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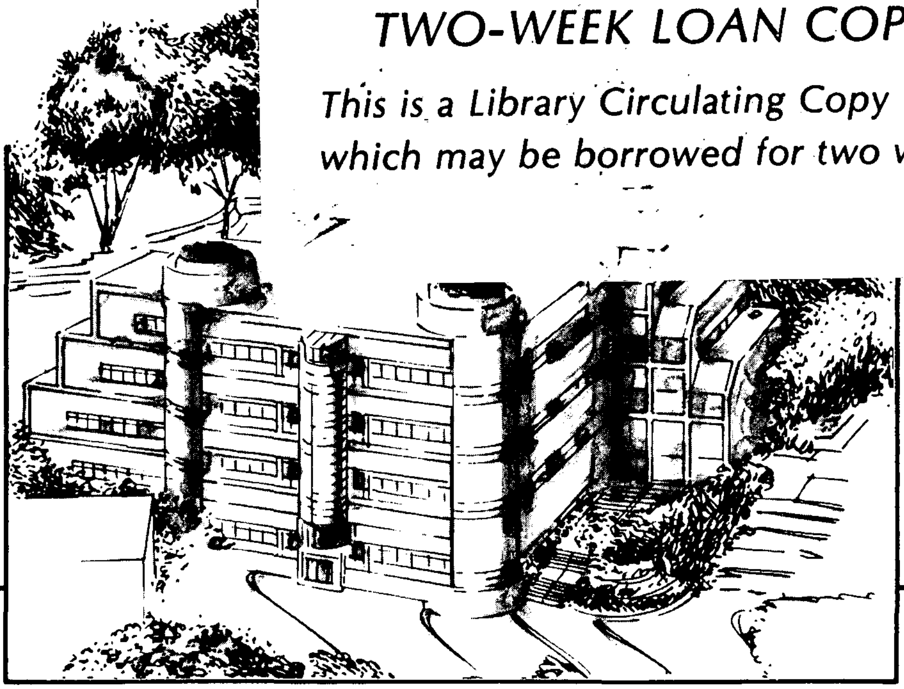

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FEASIBILITY OF THE HIGH T_c SUPERCONDUCTING BOLOMETER

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A design analysis is given for a bolometric infrared detector that uses the resistive transition of a high temperature superconductor as the temperature sensing element, and liquid nitrogen (LN) as the coolant. It is shown that for highly oriented c-axis films, the measured low frequency noise causes little or no degradation of the performance. With the incoming radiation chopped at 10Hz, noise equivalent powers (NEP) in the range $(1\text{-}20)\times10^{-12}\mathrm{WHz}^{-1/2}$ should be achievable. These values compare favorably with the NEP of other detectors operating at or above LN temperatures for wavelengths greater than 20μm.

A bolometer consists of a radiation absorber and an electrical resistance thermometer coupled to a heat sink via a thermal conductance. Such bolometers are used as sensitive detectors of electromagnetic radiation at wavelengths ranging from microwaves to X-rays. One type of thermometer consists of a superconducting film near the midpoint of its resistive transition.[1] Although such devices have excellent performance when operated in the liquid ^{4}He (LHe) temperature range, they are more complicated to use than doped semiconductor thermometers,[2] and therefore are rarely used in practical applications. The discovery of high transition temperature (T_c) superconductors, however, offers the possibility of using such sensors at temperatures somewhat above the 77K boiling point of liquid nitrogen (LN). For wavelengths <20μm, LN-cooled photovoltaic infrared detectors such as HgCdTe are widely used. For longer wavelengths, however, there is no satisfactory cooled detector technology above LH temperatures, and room temperature thermal detectors such as the Golay cell or the pyroelectric detector are often used in applications where LN would be acceptable. This Letter demonstrates that high-T_c superconducting transition edge bolometers potentially have much better sensitivity at wavelengths >20 μm than any competing sensor at or above LN temperatures. We believe these bolometers have an important range of applications.

We consider a substrate of area A, coated with an ideal absorbing element, to which is attached a resistance thermometer. The total heat capacity of the bolometer C is coupled to a heat sink at temperature T_0 via a thermal conductance G, giving a thermal time constant $\tau = C/G$. In most practical applications, the bolometer will absorb significant power P_{IR} from a background at $T_B = 300K$. Values of P_{IR} computed from the Planck blackbody expression are shown in Fig. 1 for a throughput $A\Omega=10^{-2}\mathrm{srcm}^2$. The optical efficiency is assumed to be unity from zero frequency up to the infrared cutoff frequency ν_c of a cooled low-pass filter. The value of $G=P_{IR}/(T_c-T_0)$ required to operate the bolometer at T_c is also shown in Fig. 1 for the assumed temperature difference $T_c-T_0=10K$.

