relaxation process (which acts like a flux pump) violates flux conservation. Flux conservation is inherent in the recombination model of Bancel and Gray[3] which is *not* restricted to the symmetric excitation mode ($n_f^+ = n_f^-$) as suggested by GV. We suggest that Eq. (1) above should be written, for a variation in one dimension, as[3]

$$\frac{dn_f^{\pm}}{dt}=\frac{\partial}{\partial x}\left(D\frac{\partial n_f^{\pm}}{\partial x}\mp v_d n_f^{\pm}\right)-8\pi\mu k_B T(n_f^+n_f^- - n_{f0}^+n_{f0}^-), \qquad (2)$$

where μ is the flux flow mobility, D is the flux diffusion constant, and $n_{f0}^+n_{f0}^-$ accounts for thermal generation (if any) of free vortices in the interior of the film. It is not clear whether the *ad hoc* relaxation term of Eq. (1) can be a sufficiently good approximation to Eq. (2), but it seems unlikely since it neglects pairwise recombination and is independent of the gradient of n_f.

The experimental results[2] of LRG can, in fact, also be qualitatively explained by an asymmetry in the injection of vortices at the film edges due to the applied current, *without* recourse to thermally generated vortices.[4] Such an asymmetry has been observed in foils of type-II superconductors[5] and in films of type-I superconductors[6] and can be caused by differences in the sharpness of opposite edges of the sample, leading to different barrier heights for flux injection. In a similar manner, the temperature differences imposed by LRG on opposite film edges can lead to asymmetries in the thermally activated edge injection of flux over the "image-force" potential,[4] even without unequal pinning due to structural irregularities. It is easy to show that the polarity of such a thermoelectrically generated flux due to edge injection is the same as in the GV model (including a sign change if either the electric field or ∇T is reversed) and these are presumably consistent with experiments.[2] Note that while the edge injection rate of vortices, compared to thermal generation, contains an additional factor of the sample current, I_s, this factor cancels in the average flux density since the vortex lifetime in a film of width w is w/v_d (to within a factor[4] of 2) and $v_d \propto I_s$. Hence, the linear dependence of asymmetrical flux on current would also be consistent with the edge injection model. The linear dependence of asymmetrical flux on the temperature difference, ΔT, is likewise consistent with edge injection with such small values of ΔT.

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