Joule heating induced by vortex motion in a type-II superconductor

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(Received 8 January 2001; published 10 August 2001)

We present experiments that determine the temperature increase in a type-II superconductor due to Joule heating induced by vortex motion. The effect of Joule heating is detected by comparing the response of the vortex lattice to fixed amplitude current steps of short (10 μs) and long (4 s) duration, where the Joule heating is negligible and saturates, respectively. The thermometry is based on the temperature dependence of the voltage response of the vortex lattice to a driving current. By monitoring the temperature increase in $NbSe_2$ samples adhered on a sapphire substrate with GE varnish we obtain the effective heat transfer coefficient between the sample and the bath and show that the heating is primarily due to the power dissipated by the vortex motion.

DOI: 10.1103/PhysRevB.64.094511 PACS number(s): 74.60.Ec, 65.90.+i, 66.70.+f

I. INTRODUCTION

In the mixed state of a type-II superconductor vortex motion induces dissipation. Due to the finite heat-removal rate from the sample to the bath, Joule heating associated with the vortex motion leads to an increase in sample temperature. While this heating can be accompanied by interesting physical phenomena such as the hotspot effects,[1–4] it also causes difficulties in analyzing transport experiments and in determining the physical properties related to the vortex motion, especially at high dissipation levels.[5–13] Joule heating can be reduced significantly by using short pulsed currents[5–7,14] or by applying the current at high ramping rates.[8,12] In typical transport measurements, however, the current is applied continuously which leads to uncertainties in the temperature of the sample. Because most properties of the superconductor are temperature dependent it is important to determine the temperature increase in the presence of a current. This is usually estimated from the heat-flow equations by using the heat transfer coefficient h (or the thermal boundary resistance $R_{bd}=h^{-1}$) between the sample and the bath as determined from photoresponse[15–17] or by comparing the experimental data with theoretical models.[1–4,11,18] However, both methods have limited applicability since the heat transfer coefficient derived from the experimental data is model dependent. Another approach is to place the thermometer close to or on the sample[13,19] but even in this case the measured temperature is not necessarily that of the vortex lattice. In this paper we introduce a method to obtain a direct measure of the temperature increase of the moving vortex lattice by using the temperature dependence of the vortex response to a driving current as a thermometer. The measurement principle is based on the fact that for sufficiently short current pulses Joule heating is negligible. Thus by comparing the vortex response to short and long current pulses we obtain a direct and independent measure of Joule heating.

The experiment was carried out in the low-T_c superconductor 2H-$NbSe_2$. This material exhibits a pronounced peak in the temperature dependence of the critical current just below T_c. Interesting physical phenomena such as plastic flow, metastabilities, and flow induced organization were found to accompany the vortex motion in this system.[20–23] Because of the strong temperature dependence of these properties, small amounts of Joule heating can induce significant deviations of the experimental data from those without heating. For example, it can produce results similar to those expected from another mechanism—a peak in the current dependence of the differential resistance dV/dI (Ref. 24)—which is predicted to signal a dynamic phase transition in the moving vortex system.[25,26] Thus in order to correctly interpret the transport results it is necessary and important to determine the temperature increase due to Joule heating.

II. EXPERIMENTAL DETAILS

The data presented here were acquired in two pure single crystals, sample A and sample B. The corresponding dimensions are $3(L)\times0.65(W)\times0.025(D)$ and $5\times1.65\times0.020\,mm^3$. In zero magnetic field the critical temperatures are 7.1 and 7.2 K for sample A and sample B, respectively. As shown in the inset of Fig. 1(a) the samples were glued on sapphire substrates with a thin layer of GE (7031) varnish. The sapphire substrate was thermally anchored to a regulated pumped helium bath through a Cu holder. A RhFe calibrated thermometer mounted on the sapphire substrate was used to monitor the substrate temperature. In order to achieve good thermal contact and avoid mechanical stress, current and voltage pads were made by depositing a layer of gold (5–10 μm) with a thin buffer layer of titanium on both the sapphire substrate and the sample and then soldered together with $Ag_{0.1}In_{0.9}$. The same solder was used to attach current and voltage leads to the gold pads on the sapphire substrate. The solder for the current leads was wrapped around the sample edges to improve the homogeneity of current injection and to minimize contact resistance which was typically less than 0.5 Ω at room temperature. Our measurements employed a standard four-probe technique. The distance between the two voltage contacts was $l=1.5$ and 1.4 mm for sample A and

