Depinning and dynamic phases in driven three-dimensional vortex lattices in anisotropic superconductors

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We use three-dimensional molecular dynamics simulations of magnetically interacting pancake vortices to study the dynamic phases of vortex lattices in highly anisotropic materials such as BSCCO. Our model treats the magnetic interactions of the pancakes exactly, with long-range logarithmic interactions both within and between planes. The pancake vortices decouple at low drives and show two-dimensional plastic flow. The vortex lattice both recouples and reorders as the driving current is increased, eventually forming a recoupled crystalline-like state at high drives. We construct a phase diagram as a function of interlayer coupling and show the relationship between the recoupling transition and the single-layer reordering transitions.

In highly anisotropic superconductors such as BSCCO, the vortex lattice is composed of individual pancake vortices that may be either coupled or decoupled between layers depending on such factors as the material stoichiometry or the magnitude and angle of the applied magnetic field. Of particular interest is the possible relationship between a coupling/decoupling transition and the widely studied second peak or fishtail effect \cite{1}. As a function of interlayer coupling strength \(s\), there are two limits of vortex behavior in a system containing pointlike disorder. For zero interlayer coupling \(s = 0\), each plane behaves as an independent two-dimensional (2D) system. For infinite interlayer coupling \(s = \infty\), the vortices form perfectly straight three-dimensional (3D) lines, and all of the planes move in unison. At finite coupling strength \(s \neq 0\), a transition between these types of behaviors should occur with coupling strength, but it is unclear whether this transition is sharp or if an intermediate state of the lattice exists. Furthermore, it is known that 2D systems with pointlike pinning can exhibit dynamic reordering under the influence of an applied driving current, passing from a liquid-like state at zero drive to a recrystallized state at high current \cite{2}. Thus, in a 3D system, a dynamically driven recoupling transition could be expected, but it is unclear where this transition falls in relation to the 2D reordering transitions already seen.

To study the coupling transitions, we have developed a simulation containing the correct magnetic interactions between pancakes \cite{5}. This interaction is long range both in and between planes, and is treated according to Ref. \cite{6}. The overdamped equation of motion, \(T = 0\), for vortex \(i\) is given by

\[
\mathbf{f}_i = \sum_{j=1}^{N_v} \nabla U(\rho_{i,j}, z_{i,j}) + \mathbf{f}_i^{vp} + \mathbf{f}_d = \mathbf{v}_i,
\]

where \(N_v\) is the number of vortices, \(\rho\) and \(z\) are the distance between pancakes in cylindrical coordinates. The magnetic energy between pancakes is

\[
U(\rho_{i,j}, 0) = 2\epsilon_0 \left(1 - \frac{d}{2\lambda}\right) \ln \frac{R}{\rho} + \frac{d}{2\lambda} E_1(\rho)
\]

\[
U(\rho_{i,j}, z) = -s \frac{d^2\epsilon_0}{\lambda} \left(\exp(-z/\lambda) \ln \frac{R}{\rho} - E_1(R)\right)
\]

where \(R = \sqrt{z^2 + \rho^2}\), \(E_1(x) = \int_{\rho'}^\infty \exp(-x/\lambda)/\rho'\) and \(\epsilon_0 = \Phi_0^2/(4\pi\xi)^2\). The pointlike pins are randomly distributed in each layer and modeled by parabolic traps. We vary the relative strength of the interlayer coupling using the prefactor \(s\). We
have simulated a $16\lambda \times 16\lambda$ system containing 89 vortices and 4 layers, with a total of 356 pancake vortices. Further work on systems containing up to 16 layers will be reported elsewhere \cite{7}.

In Fig. 1(a) we present a phase diagram as a function of interlayer coupling strength $s$ and driving force $f_d$. At zero drive, we find a recoupling transition for a coupling strength of $s > 4.5$. In samples with $s \geq 5$, the pancakes remain coupled into lines at all drives and show the same transitions seen in previous work \cite{3}, exhibiting plastic flow of stiff lines above depinning, and reordering into first a smectic state and then a recrystallized state of stiff lines at higher drives.

For samples with weaker interlayer coupling, $s < 5$, the vortex lattice is broken into decoupled planes at zero drive. Upon application of a driving current, the samples exhibit 2D plastic flow in which each layer moves independently of the others. Once the individual layers reach the driving force at which a transition to a smectic state occurs, the vortices simultaneously form the smectic state and recouple, as can be seen from the measure shown in Fig. 1(c) of the $z$-axis correlation

$$C_z = 1 - \langle (\mathbf{r}_{i,L} - \mathbf{r}_{i,L+1}) \Theta (a_0/2 - |(\mathbf{r}_{i,L} - \mathbf{r}_{i,L+1})|) \rangle,$$

where $a_0$ is the vortex lattice constant. The dynamic recoupling transition line follows the smectic transition line down to $s = 2$ and is associated with a peak in the $dV/dI$ curve seen in Fig. 1(b). Both the static and dynamic transition lines between decoupled 2D and recoupled 3D behavior are sharp.

As a function of the number of layers, we observe the same behavior, but the depinning current in the 3D stiff state drops with the number of layers. The depinning current in the 2D decoupled phase is not affected since in this case the individual planes behave as isolated entities. The recoupling transition sharpens as the number of layers is increased \cite{8}.

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Figure 1. (a) Phase diagram for varying interlayer coupling $s$ and driving force $f_d$. Circles: depinning line; diamonds: decoupling line; squares: smectic transition line; triangles: recrystallization line. (b) $V_x$ (circles) and $dV/dI$ (+ signs) for $s = 2.0$. (c) $C_z$ for $s = 2.0$ (d) $V_x$ (circles) and $dV/dI$ (+ signs) for $s = 8.0$. (e) $C_z$ for $s = 8.0$

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