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AUTHOR(S): Niels Grønbech-Jensen
Alan R. Bishop
Daniel Dominguez

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Multiple routes for vortex depinning in amorphous thin film superconductors

Niels Grønbech-Jensen, Alan R. Bishop and Daniel Domínguez

Theoretical Division, MS B262, Los Alamos National Laboratory, Los Alamos NM 87545, USA

We present simulations of vortex dynamics in amorphous two-dimensional thin film superconductors, using a new exact method to evaluate long range interactions between vortices. We find that the onset of vortex motion is dominated by filamentary channels of flow. There are multiple patterns of filamentary flow which are stable in a wide range of bias current. As a consequence, there are multiple steps in the differential resistance, each step corresponding to a different pattern of filamentary flow. This results in a strong history dependence of the depinning current and current voltage characteristics. Our results are in agreement with recent experiments on amorphous $Mo_{77}Ge_{23}$ thin films

1. INTRODUCTION

The problem of depinning in disordered type-II superconductors driven by an external current has attracted much attention lately, both experimentally [1, 2] and theoretically [3]. The onset of vortex motion takes place through "channels" of flow [3]. In all the molecular dynamics (MD) simulations [3], the onset of flow occurs at a single threshold force (critical current), above which the voltage increases continuously and nonlinearly. This type of behavior was observed in most of the experiments [1]. However, recent experiments by Hellerqvist *et al.* [2] in amorphous thin films, show a strong history dependence of the threshold force and abrupt rises of the voltage with steps in the differential resistance. We have done realistic MD simulations of amorphous thin films that reproduce this behavior [4].

2. MODEL

The previous MD simulations of [3] were in 2D systems with *short-range* vortex-vortex interactions. A short range 2D potential corresponds to the interactions of 3D vortices considered as rigid rods. However, in 2D thin films (like the ones of [2]) the vortex-vortex interactions are truly *long-range* [5], with a normalized vortex-vortex interaction energy:

$$U_{vv}(r_{ij}) = H_0(r_{ij}) - N_0(r_{ij}) \ , \qquad (1)$$

where H_0 and N_0 are the Struve and Neumann functions, respectively, and $r_{ij} = |\mathbf{r}_i - \mathbf{r}_j|$ is the distance between the ith and jth vortex, normalized to the effective 2D penetration depth, $\Lambda = 2\lambda^2/d$. The energy is normalized by $E_0 = \Phi_0^2/2\mu_0\Lambda$, with $\Phi_0 = h/2e$. The pinning interaction potential between a vortex and a pinning center is $U_{vp}(r) = -A_p e^{-(r/\tilde{a}_p)^2}$ [3], with $\tilde{a}_p$ the pinning interaction range. The normalized equation of motion for the ith vortex is,

$$\frac{d\mathbf{r}_i}{dt} = -\sum_{j\neq i} \nabla_i U_{vv}(r_{ij}) - \sum_k \nabla_i U_{vp}(r_{ik}) + \mathbf{F} \ , \qquad (2)$$

where $\nabla_i = (\frac{\partial}{\partial x_i}, \frac{\partial}{\partial y_i})$. Time is normalized to $\tau = \Lambda^2\nu/E_0$, with $\nu = \Phi_0 B d/\rho_f$, the magnetic field perpendicular to the system is B, and the flux flow resistivity is $\rho_f \approx B\rho_n/H_{c2}$. The force on the vortices arises from the applied current density $\mathbf{J}$, $\mathbf{F} = \mathbf{J} \times \hat{z}\Phi_0 d\Lambda/E_0$, with $\hat{z} \| \mathbf{B}$. We take $\mathbf{J} \| \hat{x}$, and thus, $\mathbf{F} \| \hat{y}$. The voltage response (vortex speed) from the ith vortex is then $V_i = dy_i/dt$ (normalized to $\pi h/\tau e$). The summations over j and k represent the vortex-vortex and vortex-impurity interactions, respectively. A new method to simulate a system with periodic boundary conditions and long-range interactions is used [4]. To connect our simulations to the experiments of [2] we adopt parameter values appropiate for their sample of amorphous $Mo_{77}Ge_{23}$. The length scales are: $\Lambda \approx 198\mu m$, the mean intervortex distance $a_0 = (\Phi_0/B)^{1/2} = 1.03 \cdot 10^{-3}\Lambda$, and the pinning range is taken as the coherence length, $a_p \approx \xi = 2.8 \cdot 10^{-5}\Lambda$. This places us in the regime $a_p \ll a_0 \ll \Lambda$. From the value of the critical current density, we estimate the pinning strength from collective pinning theory $A_p \approx 5 \cdot 10^{-2}\sqrt{n_v/n_p}$, where $n_v = 1/a_0^2$ and n_p are the densities of vortices and pinning centers respectively. We take $n_p/n_v = 5$ and we simulate a system of size $L^2 = 0.01 \times 0.01$, giving $N_v = 100$ vortices and $N_p = 500$ pinning centers. The positions of the pinning centers are distributed randomly. Each simulation was started with a different random initial configuration of vortices.

