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Resistive behavior of high-T_c superconductors with a logarithmiclike pinning potential

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The flux motion in a superconductor with a periodic logarithmiclike bare pinning potential is investigated. The effective barrier $U_J(J)$ is derived and is shown to bear close resemblance with the related experimental results. The details of the pinning potential profile turn out to have significant influences on the functional form of the effective barrier. The linear response of the superconductor under a small current is analyzed and a slightly new formula is derived for resistivity in the thermally activated flux flow regimes. The distinct regimes for flux creep and flux flow and the crossover in between are treated simultaneously, and the familiar power-law behavior is demonstrated and is further confirmed by examining the $d\ln E/dJ$ versus J relation. Satisfactory agreement is found between our results and related experimental observations. The experimentally observed field-dependent resistance broadening effect is also reproduced in this model.

I. INTRODUCTION

The resistive behavior of a high temperature superconductor in connection with flux motion has attracted much attention in the literature. Most aspects of the experiments and interpretations remain highly controversial. As for the flux creep, the basic theory first introduced by Anderson and Kim[1] assumes thermal activation of uncorrelated vortices or vortex bundles over a net potential barrier which depends linearly on the applied current density J;

$$U_J = U_0(1 - J/J_{c0}), \tag{1}$$

where U_0 is the barrier for $J = 0$, and J_{c0} is the critical current density in the absence of thermal activation. The important predictions of this theory are that the magnetization should follow a logarithmic decay, and that there should be a thermally activated flux flow (TAFF) regime when the applied current is essentially small. While it is a good model for conventional superconductors, the Anderson-Kim model is unable to explain many experimental aspects for high-T_c superconductors, the nonlogarithmic magnetization relaxation is but one example.[2] A possible explanation for these experimental results emerges from recent theories involving collective vortex pinning. One particular version of collective pinning introduced by Fisher[3] hypothesizes a phase transition line in the field-temperature plane and is usually referred to as the vortex-glass theory. Another version was introduced by Fiegel'man *et al.*[4] These two theories lead to a common prediction for a form of the flux creep at a temperature well below T_c, with an effective barrier depending on current density in a highly nonlinear way,

$$U_J = (U_0/\mu)[(J_{c0}/J)^\mu - 1], \tag{2}$$

where μ is an exponent of order 1. The importance of nonlinearity in the barrier current-density dependence had originally been recognized by Beasley *et al.*,[5] and recently there have been a number of articles investigating possible forms for U_J. Equation (2) predicts a divergence in U_J as J goes to zero, which arises from cooperative interactions between vortices since larger and larger flux line volumes V have to jump if the flux line lattice (FLL) is elastic, and therefore the resistivity $\rho \propto \exp[-(J_2/J)^\mu]$. Several experiments reported possible vortex-glass behavior in YBCO films,[6] single crystals,[7] and ceramics.[8] But as yet one does not see convincing evidence that there is a finite "glass temperature" T_g below which the pinned FLL "freezes" as $J \to 0$. One example beyond the vortex-glass description is the TAFF regime observed by Palstra *et al.*[9] A competing form for the power-law J-dependent potential barrier U_J is a logarithmic one:[10]

$$U_J = U_0 \ln(J_{c0}/J), \tag{3}$$

which in a similar way leads to vanishing resistance at finite temperatures in a power-law fashion in J for $J \to 0$. Evidence for this kind of barrier first emerged from studies of the transport I-V characteristics of YBCO films

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near T_c.[10] More recently studies made for flux creep in aligned grains of YBCO and in LaSrCuO crystals showed their favor of this logarithmic dependence.[11] Further evidence for the logarithmic barrier comes from the widely reported quasiexponential dependence of the measured critical current density dependence on temperature.[12] Alternatively, we note that Griessen[13] suggested a model to explain the reported power-law behavior in resistivity versus current-density curves and the continuous crossover from the creep to the flow regime. In his model, complexity is introduced by the assumed activation energy distribution in a parallel summation of channels within the sample.