The resistance thermometer is a film of high T_c superconductor operated at the midpoint of the transition where the resistance is R. The temperature coefficient $\beta=d\ell nR(T)/dT$ in conventional bolometer theory can then be identified as the inverse of the half-width δT of the superconducting transition. The bolometer is biased with a current I which produces an average voltage $\overline{V}=IR$. The positive thermal feedback caused by this current bias reduces the thermal conductance to an effective value $G-I^2R\beta$. To maintain thermal stability, we require $I^2R\beta/G=a<1$, and arbitrarily take $a=0.3$. This assumption limits the temperature rise due to bias heating to $a\delta T$. To simplify the ensuing discussion, we will neglect the effect of thermal feedback on G and τ. We can then calculate an expression for the responsivity of the bolometer, $S=\overline{V}\beta/G(1+i\omega\tau)$, where $i=\sqrt{-1}$ and $f=\omega/2\pi$ is the frequency at which we chop the incoming radiation. Substituting for $\overline{V}$, we find

$$|S|^2=aR\beta/G(1+\omega^2\tau^2) \simeq aR/G\delta T(1+\omega^2\tau^2). \qquad (1)$$

The noise equivalent power (NEP) of the bolometer can be computed by summing the squares of statistically independent contributions,

$$\mathrm{NEP} = \left| \frac{4k_B^5 T_B^5 A\Omega}{c^3 h^3} \int_0^{x_c} \frac{t^4 e^t dt}{(e^t -1)^2} + 4k_B T_c^2 G + \frac{4k_B T_c R_c}{|S|^2} + \frac{A\bar{V}^2}{f|S|^2} + \frac{4k_B T_N R_c}{|S|^2} \right|^{1/2} . \tag{2}$$

The first term in the square bracket represents the photon noise in the incident radiation; here $x_c = h\nu_c / k_B T_B$ is the normalized cutoff frequency. The second is thermal noise due to the exchange of phonons between the bolometer and the heat sink. Both of these terms, and their combined value, are plotted vs. ν_c in Fig. 1, and represent fundamental limits to the sensitivity of any bolometer with the given values of ν_c, T_c and T_0. The third term is the limit imposed by the Johnson noise in the thermometer, which has a voltage spectral density $4k_B T_c R$. The fourth term arises from the 1/f noise in the film, which we assume has a spectral density of the form $S_V(f) = A\bar{V}^2/f$, where A is a measured quantity that depends on the properties of the film and is expected to scale inversely with its volume. The last term is the noise associated with an amplifier with noise temperature T_N used to read out the thermometer, henceforth we will neglect this term because we assume that we can make T_N small compared with $T_c \approx 90$K, by using a large enough value of R or, if necessary, by biasing the thermometer with an alternating current and coupling it to the amplifier with a transformer.[1]

To optimize the NEP, it is convenient to neglect the photon noise, which is always smaller than the phonon noise, and also to neglect the 1/f noise, which will not prove to be dominant. The optimal operating point can then be found by equating the phonon noise and Johnson noise terms in Eq.(2). We find $\omega^2\tau^2 = a\beta T_c - 1$, a result involving neither G nor R that fixes $\omega\tau$ for given values of a, $\beta \approx (\delta T)^{-1}$, and T_c.

