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Viscous flow of vortices in ideal type-II amorphous superconductors

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Low-field flux-flow resistivity in ideal type-II amorphous bulk superconductors Zr_3Ni and Zr_3Rh in both as-quenched and annealed states has been studied. The results provide the first experimental evidence that it is necessary to include all the energy-dissipation terms arising from normal current in the vortex cores (Bardeen-Stephen mechanism), relaxation of the order parameter (Tinhkam mechanism), and as well the slow diffusion mechanism of relaxation of the order parameter caused by the anomalous term in the time-dependent microscopic theory (Gor'kov-Kopnin mechanism) in the viscosity coefficient at low field. The last term is absent in "clean" alloys.

The origin of the viscous force in the flux-flow state of a type-II superconductor had been studied by various authors.[1–5] The viscosity was attributed to different energy-dissipation mechanisms originating from the normal current in the vortices and an electric field induced by their motion[2] [Bardeen-Stephen (BS) term], the relaxation of the order parameter towards its equilibrium value when it was forced to vary in time by the motion of a vortex line[3] [Tinkham (T) term], and the slow-diffusion mechanism of the relaxation of the order parameter caused by the anomalous term in the time-dependent microscopic theory[4] [Gor'kov-Kopnin (GK) term]. Kupriyanov and Likharev[5] (KL) had shown within the framework of the GK model by including the contribution of the normal electron dissipation and that connected with the time derivative term of the order parameter that the BS, T, and "anomalous" terms could be obtained from the microscopic theory. Explicit expression for the anomalous viscosity coefficient in "dirty" bulk alloys with $l << \xi_0$ (l is the electronic mean free path and ξ_0 is the zero-temperature coherence length) in the low-field regime $H_{c1} < H << H_{c2}$ (H_{c1} and H_{c2} are the lower and upper critical fields, respectively) was worked out by GK (Ref. 2). Until recently, these theoretical results have only been tested in several bulk and thin-film superconductors.[1,6–8] In one thin-film experiment,[8] it was found that the GK term alone could explain the data in the temperature range $t < 0.95$ (t is the reduced temperature) rather well. In other thin-film[6] and bulk superconductors,[7] the viscosity coefficient seemed to follow the sum of both BS and T terms over a wide temperature range. Several remarks on these experiments could be made. It was aruged that in thin films,[8] the BS and T terms were negligible under the condition of slow motion of flux lines, as suggested by GK (Ref. 4). Except for the thin-film experiments, results on bulk samples[7] were not compared with theoretical predictions at low field. Moreover, significant curvatures in the ρ_f/ρ_n (ρ_f and ρ_n are the flux-flow resistivity and normal-state resistivity, respectively) versus h (reduced field H/H_{c2}) plots could be seen in the region $h < 0.2$ (Ref. 7). Therefore it is preferable to measure low-field flux-flow resistivity in ideal type-II bulk superconductors with very short electronic mean free path where flux pinning is minimized. Then a direct comparison with existing theories can be made.

In this paper, we show that the universal behavior in the low-field flux-flow resistivity of ideal type-II amorphous bulk superconductors can only be explained satisfactorily by invoking all the aforementioned energy-dissipation mechanisms (BS, T and GK). The superconducting properties of these homogeneous materials are characterized by sharp superconducting transitions at zero field, reversibility in low-field magnetization, independence of $H_{c2}(T)$ on current density,[9] and almost field-independent weak flux pinning force ($\sim 10^4 N/m^3$ at half the transition temperature T_c).[10] Flux-flow measurements were performed on as-quenched and annealed Zr_3Ni (210 °C, 89 h) samples and Zr_3Rh (280 °C, 68 h) samples. The annealed samples were found to exhibit similar properties as the as-quenched samples.[10] Therefore thermal annealing only provides samples with a range of T_c values (see figure captions). Amorphous ribbons were prepared in the manner discussed elsewhere.[10] Structural analysis, thermal annealing, and electropolishing of samples were also described there. The flux-flow resistivity was obtained by tracing I-V (current-voltage) curves at constant field and temperature. The voltage was measured along the direction of the transport current. Applied field was normal to the sample plane. Temperatures were stablized to within 5 mK.