While there exist controversial viewpoints on the low temperature and vanishing current behaviors of high-T_c superconductors, it is a common recognition that there exists a continuous crossover from the flux creep regime (where the pinning force dominates) to the flux flow regime (where the Lorentz force dominates). However, a satisfactory theory that would interpolate these two regimes awaits, since the existing creep model is valid for $U_J \gg k_B T$ only, a condition which is violated at $J > J_{c0}$. Furthermore, the creep model frequently cited in the literature assumes *a priori* that the attempt frequency and hopping probability of a vortex depends on the barrier height only, irrespective of the concrete profile of the potential. To these ends and from a first-principles consideration, it is pertinent to start with the dynamics of a flux line, or an overdamped flux diffusion in a real space, as is to be discussed in detail in this paper for a specific model in which the bare pinning potential attains a logarithmiclike function of space. It will be demonstrated that this model reproduces many experimental observations and theoretical predictions in their justified parameter regimes and reveals interesting predictions. The remainder of this paper is structured as follows. Section II is attributed to the description of the model and related discussions. In Sec. III, the linear resistivity in the TAFF regime in this model is analytically described, and the isothermal I-V characteristics and field-dependent resistive transition of this model are explored. Finally, a summary is presented in Sec IV.

II. MODEL DESCRIPTION AND THE EFFECTIVE BARRIER U_J

The equation describing the thermally assisted vortex motion in a pinning potential along the longitudinal direction can be written as an overdamped Langevin equation,[14]

$$a\eta\dot{x} = -\frac{\partial}{\partial x}U(J,\,x) + \mathcal{L}(t)$$
$$= -\frac{\partial}{\partial x}U_p(J,\,x) + \frac{1}{c}J\Phi_0 a + \mathcal{L}(t), \qquad (4)$$

where x describes the location of the flux, $\dot{x}$ denotes the differential of x with respect to time t, a is the longitudinal length of the flux line and η is the damping coefficient. In Eq. (4) $\mathcal{L}(t)$ is the thermal noise force and is assumed to be Gaussian white,

$$\langle \mathcal{L}(t) \rangle = 0,$$
$$\langle \mathcal{L}(t)\mathcal{L}(t') \rangle = 2a\eta k_B T \delta(t - t'). \qquad (5)$$

$U_p(J,\,x)$ is the pinning potential which might be current dependent (the apparent field and temperature dependences are not explicitly written in the arguments, and will be specified in the following discussion). The second term on the rhs of Eq. (4) is the Lorentz force due to the applied current (Φ_0 is a flux quantum). It is straightforward to argue from this phenomenological model that so long as U_p does not diverge in the limit $J \to 0$, the pinning force $f_p(J) = -\partial U_p/\partial x$ should linearly depend on J at low J (with probably a nonzero interception at $J = 0$), a fact overlooked in Eqs. (2) and (3). For a more comprehensive understanding of the vortex behavior, we simplify this model by taking U_p to be independent of J and periodic in space. The flux length a can be approximated as being of the same order as the average impurity spacing $l_{\rm imp}$ at low temperatures where the impurity energy dominates the elastic stiffness of the flux line; and is better estimated (for YBCO superconductors especially) by the correlation length ξ at still higher temperatures.[15] On the other hand, the correlation between vortices is so weak in the low field regime $[(\Phi_0/B)^{1/2} > \lambda]$ that the vortex lattice is soft enough to justify an independent particle treatment of the vortices in the lowest-order approximation.[16] The functional $U_p(x)$ has so far been frequently postulated rather arbitrarily as being sinusoidal.[17] The same model as Eq. (4) (with a sinusoidal bare potential) in the context of Josephson junction was originally worked out by Ambegaokar and Halperin,[18] and was exploited by Tinkham who successfully explained the resistance broadening effect[19] (although the sinusoidal feature of the bare potential is not essential there). However, alternative trial functional forms of $U_p(x)$ also deserve attention. A specific profile of $U_p(x)$ is depicted in Fig. 1.

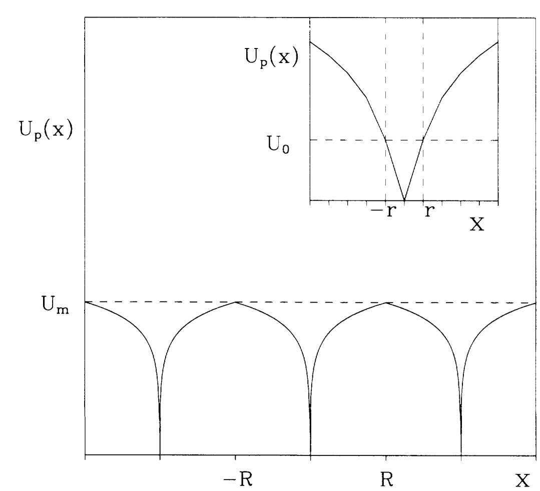

FIG. 1. A schematic plot (solid line) of the profile of a logarithmiclike pinning potential (see the text for details). The inset (solid line) is a local blowing-up of the profile at one of the local minima.