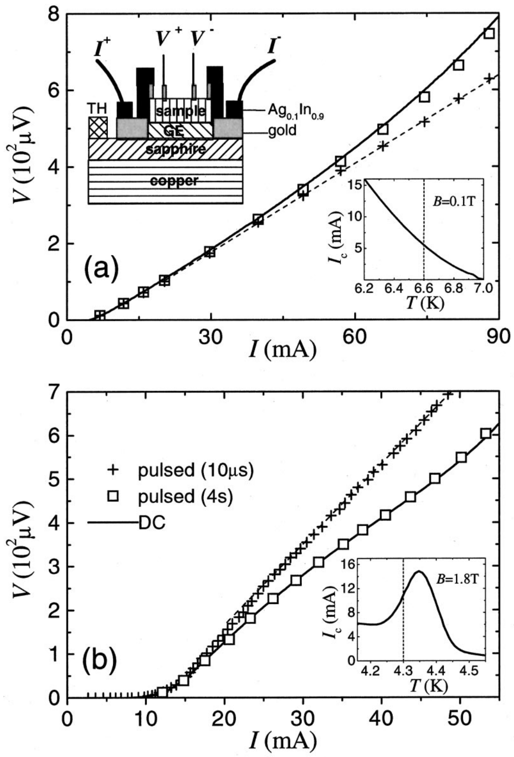

FIG. 1. I-V curves obtained in sample A with dc, short (10 μs) and long (4 s) pulsed currents: (a) $B=0.1$ T, $T=6.6$ K (below the peak region); (b) $B=1.8$ T, $T=4.30$ K (in the lower part of the peak). Dashed line: calculated free flux flow response. Lower right insets show the temperature dependence of the critical current (defined with a 5 μV criterion) and the temperature at which the I-V curves were taken (dotted lines). The upper left inset in (a) illustrates the thermal anchoring of the sample (TH represents the thermometer).

sample B, respectively. A wave form generator was used to apply the current steps and the corresponding voltage response was amplified with a low noise (1 nV/Hz$^{1/2}$) fast amplifier and recorded with a 100-MHz digital oscilloscope. For the dc resistance and differential resistance measurements we used a commercial current source, a nanovoltmeter and a low-frequency lock-in detector. The magnetic field was kept along the c axis of the sample and the current flow was in the a-b plane. The vortex lattice was prepared by a zero-field-cooling procedure to avoid the metastabilities observed in the field-cooled vortex system.[21–23] The data reported here were recorded on vortex lattices annealed with slow cycles of current $I<2I_c$.

III. RESULTS AND DISCUSSION

The effect of Joule heating are clearly seen in Fig. 1 by comparing the current-voltage (I-V) curves obtained with dc and short pulsed currents. The pulses consisted of intervals with current ‘‘on’’ followed by cooling intervals without current. The duration of the pulses was varied to find the optimal conditions of no heating while minimizing the noise level. We determine the presence of heating from the I-V curves at high currents. At high currents $I \gg I_c$, if no heating is present one observes the expected free flux flow behavior[27] $V=R_f(I-I_c)$ where I_c is the critical current, $R_f=R_n H/H_{c2}(T)$ is the Bardeen-Stephen free flux flow resistance, R_n is the normal-state resistance, and $H_{c2}(T)$ is the upper critical field. Deviations from this linear behavior signal heating. We find that Joule heating is negligible for pulses of duration $\leqslant 10$ μs spaced by long cooling intervals (500 μs) as is clearly seen in the pulsed data in Fig. 1. Thus we detect the presence of Joule heating in slow measurements by comparing the I-V curves to those obtained in pulsed measurements. Heating affects the I-V curves mostly through the temperature dependence of the critical current I_c. If $dI_c/dT>0$—as is the case in the lower part of the peak effect region [inset of Fig. 1(b)]—Joule heating leads to a lower voltage response, so the ‘‘hot’’ I-V curve is *below* the pulsed curve as in Fig. 1(b). The opposite is seen when $dI_c/dT<0$, where the ‘‘hot’’ I-V curve is *above* the pulsed curve. Another contribution to the temperature dependence of the I-V curves comes from the free flux flow resistance R_f, which increases monotonically with increasing temperature.

