Modes of disorder and plastic flow of flux lines in superconductors

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(Received 28 December 1995; revised manuscript received 12 June 1996)

Signatures of plastic flow of the flux-line lattice (FLL) were observed in a narrow region of the (H,T) phase diagram for $2H$-$NbSe_2$ superconductors. In this field regime, the system is neither a rigid lattice nor a melted fluid. A model is presented to explain this nonequilibrium plastic flow based on the static interaction energy between a moving dislocation field and a pinning center. The model accounts for the observed experimental measurements and reproduces most of its features. An explicit expression is derived for the length scale $R_L = \delta^{[1/(\delta-\gamma)]}\xi$, where ξ is the superconducting coherence length, $\delta = U/kT$ the ratio of the pinning energy to the thermal energy and $\gamma = \Omega_0 \Delta B/kT$. Ω_0 is the increase in the lattice volume due to the presence of single point defect and ΔB is the difference between the drag coefficient of the dislocation at the normal state and the superconducting state. This length characterizes the interaction domain where forces on the FLL's are uniform and consequently, their velocities within that domain are correlated. [S0163-1829(96)01341-0]

INTRODUCTION

Plastic deformation of type-II superconductors results in magnetic hysteresis and enhanced critical currents. These effects are due to the interaction between dislocations introduced by deformations and the flux lines which restrict its motion in the lattice. The motion of dislocations is influenced by their interaction with defect centers and, for dislocation velocities much smaller than the velocity of sound, by a viscous drag caused by phonons and conduction electrons. At low temperatures, electronic drag will dominate. However, at high temperatures the interaction of dislocations with the flux-line lattice (FLL) plays a critical role. In the presence of strong disorder, this behavior indicates that the dynamics of flux-line lattice (FLL) in superconductors can be treated as nonlinear transport in random media. This approach may yield insight into the competition between randomness of the lattice and interactions of flux lines. Dynamically created disorder through the interaction between the lattice and the quenched pinning centers has been recently experimentally realized.[1] The nonlinear current-voltage characteristics of the superconductors imply that the impurity pinning strength may be smaller than the flux-line rigidity. The transition between pinned and moving flux lines in the presence of driving forces and thermal fluctuations may be considered as dynamical critical phenomena. When impurities, and consequently the randomness, are strong the elastic medium collapses and the motion is highly inhomogeneous. Finite and randomly distributed pinning strengths lead to the existence of a spatially nonuniform time-averaged flux-line velocities indicating that the depinning transition is always discontinuous. In recent experimental measurements on the $2H$-$NbSe_2$ compound in the crossover region between weak and strong disorder, it was observed that depinning of the FLL proceeds via a series of specific and exactly reproducible jumps in the I-V curves.[2] It was suggested that this type of behavior is due to breaking up the FLL and the onset of an inhomogenous plastic flow at the crossover between elastic and fluid flow. In order to explain the experimental results, the authors proposed the existence of regions in the elastic medium where the flux lines break forming ''chunks'' characterized by a length scale L_ν over which the time averaged velocity is correlated. The onset of plastic flow is determined by the finite value of L_ν at the onset of the motion which measures the size of the chunks. As the magnetic field increases, L_ν decreases until it is equal to the lattice spacing a_0 beyond which the chunk is not a meaningful concept and a fluid flow is the appropriate description. The plastic flow will be characterized by a metastable moving state due to the slow dynamics between the flux lines and lattice defects. Therefore, depinning occurs in a sequence which violates the elastic media approach to the dynamics and a plastic flow is essential. The jaggedness of the measured R_d was simply related to the fact that the entire FLL does not depin simultaneously at a given critical current but in a sequence. Thus the change in the velocity of moving vortices (δu_i) is no longer spatially uniform at small voltages. As the current (I) increases, successive depinning occurs for the different chunks, in this case the measured voltage signal is given by $V = \Sigma_{i=1} n_i \langle \delta u_i \rangle$, where i refers to the individual chunks. These features occur at small velocities of the FLL and disappear at larger velocities where the lattice becomes more correlated and L_ν is large. A unique feature of the plastic flow is that the moving state is not uniform, unlike for an elastic medium. Due to the metastability of the moving state and anomalously slow dynamics of the FLL defects, the system becomes noisy and history dependent. The data support the idea that a transition among various ''metastable'' moving states exists, allowing the coexistence of domains with different average velocities, as is implied by the plastic flow of the FLL.