The "wave-length" of the periodic potential is $2R$. The bare potential within one spatial period is written as

$$U_p = \begin{cases} U_0|x|/r, & |x| \le r, \\ U_0[1+\ln(|x|/r)], & R \ge |x| > r. \end{cases} \tag{6}$$

Here $\kappa = R/r$ is assumed to be constant for a sample, typically of order 10^2 (see, e.g., Ref. 20). This logarithmiclike bare potential deserves attention since it appropriately describes the interaction between pinning centers and vortices in a sample where twin boundary or kink formation is operating, as has been pointed out by Manuel *et al.*[21] Furthermore, along the line of the usual creep model, the current dependence of the effective barrier U_J embodied in this potential is interesting. From Eqs. (4) and (6) the effective barrier U_J between adjacent local minima and maxima in the washboard potential $U_p(x) - (1/c)\Phi_0 Jax$ reads

$$U(J) = \begin{cases} U_0(1+\ln\kappa - \kappa J/J_{c0}), & J \le J_{c0}/\kappa, \\ U_0 \ln(J_{c0}/J), & J_{c0}/\kappa < J \le J_{c0}, \end{cases} \tag{7}$$

where

$$J_{c0} = cU_0/\Phi_0 ar \tag{8}$$

is the critical current density in the absence of thermal fluctuations. Note that both the linear and logarithmic current dependences emerge in this model with respect to different current regimes. However, the linear regime in Eq. (7) is relatively narrow for $\kappa \sim 400$, an estimation reported in Ref. 20. In this connection, it might be suggested that the model under consideration reproduce well the experimentally extracted U_J behavior in Refs. 10 and 11. On the other hand, the correspondence between the logarithmiclike potential profile and the logarithmic behavior in U_J is suggestive. For example, it is readily clear that an inverse power-law behavior in U_J (originally predicted in the vortex-glass model) can also be recovered by the assumption of a modified power-law bare potential profile:

$$U_p = \begin{cases} U_0|x|/r, & |x| \le r, \\ (U_0/\nu r^\nu)(|x|^\nu - r^\nu) + U_0, & r \le |x| \le R, \end{cases} \tag{9}$$

where $\nu \equiv \mu/(1+\mu) < 1$, μ is a constant of order 1. Indeed, the resulting effective barrier U_J reads exactly as Eq. (2) when $J_{c0}/\kappa^{1/(1+\mu)} \le J \le J_{c0}$ (here $\kappa = R/r$). From these two examples, one can see that such an experimentally extracted U_J behavior as ascribed by Eq. (1) or Eq. (2) for not vanishingly small currents might have other physical origin except the existence of a vortex-glass phase. For this reason, a detailed study of the vortex dynamics in various trial pinning potential is still of importance. Since the above-mentioned power-law-like model receives relatively less experimental and theoretical justification, we shall limit our attention hereafter on the vortex dynamics in the logarithmiclike bare pinning potential [see Eqs. (4) and (6)].

Equation (4) is associated with the Smoluchowski diffusion equation satisfied by the density distribution function $\sigma(x,t)$:

$$\frac{\partial\sigma}{\partial t} = \frac{1}{a\eta}\frac{\partial}{\partial x}\left(\frac{dU}{dx} + k_B T\frac{\partial}{\partial x}\right)\sigma \equiv -\frac{\partial S}{\partial x}, \tag{10}$$

where S is the density current and $U(x)$ is the washboard potential in Eq. (4). In the stationary state ($\partial\sigma/\partial t \equiv 0$) the solution of Eq. (10) is standard. In this case the density distribution σ must be periodic in space, $\sigma(x+2R) = \sigma(x)$. Consequently the average velocity of the flux motion from Eqs. (4) and (10) is found to be

$$\langle\dot{x}\rangle = \frac{2Rk_BT}{a\eta}\frac{1-\exp[-2\kappa(J/J_{c0})(U_0/k_BT)]}{\Gamma(J,U_0,T)} \tag{11}$$

with

$$\Gamma(J,U_0,T) = \int_{-R}^{R}\exp[U(x)/k_BT]\,dx\int_{-R}^{R}\exp[-U(x)/k_BT]\,dx - \{1-\exp[-2\kappa(J/J_{c0})(U_0/k_BT)]\}\int_{-R}^{R}\exp[-U(x)/k_BT]\,dx\int_{-R}^{x}\exp[U(x')/k_BT]\,dx', \tag{12}$$