The temperature increase due to Joule heating grows with pulse duration until, for sufficiently long pulses (~4 s), it is indistinguishable from dc measurements as illustrated in Fig. 1(b). The time scale for which heating in the pulsed and dc data become comparable is given by the heat diffusion time $\tau=\Sigma_i L_i^2/D_i \sim 10$ ms, between the sample and thermal anchoring point through the various substrate layers, GE varnish and sapphire. Here the summation is over the two substrate layers, L_i is a characteristic layer thickness, $D_i=C_{pi}/\kappa_i$ the thermal diffusion constant with C_{pi} and κ_i the specific heat and thermal conductivity, respectively. Thus, in the limit of long pulses of duration $t \gg \tau$, the temperature increase no longer depends on the pulse length and approaches that of a dc current. Indeed, as shown in Fig. 1, the I-V curves obtained with a pulsed current of $t_0=4$ s are nearly identical to those obtained with a dc current. Based on this result we used 4 s pulses to simulate heating in dc currents in order to expedite data collection and simplify analysis. Thus our experimental procedure consists of monitoring the voltage response to short (10 μs) current pulses at bath temperature T_1 followed by a long (4 s) pulse at the same bath temperature. Since heating can be ignored at 10 μs and saturates at 4 s the first measurement gives the voltage response at sample temperature T_1, while the second is the response at the heated sample temperature T_1+dT. In order to determine dT, we heat the sample to reach a bath temperature T_2 at which the voltage response to the 10 μs pulses is equal to the dc response at bath temperature T_1. The difference of the two bath temperatures $T_2-T_1=dT$ is thus the temperature change due to the Joule heating of the dc current at bath temperature T_1.

The response to long and short pulsed currents is shown in the left and right panels of Fig. 2, respectively. Panels (a1) and (a2) represent calibration curves obtained by measuring the voltage response to a current step in the normal phase ($T>T_c$) where the resistance is almost temperature independent. From this calibration we ascertain that the response

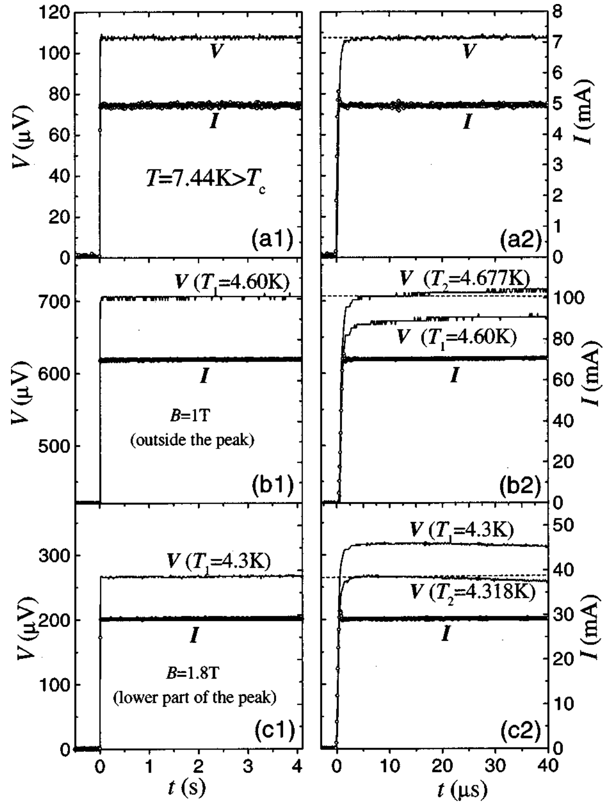

FIG. 2. Determination of the temperature increase by comparing the voltage response to short (10 μs, right panels) and long (4 s, left panels) current steps. The data in (a1) and (a2), (b1) and (b2), and (c1) and (c2) represent typical results obtained in sample A for the normal state ($T>T_c$), below the peak region and in the lower part of peak region, respectively. The dashed lines in the right panels are traced at the voltage values in the left panels. The temperature increase at a bath temperature T_1 in the presence of a dc current is given by $dT=T_2-T_1$ (see text for details).