In this paper, we provide a rigorous explanation for FLL behavior and the characteristic length L_ν considered as the range of the static interaction region between a moving dislocation field and a pinning center in a plastic lattice.

MODEL DESCRIPTION

When the driving force on a flux line $f_L > f_p$ the pinning force due to a pinning center, a steady vortex motion with speed u_L given by $u_L=(\phi_0/c\,\eta)(J-J_c)$, where ϕ_0 is the flux quantum and η is the viscous drag coefficient will occur. In a soft flux lattice, the experimental data suggests the existence of slow dynamics associated with plastic flow of dislocations or defects. We consider the motion of a dislocation associated with plastic deformations of the lattice and its interaction with a defect center. This interaction will change the vortex velocity u_L and an additional component to the flux flow voltage will appear. The interaction energy E_i between the stress field of the defect center and the field of a moving dislocation will perturb the pinning energy of a flux line within a spatial domain $\mathscr{R}$ determined by the stress field. Consequently, the velocity of the flux lines moving in this domain will be perturbed and changed by an amount δu due to this static interaction. In the absence of this interaction, the force equation on the flux line is given by[3]

$$f_p=f_L-\eta u_L\,. \tag{1}$$

The static interaction energy will change the pinning energy and consequently the pinning force by an amount δf_p which from Eq. (1) is given by

$$f_p+\delta f_p=f_L-\eta(u_L+\delta u_L). \tag{2}$$

In this equation the driving force f_L does not change due to this interaction since it is in general current dependent. From Eqs. (1) and (2), the change in the pinning force is equal to $\delta f_p=-\eta\delta u_L$. This pinning force must be equivalent to the force of interaction between the stress field of a pinning center and the field of a moving dislocation. Therefore, the change in the velocity of a flux line due to this static interaction can then be obtained from the following relation:

$$-\eta\delta u_L=-\Omega_0\nabla\tau_{00}\,. \tag{3}$$

Ω_0 is equal to the increase in the lattice volume due to the presence of a single point defect in the crystal, it is of the order of the point defect volume and τ_{00} is the stress tensor at the defect location in the lattice. Equation (3) determines the magnitude of the change in the velocity of the flux line:

$$\delta u_L=(\Omega_0/\eta)\nabla\tau_{00}\,. \tag{4}$$

This component of the flux-line velocity will generate a voltage signal which can be measured in a flux-flow experiment particularly at small frequencies. When the sample has regions of strong pins, they may be overcome by the interaction among flux lines when the lattice is sufficiently rigid. As the rigidity disappears due to the meltin transition, the strong pins create a puddle of immobile vortices around which flux flow continues. This puddle would require a much larger force in order to be free and to participate in the flow. In this type of partial flow with steady-state velocity gradients that one may invoke the notion of flux line viscosity, in addition to the coefficient of friction η, in order to account for the extra damping and the reduced flow of the vortices. This is a clear example of the absence of coherent motion even at very large forces of what presumably is a flux-line liquid.

VOLTAGE DUE TO DISLOCATION GROUP DYNAMICS

A group of (n) identical dislocations in the slip plane $z=0$ will have simultaneous free expansion where the veloc-

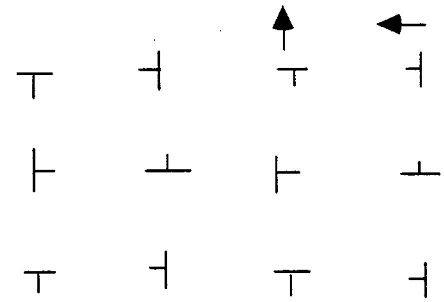

FIG. 1. Two-dimensional array of edge dislocations, showing the direction of climb of each dislocation under the stresses indicated by the arrows.

ity of each dislocation is proportional to the total stress field σ (see Fig. 1). These dislocations are characterized by the set of differential equations[4]

$$dr_i/dt=M\{\sigma(r_i)\},\quad i=1,\ldots,n. \tag{5}$$

In this equation it is assumed a linear stress-velocity relationship $\nu=M\sigma$ for an individual dislocation where M is the mobility constant. The total stress field σ is the sum of any applied stress field $S(r)$ and the inverse first power stress field of all other dislocations

$$\sigma(r_i)=S(r_i)+A\sum_{j=1,i\neq j}^{n}1/(r_i-r_j),\quad i=1,\ldots,n. \tag{6}$$

A is a constant equal to $\mu b/2\pi$ for screw dislocations and $\mu b/2\pi(1-\gamma)$ for edge dislocations, where b is the magnitude of Burger's vector of the dislocations, μ the elastic shear modulus and γ Poisson's ratio. For mixed dislocations the value of A will be intermediate between values for screw and edge.