For 2D long-range vortex potentials [Eq. (1)], the shear modulus is $C_{66}d = B\Phi_0/8\pi\mu_0\Lambda$, and the compression modulus is $C_{11}d = 2B^2/\mu_0 k(1 + \Lambda k)$. Therefore, *in thin films elasticity is non-local at all length scales*, and the vortex lattice is incompressible: $C_{11}(k \to 0) = \infty$. Since $C_{66} \ll C_{11}$, the interaction favors an overall uniform density while being unaffected by deformations such as filamentary flow.

3. RESULTS

We now discuss our simulation results. Fig. 1 shows 7 IV curves obtained for different initial conditions but the same distribution of pinning sites. The voltage $\langle V \rangle$ is the normalized voltage per vortex. For small forces there is a pinned vortex state. Due to the many metastable minima of this strongly disordered system, there are many possible pinned states. By increasing F, the basin of attraction of the less stable fixed points (pinned states) shrinks until they become unstable, sequentially. When the last pinned state becomes unstable the vortices move. This argument leads to a unique, well defined threshold force. However, it is possible to have, for the same F, a coexistence of fixed points (pinned states) and attractors corresponding to moving vortices. In this case there is no well defined threshold force and the IV curve should be history dependent and hysteretic. Fig. 1 indeed shows that there are *multiple routes for the onset of voltage*. For each route, there are different sequences of abrupt jumps to states with a linear voltage-current dependence with a small slope. This behavior closely resembles the experiments on amorphous $Mo_{77}Ge_{23}$ (see Fig. 1 in Ref. [2]). We have looked at the vortex dynamics in each of the steps in dV/dI. We find that there are flow channels, which correspond to *one-dimensional* paths, i.e. the flow is filamentary. Strikingly, the only effect of increasing F is to increase the speed of the vortices inside the channels, while the structure of the channel and pinned vortices remains stable *in a wide region of F*, resulting in a linear voltage. Each individual channel has periodic motion with period given by the incompressible nature of the vortex system as $T = \langle t_{i+1} - t_i \rangle \simeq a_0/v$ with $v = \langle V_i \rangle$. When increasing F, at a given moment the channel structure becomes unstable and the system switches to a different attractor characterized by a new spatio-temporal channel structure, which is again stable in a range of F. This results in the sudden jumps in the IV curve between different linear regimes. If one assumes that in a large sample there are n_{ch} widely separated channels, each step in the differential resistance is then given by $dV/dI \approx n_{ch}(a_0/L_y)R_f$ [4]. This gives $n_{ch} \simeq 180$ for the lowest steps in [2], with a typical distance between channels of $\approx 80a_0$.

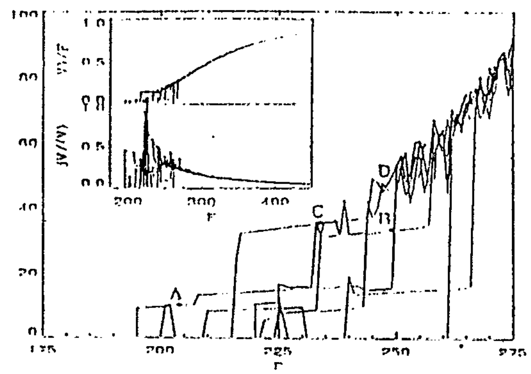

Figure 1: Simulated IV (force-velocity) characteristics for increasing bias current. Insets: full IV curves (upper) and the corresponding noise (lower).

4. CONCLUSIONS

We reproduce the history dependent structure of sudden jumps and steps in dV/dI as observed in [2]. They are a consequence of $C_{66} \ll C_{11}$, the non-local elasticity, and the numerous metastable pinned states of this disordered system.

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