time of the voltage amplifier is sufficiently short (<2 μs) to ensure good temporal resolution of the pulsed measurements. In panels (b1) and (b2) we present the response to short and long 70 mA current pulses below the peak effect region, at a field of 1 T and bath temperature $T_1=4.60$ K. Since in this region $dI_c/dT<0$ Joule heating reduces the critical current and should result in an increased voltage response. Indeed the data show that the long pulse voltage response is larger than the 10 μs response, as expected of Joule heating. By raising the bath temperature to $T_2=4.677$ K the 10 μs response becomes equal to the 4 s response at $T_1=4.60$ K. It follows that for bath temperature 4.60 K, the sample temperature increases to 4.677 K in the presence of a dc current of amplitude 70 mA. This gives a temperature increase $dT=77$ mK in the presence of a 70 mA dc current. In panels (c1) and (c2) we present data in the lower part of the peak regime where $dI_c/dT>0$, for a field of 1.8 T and temperature $T_1=4.30$ K. Using a similar procedure we find that in the presence of a 29 mA dc current the sample temperature is $T_2=4.318$ K and the corresponding temperature increase is $dT=18$ mK.

Repeating this procedure at various driving currents we

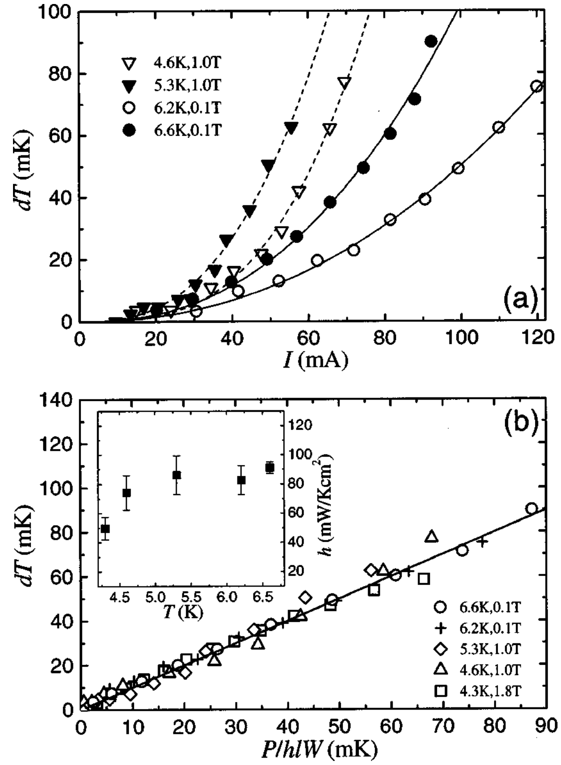

FIG. 3. (a) Current dependence of temperature increase in sample A. The solid curves are fits of the data to $dT\sim I^n$, with $n=2.642$, 3.090, 2.372, and 2.172 for the curves from left to right; (b) temperature increase versus normalized power dissipated by vortex motion, showing linear dependence (solid line). The temperature dependence of the heat transfer coefficient is shown in the inset of (b).

map out the current dependence of the temperature increase for various temperatures and magnetic fields, as shown in Fig. 3(a). For all the data sets we find that dT is linear in $P=IV$, the power dissipated due the vortex motion, suggesting that the Joule heating induced by the vortex motion is the primary contribution to the temperature increase. The slope of these data gives the effective heat transfer coefficient, $h=P/lWdT$, with lW the sample area between the voltage leads in contact with the substrate. By plotting dT against the reduced power P/lWh all the data in Fig. 3(a) collapse onto a single straight line as shown in Fig. 3(b). The values of h shown in the inset of Fig. 3(b) are in the range 40–100 $mW/cm^2 K$. This indicates that for our samples which were adhered on the sapphire substrate with GE varnish, the heat transfer coefficient is at least three orders of magnitude below the values reported for samples directly grown on sapphire or $SrTiO_3$ substrates.[4,15–18]

