Phase transition in vortex matter driven by bias current

Boris Ya. Shapiro [1], Moshe Gitterman, Irena Shapiro
Department of Physics, Bar-Ilan University, 52100 Ramat Gan, Israel

Abstract

The phase transition in vortex matter subjected to external magnetic field and bias current are described by the generalized Ginzburg-Landau equations with additional convective and effective field terms. Analytical and numerical solutions of this equation provide the interface between ordered and disordered vortex phases. The location of this interface boundary depends nonmonotonically on the strength of a bias current. We predict a sudden extention of the disordered vortex state across the entire sample at some critical value of the bias current.

Key words: Phase transition;Vortex matter;Dynamics

1. Introduction

Although the phase transitions in systems at equilibrium are presently well understood, there are still some open questions in this field such as the phase transitions in moving systems. The latter appear in different systems, such as liquids in the presence of flow, crystal growth [1], chemical reactions with diffusion [2], some optical systems [3], and even population biology [4]. A similar situation exists in superconductors. While the phase transitions in type-II superconductors (Abrikosov vortex lattice and connected phenomena) are being studied intensively, a new phenomenon, the formation of an ordered vortex phase in superconducting films subjected to the simultaneous effect of external magnetic fields and bias current, has only recently become a subject for study [5]. This process has been observed in the vortex system in high-temperature superconducting crystals. The vortex phase diagram in these crystals includes two distinct vortex solid phases which are identified as ordered ($B < B^*$) , where B^* is some critical field, and disordered ($B > B^*$) vortex phases, while the latter is caused by strong vortex interaction with spatial defects (pinning centers).

The vortices passing through the surface barrier into a superconductor subjected to a magnetic field $B < B^*$, are initially present in the disordered vortex state (transient vortex state). Transformation of this disordered vortex phase into an ordered one in the presence of a bias current is observed by magneto-optical measurements of high temporal resolution, where a sharp interface between ordered and disordered vortex phases has been detected [5]. It turns out that the position of the interface depends non-monotonically on the bias current. While the problem of the phase separation in a varying magnetic field has been intensively studied both theoretically and experimentally, the problem of the phase separation governed by the bias current has not been considered theoretically.

The purpose of this paper is to analyze theoretically the location of the disordered vortex phase domain as a function of the bias current.

2. Model and basic equation.

Let us consider the process of ordering of disordered vortices penetrating a sample which carries the bias current. The sample is subjected to a magnetic field $B < B^*$ at which, in the absence of a bias current, the ordered vortex phase is preferable. In the presence

[1] Corresponding author. E-mail: shapib@mail.biu.ac.il

of the bias current j, the vortices move as an entire coherent vortex state with a constant velocity $v \propto j$. In the disordered state a vortex coherency is conserved, due to the small mobility of the vortices overcoming the large potential barriers which diminish the non-coherent inter-vortex mobility. On the other hand, the bias current tends to destroy the disordered state by assisting the vortices to climb the pinning barriers.

In our phenomenological approach we consider the vortex matter as a whole rather than the motion of individual vortices. The scalar real order parameter $\Psi(\mathbf{r}, t)$ distinguishes the two thermodynamic solid phases of the vortex matter: $\Psi = 0$ for the disordered state and $\Psi = \Psi_0 \neq 0$ for the ordered state.

In the Ginzburg-Landau formalism, the phase transition between the ordered and disordered phases may be described by a Ψ-dependent part of the free energy density functional F,

$$F = \frac{1}{2} D(\nabla\Psi)^2 - \frac{1}{2}\alpha\Psi^2 + \frac{1}{4}\gamma\Psi^4$$

where α, γ, D depend on the vortex-vortex and vortex-pinning interactions, and their evaluation requires a microscopic theory that has yet to be developed.

The order-disorder vortex phase transition is driven by the bias current as well as by an external magnetic field B. Therefore, we express the parameter α in as

$$\alpha = \alpha_0(1 - B/B^*),$$

where B^* is a characteristic critical field for a order-disorder vortex phase transition.For spatially homogeneous systems the vortex matter would be in the ordered phase at this magnetic field. However, the new vortices penetrating a superconductor through the potential barrier at the sample surface turned out to be disordered. Only after passing some interface domain of size L did they become ordered. In the absence of a bias current, one can also induce the phase separation also by changing the magnetic field, passing from $B < B^*$ to $B > B^*$. Here we study the influence of a bias current while keeping a constant value of the magnetic field, $B < B^*$.

Vortex phase dynamic evolution in the vortex matter can be studied in the framework of the Landau-Khalatnikov (LK) time - dependent equation :

$$\frac{d\Psi}{dt} = \frac{\partial\Psi}{\partial t} + v\nabla\Psi = -\Gamma\frac{\delta\Omega}{\delta\Psi} + f, \qquad (1)$$

where Ω and Γ are the Ginzburg-Landau (GL) free energy, and the damping coefficient, respectively.

There are three terms in equations (1) that are responsible for vortex phase evolution: the first, time-dependent term describes the phase dynamics in the non-flowing vortex matter; the second, convective term corresponds to the motion of the vortex substance, and the third term which describes the disentanglement of vortices by the Lorentz dissipative force f. The latter arises when the flow velocity exceeds some characteristic value ν_p , $\nu > \nu_p$ where ν_p is defined by the critical current j_p which disentangles the vortices, thereby establishing the ordered phase.

The magnitude of the dissipative force can be represented in its mostly general form as: $f = 0$ for $v < v_p$ and $f = \eta(v - v_p)$, for $v > v_p$. Here v_p is the velocity of the vortex substance needed to destroy the disordered vortex phase and transform it into the ordered one.

The boundary conditions for Eq. (1) are

$$\Psi = 0 \quad \text{at} \quad x = 0$$

$$\Psi = const \quad \text{at} \quad x \to R$$

The new features of our analysis is the importance of the convective term in (1) which contains the bias current, and the threshold effect of the release of pinned vortices by the bias current as described by the last term in (1).

3. Results

The vortices, which penetrate a superconducting sample in a disordered phase, are transferred, under the influence of a bias current and magnetic field, into an ordered vortex phase starting from some distance L from the sample boundary which, in turn, depends on the current strength proportional to μ. In this manner there arises a problem of phase transitions in the vortex matter which, unlike the equilibrium phase transitions, occurs in a moving system. There are three different regions, depending on the value μ of the velocity, where the characteristic size of the disordered vortex domain (DVD) L is essential different:

1. A monotonic increase of the DVD at small vortex velocities $\mu < \mu_c = 2\sqrt{2}$

2. Sudden extension of the DVD across the entire sample as μ exceeds μ_c.

3. The DVD shrinks when the dimensionless velocity μ reaches its depinning value μ_p, with $\mu > \mu_p$,assisting the ordering.

References

[1] R. M. White and T. H. Geballe, *"Long range order in solids"*, Academic Press, New-York, *1979.*

[2] Y. Kuramoto and T. Tsuzuki, Progr. Theor. Phys. 52, (1974), 1399.

[3] R. Graham and H. Haken, Z. Phys. 237,(1970),31 .

[4] J. Lin and P. Kahn, J. Math. Biol. 13,(1982),383 .

[5] Y. Paltiel et al., Nature **403**,(2000), 398 .