To produce numerical estimates, we have measured[3,4] both R(T) and the low frequency noise in films of $YBa_2Cu_3O_{7-\delta}$ (YBCO) and $ErBa_2Cu_3O_{7-\delta}$ (EBCO) which were typically 300 nm thick and 2 mm long with widths of 10μm, 20μm and 400μm. These films were deposited on $SrTiO_3$ substrates by electron-beam co-evaporation[5,6] of metallic Y, Er, and Cu and the salt BaF_2, post-annealed in wet oxygen and patterned photolithographically. Gold current and potential pads were deposited using conventional procedures.[7] Each substrate was mounted in turn on a cold stage which produced stable temperatures near T_c. The current leads were connected in series with a large resistor and a battery. The voltage leads were coupled capacitively to a low noise preamplifier. The output of the preamplifier was connected to a digital Fourier transform spectrum analyzer. We found that c-axis oriented films exhibited lower noise levels than films of the same dimensions with a- and c-axes mixed. We report here the results on the sample that had the best figure of merit as a thermometer. There is no reason to suppose, however, this value is the best that can be achieved. The resistive transition of the 400 μm wide YBCO film is shown in Fig. 2(a), together with the variation of β withT. We note that β exceeds 0.5 K^{-1} over a temperature range of about 5K. In the presence of a sufficiently large bias current the spectral density $S_V(f)$ of the voltage noise scales as I^2/f over the measured range from 0.1 Hz to 40 Hz. We show the dependence of $S_V^{1/2}(10\ \mathrm{Hz})/\bar{V}$ on T in Fig. 2(b). The spectral density of the temperature fluctuations $S_T(f) = S_V(f)/\bar{V}^2\beta^2$ is a useful figure of merit for the film used as a thermometer in applications where the 1/f noise dominates. This will occur in applications where larger values of G and thus larger bias currents can be used. The optimal value of the temperature resolution represented by the data in Fig. 2 is $S_T^{1/2}(10\ \mathrm{Hz} \doteq 1\times10^{-8}\mathrm{KHz}^{-1/2}$.

Given these experimental parameters, we can return to the optimization of the bolometer. Using the values $a=0.3$, $\beta=0.5\mathrm{K}^{-1}$ and $T_c=90\mathrm{K}$, we compute $\omega\tau\approx3.5$. If we assume that the incoming radiation is chopped at $\omega/2\pi=10\mathrm{Hz}$, we find $\tau\approx56\mathrm{msec}$. To proceed further we have to choose reasonable values of G and C. One of the bigger challenges in the design of the bolometer is to find a substrate of sufficiently low heat capacity: For example, the heat capacity of a 1×1 mm chip of $SrTiO_3$ 20μm thick is about 20μJ/K, while that of a diamond substrate of the same dimensions is about 1μJ/K. If one could produce a high-T_c film of good quality on submicron membrane of silicon or boron nitride[8] the heat capacity could approach 0.1μJ/K. To summarize these results, in Table I we list the three values of C just mentioned, the corresponding value of G for $\tau=56$ msec, the value of ν_c obtained from Fig. 1, and the contributions to the NEP from photon noise, phonon noise and Johnson noise.

The final contribution to the NEP arises from the 1/f noise. We compute its value at 10Hz by setting $\mathrm{NEP} = G(1+\omega^2\tau^2)^{1/2}\ S_T^{1/2}(10\ \mathrm{Hz})$, where $S_T^{1/2}(10\ \mathrm{Hz}) = 10^{-8}\mathrm{KHz}^{-1/2}$ and $1+\omega^2\tau^2 = 13.5$; the results for the three values of G are listed in Table I. We see that the 1/f noise contribution is comparable to that of the phonon and Johnson noise for the highest value of C, and negligible for the other two cases. The specific heat c~0.9 J/cm^{3}K of the superconducting film near T_c makes a significant contribution only for the smallest value of C. Since the 1/f noise is expected[9] to vary inversely with the film volume V, relatively large area films, such as the one for which noise measurements are reported, should be used for bolometers with high C where 1/f noise is important. Smaller films which show more 1/f noise[3] should be used for bolometers with very low C.

The last column in Table I lists the total NEP from all four sources. These values range from 1.3 to 22×10^{-12}WHz$^{-1/2}$ for the values of C chosen. For the higher values of C it is not possible to reach the ideal limit to the NEP shown in Fig. 1. For the lowest value of C, the NEP of a bolometer designed for $\nu_c \approx 350$ cm^{-1} is only 30% above this limit. Similarly good performance can be obtained for higher ν_c by increasing G to keep the bolometer cold. We note that all of these values compare very favorably with the NEP of a typical commercial pyroelectric detector,[10] which is about 5×10^{-10} WHz$^{-1/2}$.

In summary, we have shown that bolometers operated in the LN temperature range and using the resistive transition of a high-T_c film as a thermometer make very competitive detectors of electromagnetic radiation for wavelengths >20μm.

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10. See, for example, the P-41 detector, Molectron Corp., Sunnyvale, California.

TABLE I. PERFORMANCE PARAMETERS FOR BOLOMETERS WITH THREE ASSUMED VALUES OF THE HEAT CAPACITY C.