As is the case in other transport measurements in superconducting crystals,[28] the resistance of our sample ($\sim$0.4–0.8 Ω at room temperature) is comparable to the contact resistance. The contact resistance is expected to drop significantly with decreasing temperature, but its value at our measurement temperatures is unknown. This leaves the possibility that part of the observed Joule heating is due to the power dissipated in the current contacts. If heating is generated by power dissipated due to the lead resistance as well as to

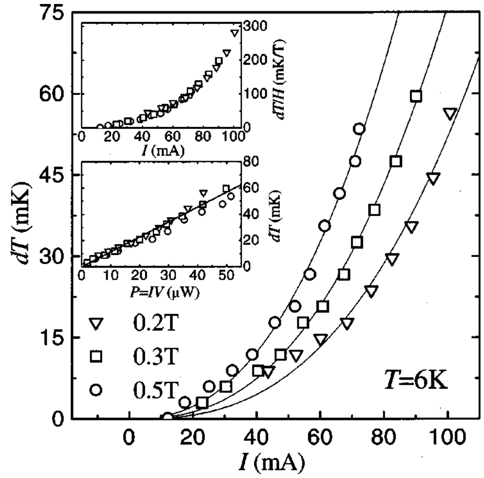

FIG. 4. Temperature increase versus current amplitude obtained in sample B at $T=6.0$ K for $B=0.2$, 0.3, and 0.5 T. The solid curves are fits of $dT\sim I^n$, with $n=2.411$, 2.533, and 2.667 for 0.2, 0.3, and 0.5 T, respectively. The upper inset shows the collapse of the data when plotted as dT/H against the applied current. The lower inset shows the temperature increase versus the power dissipated in the vortex motion. The line is a guide to the eye showing the expected linear behavior.

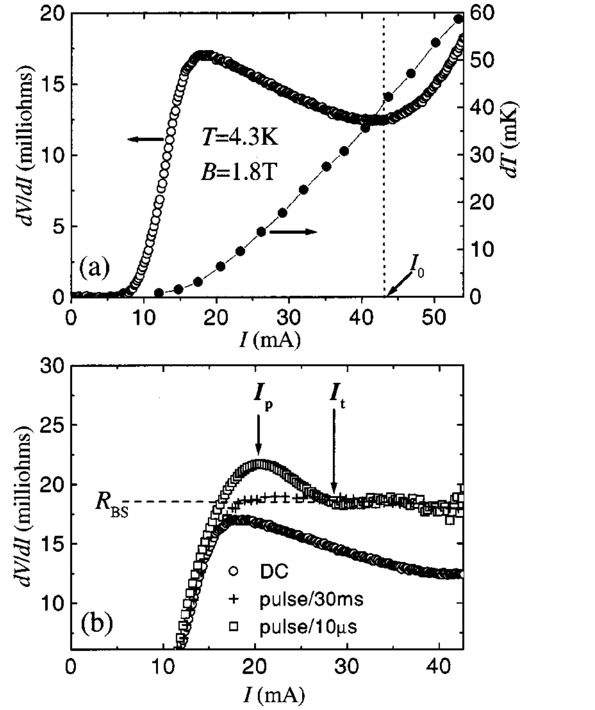

FIG. 5. (a) Current dependence of the differential resistances (dV/dI) (open circles) and the temperature increase (solid circles) obtained in sample A. I_0 is the current for which the sample temperature coincides with the temperature of the peak in critical current; (b) differential resistance versus current curves obtained with dc and pulsed currents of 10 μs and 30 ms. The R_{BS} is the Bardeen-Stephen resistance, I_p and I_t are the currents associated with dynamic phase transitions of the moving vortex lattice (see text for more details).