The change in the flux-line velocity due to the dynamic interaction of the dislocation field with a pinning center can be calculated from the knowledge of $\nabla\tau_{00}$ which is equivalent to ∇S in the above equations:

$$\nabla\tau_{00}=\nabla S=1/M[d/dt(\nabla r_j)]-A\sum_{i\neq j}\nabla(1/(r_j-r_i),$$

$$j=1,\ldots,n. \tag{7}$$

The solution of the differential equations (7) will determine uniquely the changes in the velocity of the flux line due to the dislocation dynamics. The voltage component measured in the experiment due to this static interaction and the inhomogeneous flux flow is given by

$$V\approx\sum_i n_i\langle\delta u_i\rangle=(\Omega_0/\eta)\sum_i n_i\langle\nabla S(r_i)\rangle. \tag{8}$$

n_i is the total number of moving vortices in the interaction domain and the gradient is calculated at the position of the defect center. The experimental measurements indicate a slow dynamics where the velocity of dislocations are much smaller than the speed of sound. In this case the first term on the RHS of Eq. (7) can be neglected and the voltage is determined from the knowledge of the dislocation group dynamics given by Eq. (8):

$$V \cong (\Omega_0 A/\eta)\left(\sum_k n_k \left\langle \sum_{i\neq j} 1/(r_i - r_j)^2 \right\rangle\right), \quad j=1,\ldots,n. \tag{9}$$

The first summation is taken over flux lines while the second is taken over dislocation points. For large number of dislocations it is sufficient to consider a dislocation density function $\psi(r,t)$ which is a measure of the number of dislocations per unit distance along the slip plane at position r and time t.[5] This choice is more appropriate rather than the position of each individual dislocation which will be smeared out into a continuum distribution. In this case, the average in the above equation can be replaced by integrals over dislocation density and defect density distributions. The experimental data can finally be identified from the following equation:

$$V \cong (\Omega_0 A/\eta)\int_0^{\xi} D(r)\,dr \left(\int_0^{R_L} [\psi(R,t)/(r-R)^2]\,dR\right). \tag{10}$$

$\psi(r,t)$ is the dislocation density function given by $\psi(r,t) = (1/\pi g)(r/g + a/2)[(ag - r)/r]^{1/2}$, $a = \{8(n+1)/3\}^{1/2}$, and n is the number of dislocations in the group and $g(t) = (2t)^{1/2}$. In the continuum approximation, $\psi(r,t)$ will have the form of a δ function at $t=0$.

The only unknown quantity in the integrand of the above equation is $D(r)$, the defect distribution function that describes the vortex motion between pinning centers. An explicit functional form of this quantity was derived earlier to reproduce the low-frequency noise in micropatterned YBaCuO thin films.[6] Although the derivation of this quantity was carried out for the YBaCuO compound, we argue that for anisotropic superconductors, it has a generally valid feature. In order to provide a physical explanation to the origin of this quantity, let us consider the noise spectral power arising from random processes due to the flux motion and the sample inhomogeneity in superconducting thin films. The spectral power was calculated from the integral $S(f) \approx \int H(f,U) D(U)\,dU$, where $H(f,U)$ is a Lorentzian spectrum and $D(U)$ is a distribution (convolution) function for the activation energies. Since the flux motion is an activated process associated with a pinning center, the probability of a flux-line jump assumes a simple Boltzman factor $P(U) \approx e^{-U/kT}$, where U is the activation energy. Consequently, the probability of a flux line landing at a distance r from a defect center is proportional to the product of two probabilities in the form $P(U,r) \approx e^{-(U/kT)(r/\xi)}$. In the two-dimensional planes of a superconducting strip, the defect density distribution $D(r)$ of random pinning sites is proportional to $D(r) = [1/P(U,r)]$. A simple physical picture arises if we consider the distribution function $D(r)$ of a sample consisting of a large number of pinning regions as a measure of how pinning sites are arranged within a circle of radius r in the two-dimensional planes. It is logical to assume that the product $rD(r)$ is proportional to the number of defects within that area. Since, for the flux motion between pinning sites the activation energies have the spatial dependence[7]

$$U = U_0[\ln(r/\xi) + 1], \quad r > \xi. \tag{11}$$

By substituting Eq. (11) in the expression of $D(r)$ and demanding that the distribution be normalized such that $\int_0^{\xi} D(r)\,dr = 1$, the resulting function was used to calculate the low-frequency noise spectral power. It was found that a superconducting sample consisting of a large number of pinning regions with the distribution function $D(r) = (\delta/\xi)(r/\xi)^{\delta-1}$, $\delta = U/kT$ reproduced adequately the observed spectral power (see detailed calculations in Ref. 6).

