PHYSICS

Argument for $E \sim j$ relation of high temperature superconductors

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Abstract In high temperature superconductors (HTSC), when magnetic relaxation approaches the equilibrium state and the superconductor is applied with current, the $E \sim j$ relation is calculated by considering both forward and backward hopping of thermally activated flux (where backward hopping means hopping from the barriers with low energy to the ones with high energy). It is pointed out that the $\ln E - \ln j$ curve shows positive curvature. And the results are compared with other models. The discussion on the topic that whether $\rho$ approaches zero as $j \rightarrow 0$ is carried out.

Keywords: flux dynamics, thermally activated.

The flux-dynamics behavior of high temperature superconductors (HTSC) is particularly different from that of conventional superconductors. For the $R \sim T$ transition in applied fields, conventional superconductors show a definite transition point of temperature at which $R$ value of normal state is recovered rapidly, while HTSC show a large $R \sim T$ broadening. For conventional superconductors at fixed temperatures and fields, the magnetic moment $M$ which characterizes the diamagnetism varies with time $t$ and shows an $M \sim \ln t$ behavior as a result of magnetic flux creep$^{[1]}$, while HTSC show a deviation from this behavior; as the current $I$ flowing through the conventional type II superconductors increases, the relation of voltage and current is linear, that is, $V \sim I(E \sim j)$, while the case of HTSC is complicated.

There are at least four phenomena that cannot be explained by the flux creep theory:

(i) The linear behavior of $M$ and $\ln t$ is deviated.

(ii) There is a broad peak in the $dM/d\ln t \sim T$ relation which corresponds to the “platform” region$^{[2]}$ of the normalized relaxation rate, and $dM/d\ln t$ approaches zero as $T$ approaches $T_c$.

(iii) $V \sim I(E \sim j)$ curves show both positive and negative curvatures, either in the same current range with different temperatures or at the same temperatures with different currents.

(iv) It is still an open question that whether the resistivity $\rho$ approaches zero or not when $j \rightarrow 0$.

Various models were proposed for explanations of the flux-dynamics phenomena of the HTSC, including the vortex-glass model by Fisher et al.$^{[3, 4]}$, the collective-creep model by Feigel'man et al.$^{[5, 6]}$, the logarithmic $j$-dependent barrier $U(j)$ model $U = U_0 \ln(j_c/j)$ by Zeldov et al.$^{[7]}$, the revised Kim-Anderson model by Hagen and Griessen$^{[8-10]}$, and the creep...
model with damp by Yin et al.\textsuperscript{[11]}.

All the theoretical results of these models can fit the $E \sim j$ and $M \sim t$ relation, but are not perfect. The vortex-glass and collective-creep model derive $U = U_0 \left[ (j_c/j)^\mu - 1 \right]$, in which the former requires the parameter $\mu$ to be less than 1 and the latter requires $\mu = \frac{1}{7}, \frac{3}{2}, \frac{7}{9}, \frac{9}{8}, \frac{1}{2}$, while experiments show that $\mu$ can be greater than 1.5 and even reach 2\textsuperscript{[12]}. The vortex-glass model derives that the $\ln E \sim \ln j$ curves should be straight lines at the certain temperature $T_M$, which does not fit the experiment\textsuperscript{[13]}. Moreover, it cannot give both positive and negative curvatures at the $\ln E \sim \ln j$ isotherms. The logarithmic $j$-dependent barrier $U(j)$ model gives $\ln E \propto (U_0/kT) \ln(j/j_c)$, so the $\ln E \sim \ln j$ relation has a zero curvature evidently.

Noticing that the barrier $U_0$ of the HTSC is about one order lower than the conventional superconductors, Fu et al.\textsuperscript{[14]} pointed out that the backward hopping, which means the hopping of flux from low barriers to high ones, must be considered, the $E \sim j$ relation of a hollow HTSC cylinder is derived, and the positive and negative curvatures at the same $\ln E \sim \ln j$ isotherm are derived. They also pointed out that $\rho$ approaches a non-zero values as $j \to 0$.

In the present work, considering the backward hopping in the thermally activated model, the $E \sim j$ relation for an infinite slab with different $j$ and magnetic field $B_z$ is derived strictly in theoretics and the resistivity $\rho(j \to 0)$ is discussed. The theory can explain the experiment and predict some new phenomena, and it is also compared with other models. The deficiencies of the other models are pointed out and the reason for the accordance of this theory with the experiment is discussed as well.

1 Theory

Consider an infinite HTSC slab with thickness $w$ and width $a$ satisfying $a \gg w$. Let us select $x$ axis to be perpendicular to the slab surface, and the origin of the axes is set at the center of the slab. A magnetic field $B_z$ is applied along the $z$ direction, and an external current is applied along the $y$ direction, as shown in Fig. 1. Noticing that in the conventional transport measurements, the magnetic field is applied first, and then the current $I$, so the current density induced by the magnetic field can be considered as zero because the field reaches the equilibrium state as a result of the relaxation. In this case the current in the slab is only applied currently. Denoting $j$ as the current density, and according to the Maxwell’s equations, we have

$$\frac{dB}{dx} = - \mu_0 j(x). \tag{1}$$

Suppose that the magnetic field induced by the current at the slab surface is $B_I$. Evidently $B_I$ has the opposite directions at the two surfaces of the slab, thus the total magnetic induction is $B_a + B_I$ and $B_a - B_I$ on the two sides respectively. Integrating eq. (1), there derives