In Fig. 1 we have plotted ρ_f/ρ_n as a function of h at various reduced temperatures T/T_c for an annealed Zr_3Rh sample. It should be mentioned that the I-V curves were reversible at increasing and decreasing transport current. It can be seen that for

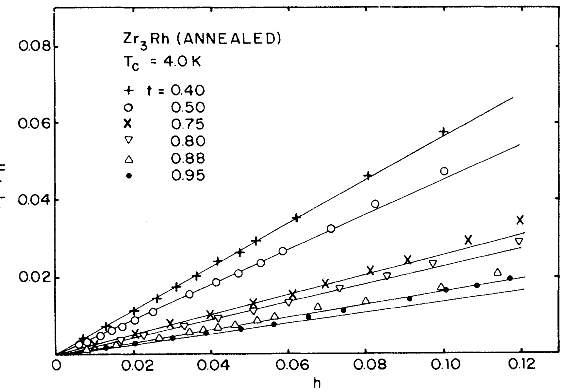

FIG. 1. Normalized flux-flow resistivity ρ_f/ρ_n as a function of normalized field h for Zr_3Rh (annealed at 280 °C for 68 h, $T_c = 4.0$ K) at various reduced temperatures t. Data can be fitted to straight lines for $h \lesssim 0.06$.

$h \lesssim 0.06$, the linearity between ρ_f/ρ_n and h can be described by the expression

$$\frac{\rho_f}{\rho_n} = b(t)h \quad . \tag{1}$$

This is in accord with the results of Ref. 8 that linearity could only be observed in the very low-field regime ($h \ll 1$). Similar results are obtained for all samples measured. In Fig. 2 is plotted the viscosity coefficient $1/b(t)$ vs $1/(1-t)$ on the log-log scale. One can observe a universal trend being followed by data obtained on different samples. Vertical bars are drawn for the Zr_3Ni (as quenched) and Zr_3Rh (annealed) samples to represent the uncertainties in defining $H_{c2}(T)$. The latter arise from the broadening of resistive transitions in an applied field [i.e., $\rho(H)$

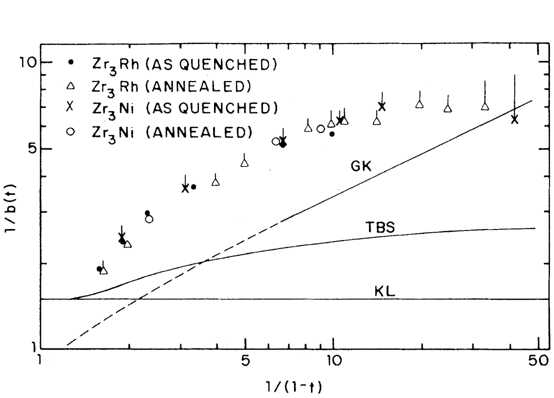

FIG. 2. Viscosity coefficient $1/b(t)$ as a function of $1/(1-t)$ on log-log scale for four different samples. T_c values for as-quenched Zr_3Rh, annealed Zr_3Rh, as-quenched Zr_3Ni, and annealed Zr_3Ni are 4.3, 4.0, 3.36, and 2.74 K, respectively. Theoretical curves and their notations are discussed in the text.

curves]. Usually, in homogeneous samples the transitions from the 0% to 50% points on the $\rho(H)$ curves are rather sharp which are followed by broader transitions to the 90% point. The latter could be caused by superconducting fluctuations. Measurements on as-quenched Zr_3Rh were not taken above $t \simeq 0.9$ because it was difficult to stabilize the temperature to high accuracy near 4.2 K in our apparatus.

Our results can now be compared with theoretical predictions. According to the GK mechanism[4] of energy dissipation due to the anomalous term alone, the viscosity coefficient is given by

$$\frac{1}{b_{\mathrm{GK}}(t)} \simeq 1.1(1-t)^{-1/2}y^2\left(\frac{0.18l}{\xi_0}\right) \text{ for } t \simeq 1 \quad , \tag{2a}$$

$$\frac{1}{b_{\mathrm{GK}}(0)} = 0.9 \text{ for } l \ll \xi_0 \quad , \tag{2b}$$

where $y = 1$ in the dirty limit, and y vanishes in the clean limit. Therefore the slow-diffusion mechanism for the damping of excitations is ineffective in clean alloys.

The GK result in the dirty limit is plotted in Fig. 2. The dashed line extending from $\log_{10}[1/(1-t)] \simeq 6$ to near $T = 0$ is only a schematic sketch since no numerical values have been computed for this region. The KL value of the viscosity coefficient obtained from microscopic theory is given by[5]

$$\frac{1}{b_{\mathrm{KL}}(t)} = \frac{a}{2}\left(\gamma_N + \gamma_R + \frac{\delta T_c}{\Delta}\right) \quad , \tag{3}$$

where $a \simeq 5.86$, the γ_N term due to the normal current equals 0.233, and the γ_R term due to relaxation of the order parameter equals 0.279. The last term in (3) is the anomalous contribution suggested by KL, where δ is a free parameter and Δ is the energy gap. This term has the same temperature dependence as (2a) for $t \simeq 1$. The first two terms yield $1/b_{\mathrm{KL}}(t) \simeq 1.50$. Since no explicit temperature dependence of b_{KL} was given in Ref. 5, we shall focus our discussion on the BS, T, and GK terms. The KL result which includes only the first two terms is also shown in Fig. 2. Comparing with the T and BS values, the T term gives