All the quantities needed to calculate Eq. (10) are in hand except the upper limit of the second integral R_I which defines the range of the static interaction between dislocation flow and pinning centers. In order to calculate the differential resistance $R_d(=dV/dI)$ and examine its jagged structure and the signatures of inhomogeneous flow, Eq. (10) is written as

$$V(I,H) \cong (\Omega_0 A/\eta)(\delta/\xi)\int_0^{\xi} (r/\xi)^{\delta-1}\,dr \times \left(\int_0^{R_L} [\psi(R,t)/(r-R)^2]\,dR\right). \tag{12}$$

The current and magnetic field dependence of the voltage in the above equation appeared in the activation energy U and its relationship to the current and magnetic field. The dependence of the activation energy U on the current was deduced from experimental measurements to have the linear relationship[8]

$$U = U_0[1 - I/I_c(T)]. \tag{13}$$

The prefactor U_0 is related to the temperature and magnetic field by[9] $U_0(T,H) = U_1[1 + (T/T_c)^2]\{[1 - (T/T_c)^2] - [H/H_{c2}(0)]\}$. This relationship was utilized to calculate the differential resistance using the experimental parameters reported in Refs. 1 and 2. In order to compare the predictions of Eq. (11) to the experimental data, the static interaction range R_I must be determined. This interaction range defines the nature of the dynamics and plays a critical role in determining the size and topology of the ‘‘chunks’’ in the FLL.

INTERACTION RANGE

If the dislocation has a length large compared to the mean distance between point defects. The equilibrium distribution of centers of dilation in the dislocation stress field is given by[10]

$$C = C_0 \exp(E_{\mathrm{int}}/kT). \tag{14}$$

C_0 is the equilibrium concentration far from the dislocation and E_{int} is the interaction energy between an elastic center of dilatation and an external elastic field given by $E_{\mathrm{int}} = -\Omega_0 \tau_{kk}$. The distribution in Eq. (14) can be written as

$$C = C_0 \exp\{-\Omega_0 \tau_{ii}/kT\}. \tag{15}$$

Ω_0 is the increase in the lattice volume due to the presence of a single defect. τ_{ii} is the stress tensor at the position of the defect. The motion of dislocation will change the stress field τ_{ii} creating a flow stress change $\Delta\tau_{ii}$. The change in the stress field $\Delta\tau_{ii}$ due to the motion of dislocations was calculated for low-temperature superconductors where changes in

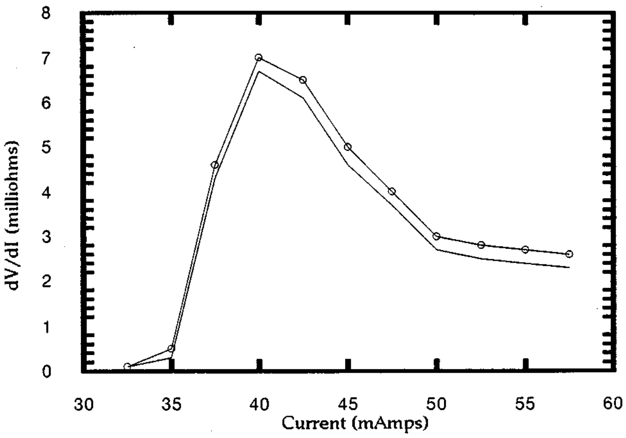

FIG. 2. The flux-flow resistance $R_f(dV/dI)$ as a function of current at applied field value $H = 5.7$ T and no time dependence (dc). The upper curve represents the experimental measurements taken from Ref. 2, Fig. 2(b), while the lower curve represents the theoretical predictions.