C	G	ν_c	NEP photon	NEP phonon	NEP Johnson	NEP(10Hz) 1/f	NEP total
μJ/K	μW/K	cm^{-1}	$10^{-12} WHz^{-1/2}$	$10^{-12} WHz^{-1/2}$	$10^{-12} WHz^{-1/2}$	$10^{-12} WHz^{-1/2}$	$10^{-12} WHz^{-1/2}$
20	355	∞	1.4	12.7	12.7	13.1	22.3
1	18	∞	1.4	2.8	2.8	0.7	4.3
0.1	1.8	300	0.1	0.9	0.09	0.07	1.3

Figure Captions

Fig. 1. Infrared power loading P_{IR} and thermal conductance G for an ideal thermal infrared detector plotted as a function of the cutoff frequency ν_c of the cold low-pass filter. The detector is assumed to view 300 K background radiation with a throughput $A\Omega=10^{-2}$srcm^2 and perfect optical efficiency and to operate 10K above the heat sink temperature. The NEP of the ideal detector is shown along with the separate contributions from phonon noise and photon noise.

Fig. 2(a). Resistivity and temperature coefficient β of a YBCO film as a function of temperature, both measured with I=1mA.

(b) Normalized noise $S_V^{1/2}(10Hz)/\overline{V}$ as a function of temperature measured with I=10mA.