where we have used the identity Eq. (8). Due to the motion of flux lines, an induction electric field E can be produced:

$$E = B\langle\dot{x}\rangle/c = \rho_0\frac{2ck_BTR}{a\Phi_0}\times\frac{1-\exp[-2\kappa(J/J_{c0})(U_0/k_BT)]}{\Gamma(J,U_0,T)}, \tag{13}$$

where $\rho_0 = B\Phi_0/\eta c^2 = \rho_n H/H_{c2}$ (Ref. 22) is the pinning-free flux flow resistivity with ρ_n being the normal-state resistivity. In the following, based upon Eq. (13), we will discuss the transport behavior in the present model.

III. RESULTS AND DISCUSSION

In the temperature regime where $U_0/k_BT \gg 1$ and $J \ll J_{c0}$, the flux flow exhibits a thermally activated behavior. The response E with respect to J is linear, since Γ in Eq. (13) can be well approximated by $\Gamma(J=0)$ at low J. The linear resistivity $\rho = E/J$ can then be analytically obtained from Eqs. (12) and(13):

$$\rho \approx [\kappa(U_0/k_BT)^2 \exp(-U_m/k_BT)]\rho_0, \qquad (14)$$

where $U_m = (1 + \ln\kappa)U_0$ (see Fig. 1) is the maximum height of the effective barrier (i.e., the pinning strength). In the derivation of Eq. (14), an approximation has also been made with $\kappa \sim 400 \gg 1$. The exponential term in the prefactor before ρ_0 on the rhs of Eq. (14) represents the usual Arrhenius behavior. Interesting is the square term $(U_0/k_BT)^2$ in the same prefactor, compared to the linear counterpart U_0/k_BT in the sinusoidal model.[17] We have tried another model in which the potential profile is triangular, and the square term appears as well. It is not clear so far whether this result is only a direct consequence of the slope discontinuity in the potential profile, or it might appear in other model even if the profile is smooth. Of course, it does not strongly affect the low temperature behavior of the resistivity ρ.

The linear response emerges again when the current density $J \gg J_{c0}$ in the flux flow regime. However, in the regime $J \sim J_{c0}$, or the flux creep regime, the response is nonlinear. In the usual creep model, the crossover between these regimes is untractable. The chief merit of the present model is that the response in the whole current and temperature regimes can be treated in a unified manner. Figures 2(a) and 2(b) are plots of the isothermal E versus J and ρ versus J relations from a numerical calculation of Eq. (13), respectively. In this calculation, usual formulas are chosen for the temperature T and magnetic induction B dependences of the parameters U_0 (and consequently of J_{c0}) from a rather general scaling method near $T = T_c$:

$$U_0 = U_{00}(1-t)^{3/2}/b,$$

where U_{00} is a constant, t the reduced temperature $T/T_c(0)$, and b the reduced magnetic induction $B/B_{c2}(0)$. The same dependence of U_0 was suggested by Yeshurun and Malozemoff[23] and was adopted by Tinkham in Ref. 19. This dependence is expected to be accurate to better than $\pm 4\%$ all the way from $t = 1/2$ up to $t = 1$ and for B in the intermediate regime.[19] From Figs. 2 we see the distinct temperature and current regimes for flux creep (FC) and flux flow (FF) and crossover in between. In the transition region just below T_c, the Lorentz force is dominant, and ρ is governed by flux flow and thermal fluctuations with ρ being current independent. At still lower temperatures, the flux creep enters as the dominant dissipation mechanism. The predicted linear response in Eq. (14) as $J \to 0$ in the TAFF regime is evident in Figs. 2. With increase in J, a nonlinear ρ-J characteristics is obtained in the FC regimes. It is noticed that the FC regime is rather narrow, and the maximum reduced current $J/J_{c0}(t, b)$ in this regime is approximately 10^{-2}, with a slight temperature dependence. Therefore, caution must be taken if the usual Anderson-Kim creep model or its derivative is to be used. In Figs. 2 the power-law behavior in the FC regimes is obvious particularly at low temperatures around $t = 0.81$ in Figs. 2, in agreement with usual experimental observations (see, e.g., Ref. 10). Notice that the same behavior was claimed in Ref. 17, however the results of this paper are apparently better defined, as is evident from Fig. 3 where the β ($\equiv d\ln E/dJ$) versus J relation is presented. The power-law behavior $E \propto J^n$ in the FC regime (e.g., at $t = 0.81$ in our case) is confirmed by the linearity of the $\ln\beta$ versus $\ln J$ curve with a slope of exactly -1 (see the dashed line in Fig. 3). In addition, this curve bends downward and goes along another parallel line at lower and higher currents, respectively, where the E versus J relation becomes essentially linear. The β versus J relation at higher temperatures are also shown in Fig. 3 for comparison.