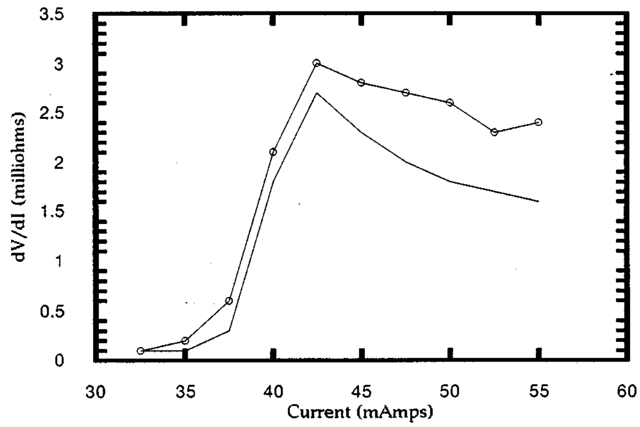

FIG. 4. The flux-flow resistance $R_f(dV/dI)$ as a function of current at applied field value $H = 5.7$ T and $t = 0.01$ s (100 Hz). The upper curve represents the experimental measurements taken from Ref. 2, Fig. 2(b), while the lower curve represents the theoretical predictions.

the electronic drag were incorporated.[11] The key idea in these investigations was based on the vibrating string model which was used to calculate $\Delta\tau_{ii}$ for lead:[12]

$$\tau_{SN} \approx \Delta B \ \ln(L_0/L). \tag{16}$$

The distance L_0 is the size of the pinning region which in our case will be taken equal to the superconducting coherence length ξ while the length L defines the effective distance between defect centers.

A superconductor in the mixed state with small dislocation damping will result in an oscillatory motion of the dislocations between defects. In this case, the distance L is primarily controlled by the short-range interactions and density of forest dislocations. However, in anisotropic superconductors, it is likely that the dislocation damping is large enough to allow overdamped dynamics to exist. This overdamped dislocation motion is characterized by a finite domain of the order of the static interaction range between dislocation and pinning center. Therefore, the interaction of dislocations with point defects at low temperature can be considered primarily due to size effects. This conclusion is consistent with the stress behavior found for low-temperature materials.[13] Accordingly, the distribution of the disorder (point defects) in the material will change to reflect the nature of that interaction. The size of the pinning centers will be of the same order as the dilatation centers due to damping and the effective barrier of a defect center and its range will change in such a way to impede the dislocation motion. This picture indicates that near the dislocation there are always regions of heightened concentration of defects of one type or another. Thus the elastic interaction of point defects with the dislocation results in the existence of clouds of point defects extending to a distance $L = R_L$. In the overdamped dynamics where plasticity is enhanced, the interactions of these clouds with the flux lines will lead to the formation of ''chunks'' of FLL extending over to a distance R_L. Within that distance the forces are uniform and the velocities of the FLL in the chunk are correlated. This distance is identified with L_ν the velocity correlation length defined in Ref. 2. The quantity ΔB is the difference between the drag coefficient of the dislocation at the normal state and the superconducting state.

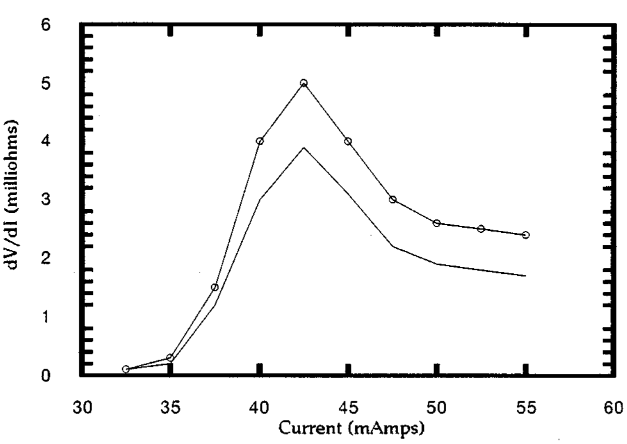

FIG. 3. The flux-flow resistance $R_f(dV/dI)$ as a function of current at applied field value $H = 5.7$ T and $t = 0.5$ s (2 Hz). The upper curve represents the experimental measurements taken from Ref. 2, Fig. 2(b), while the lower curve represents the theoretical predictions.