vortex motion the temperature increase is $dT=aP+a_cR_cI^2$, where $aP=aR_vI(I-I_c)$, $a=(hlW)^{-1}$, $a_c=(h_cA_c)^{-1}$, A_c and h_c the contact area and the heat diffusion coefficient of the current contacts, R_v and R_c the vortex and contact resistance, respectively. If contact resistance is the primary contribution to heating the expression reduces to $dT=a_cR_cI^2$. Fitting the data in Fig. 3(a) with a power law $dT=cI^n$ gives powers in the range $n\sim2.2$–3.1, which suggests that dissipation in the leads is not the dominant contribution to heating. On the other hand, if vortex motion is the primary heating mechanism, then in the limit of large currents when R_v takes the free flux flow value R_f, the expression reduces to $dT\approx aR_nI(I-I_c)H/H_{c2}$ and the temperature increase is linear in field. As a check we measured the current dependence of dT at a fixed temperature, $T=6$ K, and various magnetic fields shown in Fig. 4. Plotting dT/H versus I in the upper inset of Fig. 4(a) we note that the data indeed collapse onto a single field-independent curve. These results are consistent with heating due to vortex motion and in most cases would rule out contributions from heating in the contacts, except when the contact magnetoresistance is linear in field. In order to further study the heating effect from the contacts we consider the dependence of dT on the power dissipated by vortex motion, $P=IV$. For large currents, $dT\approx a(1+\alpha)P+\beta P^{1/2}$, where $\alpha=a_cR_c/aR_f$ and $\beta=a_cI_cR_c/R_f^{1/2}$ with $R_f=R_nH/H_{c2}$. We note that when vortex motion is the primary contribution to heating, $\alpha,\beta\ll1$, so the temperature increase is *linear* in P and independent of field. By contrast, contributions due to heating in the contacts give rise to a nonlinear power dependence and to a finite field dependence which persists even if the magnetoresistance of the contact matches the field dependence of the vortex resistance. Plotting dT as a function of P, in the lower inset of Fig. 4 we note the collapse of the data onto a straight line. This linear behavior together with the very weak field dependence lead to the conclusion that the measured temperature increase is mainly due to dissipation in the vortex lattice.

The temperature sensitivity of the I-V characteristics becomes strikingly evident when the experiment is carried out at a bath temperature that places the system in the lower part of the peak regime $T<T_p$, and then heating brings it above the peak $T>T_p$. In this case the response to a dc current initially diminishes with increasing current amplitude, since $dI_c/dT>0$ [lower right inset of Fig. 1(b)], but once the temperature exceeds T_p and $dI_c/dT<0$, the response grows with current amplitude. This leads to the nonmonotonic current dependence of the differential resistance shown in Fig. 5(a). The minimum of the differential resistance at high current corresponds to the current I_0 at which the sample temperature reaches the peak temperature $T_p=4.345$ K [see lower right inset of Fig. 1(b)]. It follows that the temperature increase at I_0 is $dT=45$ mK. The temperature increase at various applied currents obtained with the pulsed method is also shown in Fig. 5(a). From it we derive a temperature increase of 42 mK at I_0. Within our experimental resolution the effects of the Joule heating determined by these two methods are in good agreement.

The results show that Joule heating can introduce difficulties in the data analyses, especially in the lower part of the peak regime, where interesting phenomena have been reported recently.[20,22,23] For the data shown in Fig. 5(a), for example, a peak could appear in the differential resistance versus current curve solely due to the effect of Joule heating. In Fig. 5(b) we compare the results obtained with dc current and with pulsed currents of various durations. In the absence of Joule heating dynamic phase transitions of the vortex lattice can be identified in the data obtained with pulsed current of 10 μs, as indicated by the current I_p and I_t.[23] The differential resistance peak almost disappears in the curve obtained with the longer pulsed currents of 30 ms. In the dc case the maximum resistance is smaller than the Bardeen-Stephen free flux flow value despite the fact that the curve exhibits a peak. But the position of the peak is shifted from that obtained with 10 μs pulsed current and furthermore it is also impossible to identify the I_t. These results indicate that the Joule heating effect can be very important in this regime and needs to be considered when analyzing the data.

IV. SUMMARY

In conclusion, we have introduced a method to determine the temperature increase due to Joule heating in a superconductor by comparing the voltage response to short and long current steps. In the experiments presented here we find that the temperature increase in the presence of an applied current is due to dissipation associated with the vortex motion.

ACKNOWLEDGMENT

This work was financially supported by DOE DE-FG02-99ER45742.

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