Of particular interest is the slope of the $\ln\beta$ versus $\ln J$ curve. In the context of the vortex-glass theory,[3,4] $E \propto \exp[-(J_0/J)^\mu]$ at a temperature below the "glass temperature" T_g (J_0 being a constant), and this would

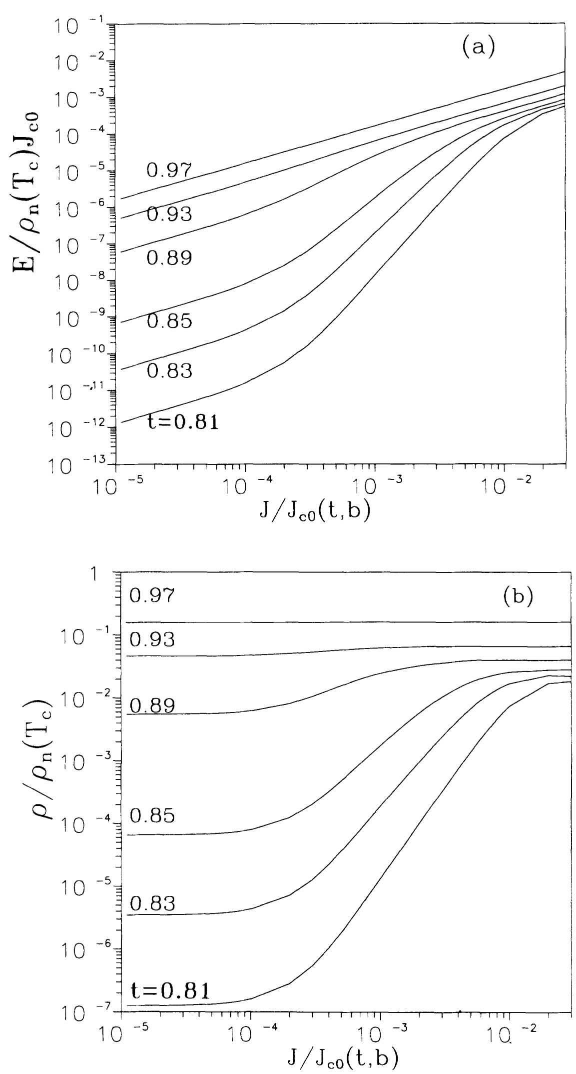

FIG. 2. (a) The calculated isothermal E-J characteristics; (b) the corresponding ρ-J characteristics. The magnetic induction is $B = 0.05\,B_{c2}(0)$. Here $\kappa = 400$ and $U_{m0} = (1+\ln\kappa)U_{00} = k_BT_c(0)$ are chosen, and $J_{c0}(t, b)$ is the critical current density as defined in the text [see Eq.(8)] with $t = T/T_c(0)$ being the reduced temperature and $b = B/B_{c2}(0)$ the reduced magnetic induction.

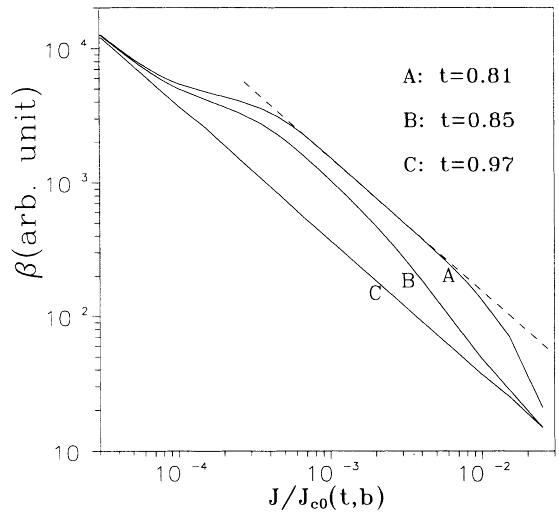

FIG. 3. The plot of the J dependence of $\beta = d\ln E/dJ$ at three temperatures (solid lines). Other conditions are the same as those in Figs. 2. The dashed line is a guide for the linearity of line A in the flux creep regime.