The cloud of point defects extending on scales equal to R_L has a concentration of defects given by the equilibrium distribution of Eq. (14). However, as was mentioned earlier, since the distribution function for the activation energy of random moving vortices $D(r_i) = (\delta/\xi)(r_i/\xi)^{\delta-1}$ can be considered as a measure of how pinning sites are located within a circle of radius r in the two-dimensional planes. Therefore, the ratio of the concentration of defects (C/C_0) can be considered as the ratio of the distribution function within distances of the order of the interaction range and the superconducting coherence length,

$$(C/C_0) = \int_0^{R_L} D(r)dr \Big/ \int_0^{\xi} D(r)dr$$
$$= \exp - [(\Omega_0 \Delta B/kT)\ln(\xi/R_L)]. \tag{17}$$

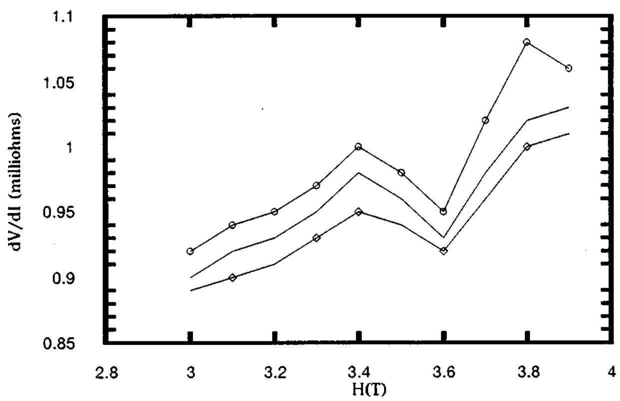

FIG. 5. The flux-flow resistance $R_f(dV/dI)$ as a function of the magnetic field H at a temperature $T=1.7$ K and current $I=100$ mA. The upper curve represents the experimental data taken from Ref. 2, Fig. 4(b). The middle curve is the theoretical calculations for $n=10\,000$ dislocations, while the lower curve is the theoretical calculations for $n=1000$ dislocations.

The above equation provides an estimate of the interaction length

$$R_L=\delta^{[1/(\delta-\gamma)]}\xi, \tag{18}$$

where $\gamma=\Omega_0\Delta B/kT$. This simple relationship supports the observations made on the FLL behavior measured in Ref. 2. In order to understand the occurrence of the fingerprints of the plastic flow in a narrow field regime we investigate the variations of δ with current, field, and temperature given by

$$\delta=(U_1/kT)[1-I/I_c(T)][1+(T/T_c)^2]\{[1-(T/T_c)^2] -[H/H_{c2}(0)]\} \tag{19}$$

for very large currents $I\gg I_c$, and for applied field values H slightly higher than H_{c2} as in the situation for the reported measurements [see Fig. 4(b), Ref. 2], the values of δ are positive and >1. In addition, near the transition temperature the change in the stress field is almost independent of ΔB and the factor γ for low temperature materials (lead) is close to unity,[13,14] in this case the effective pinning range $R_L>\xi$.

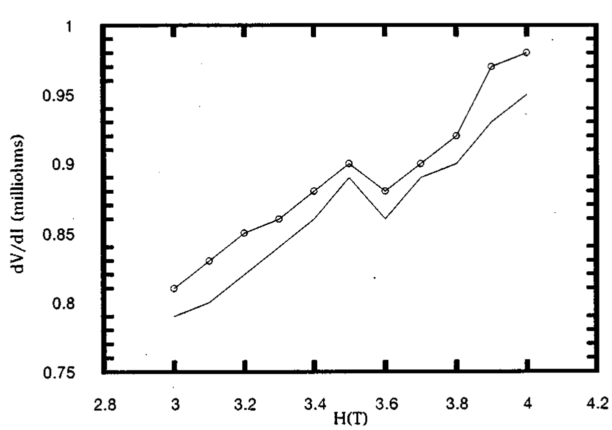

FIG. 6. The flux-flow resistance $R_f(dV/dI)$ as a function of the magnetic field H at a temperature $T=1.7$ K and current $I=80$ mA. The upper curve represents the experimental data taken from Ref. 2, Fig. 4(b). The lower curve is the theoretical calculations.