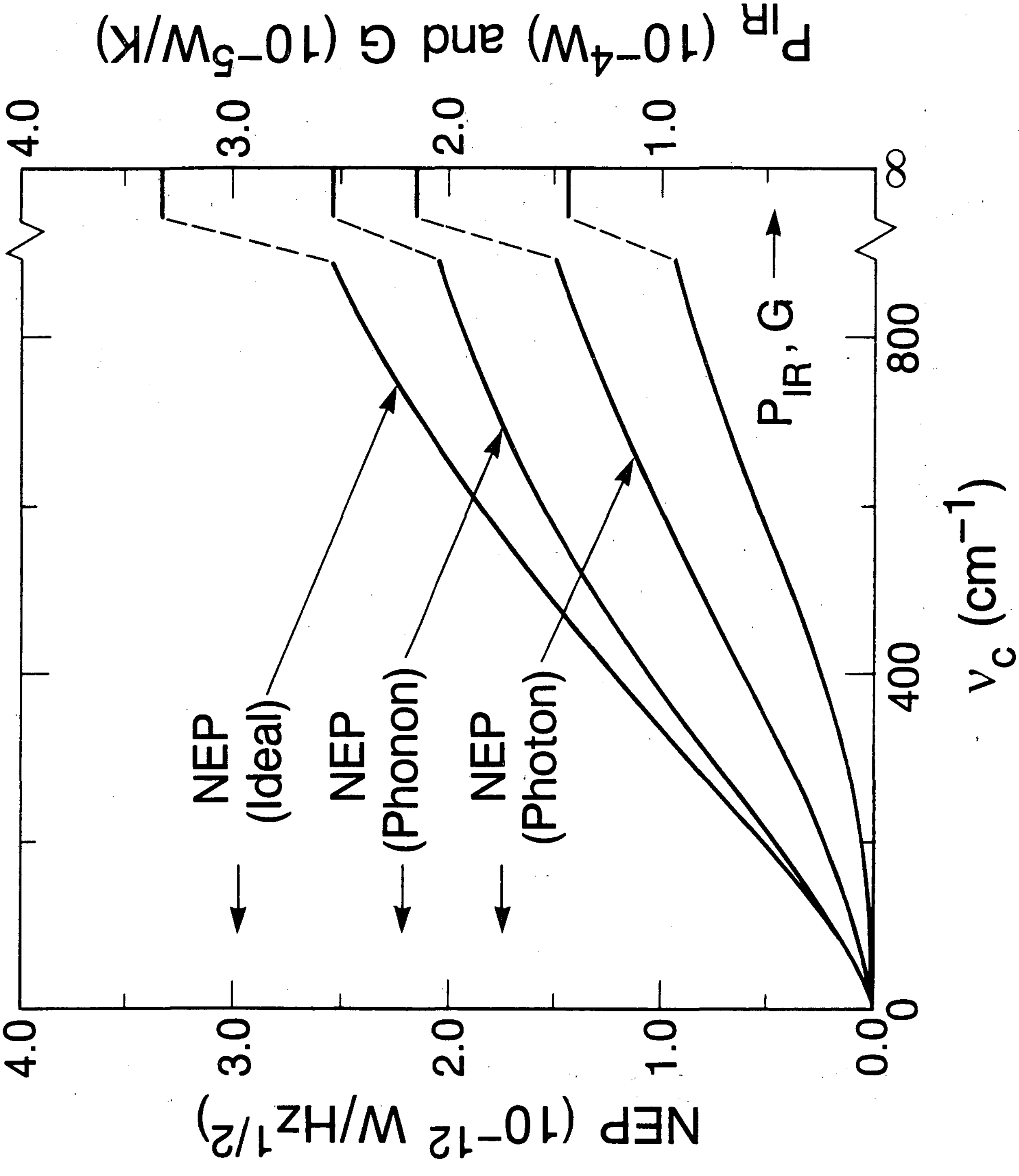

FIGURE 1

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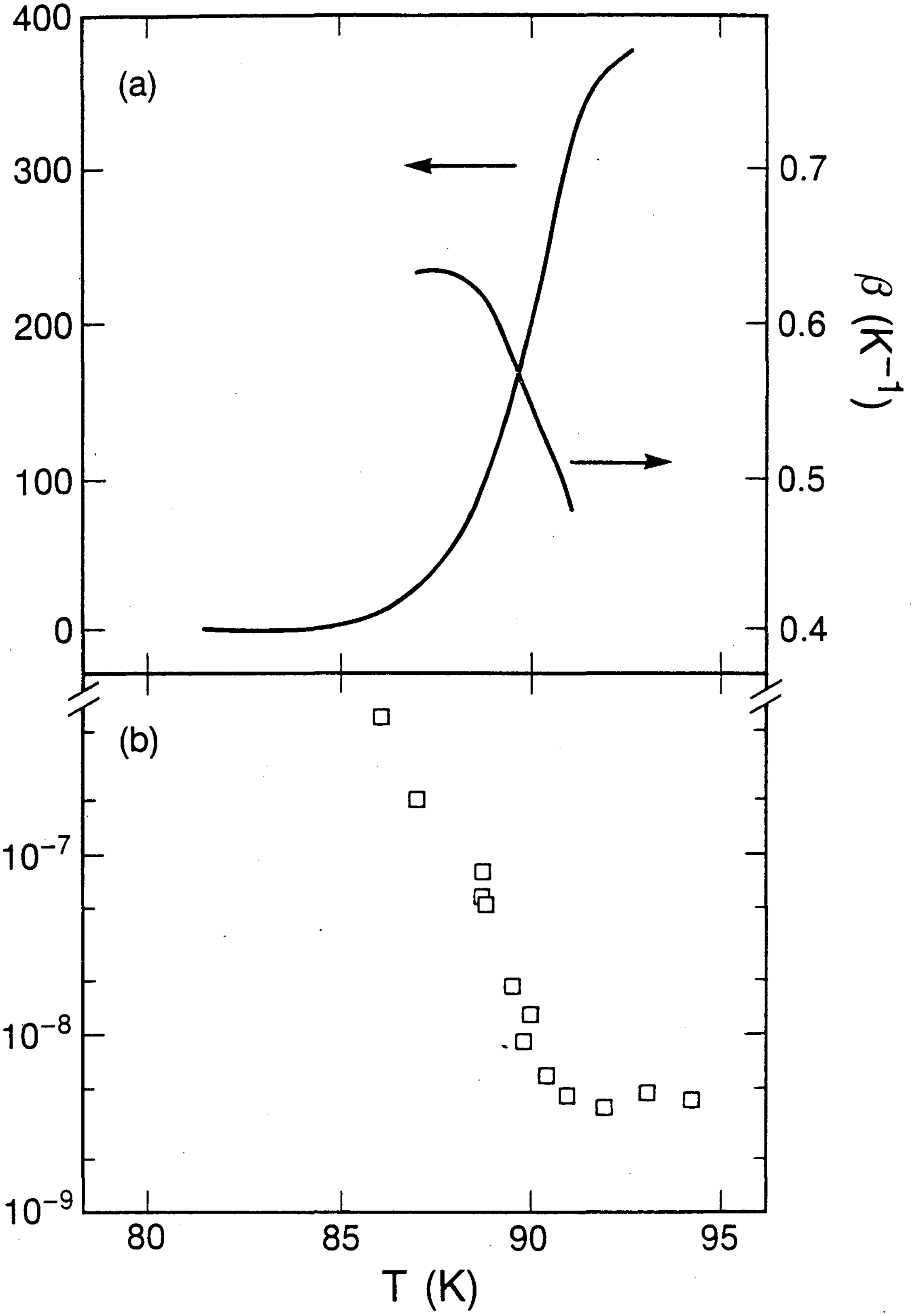

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FIGURE 2

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