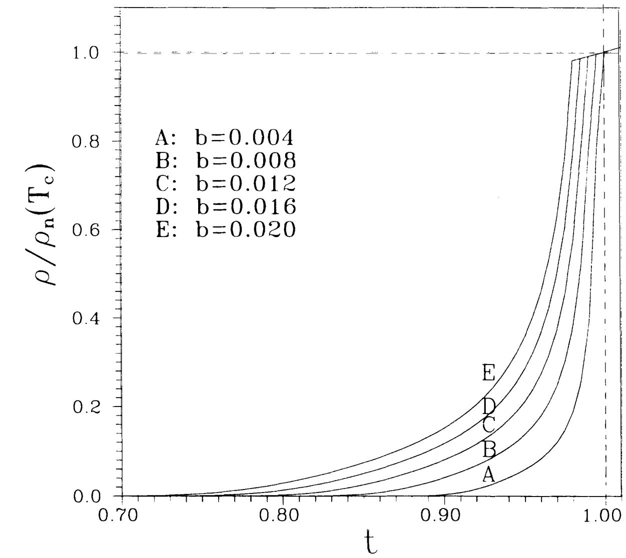

FIG. 4. The low current resistivity ρ vs temperature T of the superconductor (solid lines). Other conditions are the same as those in Fig. 2.

manifest itself in Fig. 3 a straight line of a steeper descent for $\mu > 0$, and the same (dashed) line as in Fig. 3 for $\mu = 0$. The latter equivalence between the $\mu = 0$ vortex-glass prediction and our results is best understood from the comparison of Eqs. (2) and (3) as $\mu \to 0$. Technically the β versus J relation is used as a probe to determine the exponent μ in the vortex-glass theory. As an example, we point out the observation by Küpfer *et al.* in Ref. 24, where $\mu = 0$ was claimed for a YBCO bulk sample, and further the downward bending of the $\ln\beta$ versus $\ln J$ curve was observed for lower current which is beyond the vortex-glass theory prediction, but in qualitative agreement with the results shown in Fig. 3 in this paper. In fact, this downward bending is nothing but the entrance into the TAFF regime or the FF regime from the FC regime in our case. Nevertheless, the observed sudden upward bending of the $\ln\beta$ versus $\ln J$ curve at higher currents in Ref. 24 cannot be explained in the model under present consideration, and it might be attributed to the entering of self-heating effect arising from large currents.

Finally, we present the field-dependent resistance broadening effect built in this model in Fig. 4. For simplicity, the superconductor is assumed to be in the normal state (or $\rho = \rho_n$) if ever $b \geq 1 - t$ is satisfied, irrespective of the superconducting order parameter fluctuation itself (and therefore pinning strength fluctuation) at the transition region (hence no rounding in the curves near T_c), and ρ_n is assumed to follow a simple extrapolated linear formula in T, $\rho_n = \rho_n(T_c)T/T_c$. We observe in Fig. 4 the same feature as from experiments (cf. Ref. 25), and from another phenomenological model.[19] As has been pointed out by Tinkham,[19] for a fixed level of small resistance, the scaling relation $1 - t \propto b^{2/3}$ is satisfied as long as the relation $U_0 \propto (1-t)^{3/2}/b$ is justified (the concrete pinning potential profile is irrelevant), and this is also the case in Fig. 4.

IV. SUMMARY

The flux motion in a superconductor with a periodic logarithmiclike bare pinning potential is investigated in this paper. (i) The effective barrier $U_J(J)$ under an applied current is derived and is shown to bear close resemblance with the experimentally extracted results in Refs. 10 and 11. It is shown that the details of the pinning potential profile have significant influences on the functional form of the effective barrier, which provides alternative explanation of experimental results besides that given by usual flux creep and flux flow model and the vortex-glass theory. (ii) The model is studied in detail by utilizing the Smoluchowski diffusion equation, the linear response of the superconductor under a small current is analyzed and a formula (slightly different from the counterpart built in the sinusoidal model in Ref. 17), is derived for the temperature-dependent linear resistivity in the TAFF regimes. (iii) The E-J and ρ-J characteristics in various temperature and current regimes are discussed, the distinct regimes for flux creep and flux flow and the crossover in between are treated simultaneously, and the familiar power-law behavior is recovered and is further confirmed by the $d\ln E/dJ$ versus J relation. Satisfactory agreement is found between our results and the experimental observation in Ref. 24. (iv) The experimentally observed field-dependent resistance broadening effect is reproduced in this model.

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