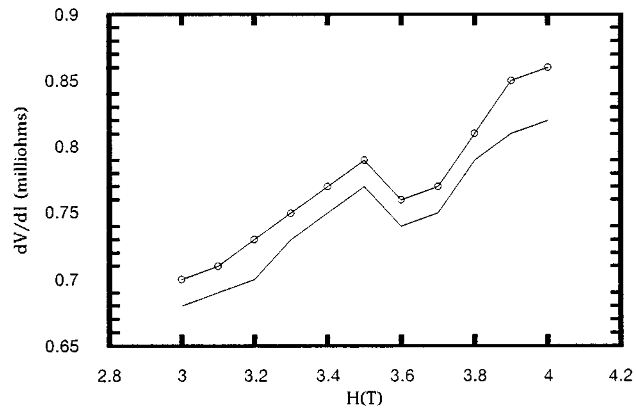

FIG. 7. The flux-flow resistance $R_f(dV/dI)$ as a function of the magnetic field H at a temperature $T=1.7$ K and current $I=60$ mA. The upper curve represents the experimental data taken from Ref. 2, Fig. 4(b). The lower curve is the theoretical calculations.

This extended domain for the interaction region explains the existence of flux bundles with correlated velocities since in these domains the forces are spatially uniform. On the other hand, for field values less than H_{c2}, the parameter δ is negative and is of the order of unity, the distribution of activation energies of random moving vortices in this case, corresponds to an elastic medium for which the time-averaged velocity is uniformly correlated and consequently the disappearance of plastic flow signatures. This behavior can clearly be seen from the appearance of kinks in the flux-flow resistance measurements at different driving currents for field values higher than the upper critical fields H_{c2} and its disappearance at lower field values [see Fig. 4(b), Ref. 2].

The predictions of Eq. (12) were compared to the measurements reported in Figs. 2(b) and 4(b) of Ref. 2 for the three cases corresponding to no time dependence (dc), $t=0.5$ s which corresponds to 2 Hz and $t=0.01$ s that corresponds to 100 Hz. All the experimental parameters were taken from Refs. 1 and 2. The viscous drag coefficient was calculated $\eta=\Phi_0H_{c2}(0)/c^2\rho_n$ using the Bardeen-Stefan theory,[15] where ρ_n is the normal-state resistivity. The critical temperature used in the calculations T_c was set equal to 7.2 K, while the critical current density I_c was equal to 12 mA. The upper critical field $H_{c2}=3.3$ T and the applied field value was chosen to be 5.7 T. The Burger's vector b was set equal to unity and the value of the unperturbed activation barrier $U_1=40$ meV. The comparison between the experimental data and theoretical predictions are shown in Figs. 2–7. In Fig. 5 it is evident that the voltage signals are insensitive to the number of dislocations (n) in the group. This is in fact consistent with the assumption of continuum approximation for the dislocation dynamics. The lower values of the flux-flow resistance calculated from our model are due to the fact that the distribution of activation energies used in the calculations correspond to YBaCuO compounds which have the same behavior as $2H$-$NbSe_2$.[16] Nonetheless, this analysis reproduces the general features of a plastic flow which is supported by the reported measurements.

CONCLUSIONS

Plastic deformations of type-II superconductors were examined by taking into account the interaction between the stress field of a pinning center and a dislocation strain field. The interaction energy of the stress field is characterized by the increase in the lattice volume due to the presence of a single point defect in the crystal. In this model, the effects of this static interaction on the FLL dynamics and the flux-flow resistance in anisotropic superconductors were explored. The analysis shows that the interaction of point defects with the dislocation field results in the existence of clouds of defects extending to a distance R_L of the order of the interaction range. The effects of these clouds on the flux-line dynamics will lead to the formation of ''chunks'' of FLL extending over to the same domain. Within that domain the forces acting on FLL are uniform and consequently, the velocities of the FLL in the chunk are correlated. The model accounts for the recent observations which mark the existence of domains with different average velocities. These domains are attributed to the formation of flux ''chunks'' as a result of the plastic flow of dislocation fields. This behavior indicates the presence of ordered and disordered phases associated with the first order depinning transition for a defective FLL. Moreover, the model indicates that the motion of dislocations and its interaction with point defects accounts, at least qualitatively, for the enhanced plasticity of the superconducting state as observed in the experimental measurements reported in Ref. 2.

These results are consistent with recent theoretical investigations on the effects of random forces due to pinning potentials on the FLL which show that the vortex lattice will be distorted on length scales larger than the pinning length L_p.[17] In such models, the effects of elastic strain were only included; however, it was recognized that on length scales larger than L_p, dislocations will also appear and become energetically favorable.[18] Our simulation provides a detailed analysis for these effects which are supported by the reported experimental measurements.

ACKNOWLEDGMENTS

The author wishes to thank Professor J. R. Clem for stimulating discussions during the course of this work. Part of this work was completed while the author was visiting the International Institute of Theoretical and Applied Physics at Iowa State University.

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