$$\frac{1}{b_{\mathrm{T}}(t)} \simeq \frac{\alpha\pi}{4}\frac{H_{c2}(0)}{H_{c2}(t)}\frac{\lambda^2(0)}{\lambda^2(t)} \tag{4}$$

at low field, where $\alpha \simeq 1$, and $\lambda(t)$ is the penetration depth given by the microscopic theory. The temperature dependence of the relaxation time has been expressed in terms of $H_{c2}(t)$. The BS term[2] gives approximately $1/b_{\mathrm{BS}}(t) \simeq 1$. When combined with the T term, it gives at $T = 0$ a combined viscosity coefficient of 1.79. According to the estimates of Galaiko cited in Ref. 7, the $1/b_{\mathrm{BS}}(t)$ in the dirty limit should be about 0.55. This would give a total viscosity coefficient of about 1.33. The values obtained so far are rather close to the KL value without the anomalous term. Without loss of generality, one can set the zero-temperature value of the TBS viscosity coefficient equal to the KL value and evaluate its temperature dependence according to Eq. (4). The results are shown in Fig. 2. Thus the TBS value differs from the KL value by at most unity. It is clear from Fig. 2 that neither one of the energy-dissipation mechanisms alone can describe the universal trend in the present data, contrary to previous findings.[6–8]

Adding all the energy-dissipation terms discussed above, we plot in Fig. 3 the GKTBS curve. For comparison, the GKKL curve is also included. There is no adjustable parameter in the curve fittings. It can be seen that within experimental uncertainties (vertical bars) the data follow the theoretical curves rather well, suggesting that, indeed, all the three mechanisms (BS, T, and GK) are present. The agreement is especially good for $0.66 < t < 0.95$. Discrepancy between experimental and theoretical values can be seen, however, in the low-temperature region, $t < 0.66$. Since the disagreement is within unity, it might be due to the unknown temperature dependence of the KL term or the inexact value of the TBS contribution at $T = 0$. On the other hand, an additional energy-dissipation mechanism due to the local temperature gradient near the core of the moving vortex was also proposed.[11] But this term can only account for about 30% of the BS term. At this point, it might be too premature to try fitting the low-temperature data by assuming some functional form for either the TBS or KL mechanism. The discrepancies in the region $t > 0.95$ are due to the uncertainties in the determination of $H_{c2}(t)$ and/or pair-breaking effect.[12] The latter is known to suppress the high-field flux-flow resistivity near T_c.[13]

Finally, two points need to be mentioned. The velocity of flux lines v_L can be estimated from the simple expression $v_L = E/H$, where E is the electric field.[14] The estimated values in the depinning region with linear I-V and ρ_f/ρ_n-h curves are of the order of 10^3–10^4 cm/sec at all temperatures, comparable to those observed in thin films.[8] Thus slow motion of

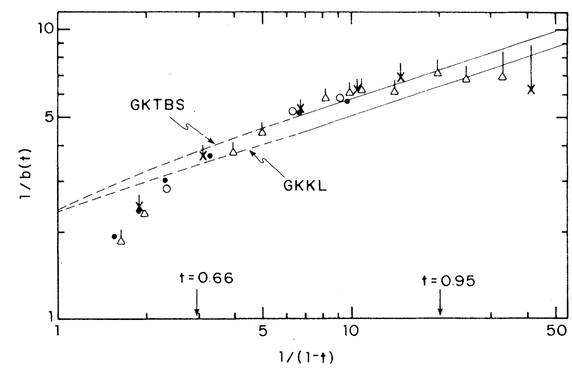

FIG. 3. Same as in Fig. 2. Theoretical curves are obtained by combining those of Fig. 2 (see text for details).

flux lines is also found in the present samples. Moreover, the penetration depth $\lambda(0)$ is estimated to be ~ 5000 Å, which is comparable to the effective penetration depth $\lambda_{\mathrm{eff}} = \lambda^2/d$ in thin films, where d is the film thickness. Therefore the different behavior in the viscosity coefficient between thin-film and bulk samples remained unexplained. It is conjectured that superconducting fluctuation in two dimensions might have affected the flux motion in thin films.

In closing, it can be said that homogeneous amorphous superconductors ($l << \xi_0$) with minimal flux pinning force provide ideal systems for the study of energy-dissipation mechanisms in the low-field flux-flow state. It is shown that the effects due to normal current, relaxation of order parameter, and anomalous term in the microscopic theory are responsible for the observed flux-flow properties. This provides an additional test of the formulation and solution of the time-dependent theories in type-II superconductors.

ACKNOWLEDGMENT

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