Hyperconductivity in chilled beryllium metal

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It is shown that in the vicinity of 77 K beryllium has a superior specific conductance compared with the nominally excellent metallic conductors aluminum and copper. It is concluded that beryllium should be considered for some conduction applications, despite its well known toxicity problems.

Beryllium has several unusual and even unique properties when compared with other metallic conductors. It is a good conductor at room temperature (3.328 $\mu\Omega$ cm in polycrystalline form) compared with Al (2.24 $\mu\Omega$ cm) and Cu (1.64 $\mu\Omega$ cm). It has a Poisson ratio of 0.02–0.08 and an elastic modulus of 275–300 GPa,[1] has a high Debye temperature θ^2 (1481 K), a modest magnetoresistivity,[3] a high melting temperature (1575 K), and excellent thermal conductivity.[4] In a sense, Be is an hcp metallic form of diamond, sharing diamond's covalent $s-p$ bonding, strength, and phononic properties, but with the added feature of high electrical conductivity.

In this letter we focus on a figure of merit defined as the specific conductance (the ability of a material to conduct electrical current per kilogram). We show that Be is so superior in this regard compared to other metallic conductors at 77 K that it may have important new hyperconductivity[3] applications, despite its toxicity and expense.[5] Beryllium in the form of airborne fine particulates has a nasty toxicity which became notorious. This makes fabrication of Be a process requiring careful control, whose safety was embodied in specific laws even before awareness of other possible environmental problems had become so common. It is possible for such reasons that Be has perhaps been neglected and its unusual properties forgotten.

That most metals have lowered resistivity at low temperatures has been studied since at least the time of Matthiessen and Vogt[6] with the result that generally the resistivity of any metal is separable into two components:

$$\rho(T)=\rho_0+\rho_i(T), \tag{1}$$

where for reasonably pure materials ρ_0 is temperature independent and primarily due to residual impurities or surface scattering and $\rho_i(T)$ is due to the temperature-dependent occupation of fluctuating phononic, magnetic, or other dissipative vibronic modes. It is common[7] to plot the normalized resistivity $[=\rho(T)/\rho(298)]$ as a function of reduced temperature $t(=T/\theta)$. In this case the electrical resistivity of many metals falls on a single curve: an early triumph for solid-state physics and the Bloch–Grueneisen law. But this common practice precisely conceals the point we wish to emphasis here. In Fig. 1 we show the normalized resistivity for three samples of beryllium metal. The square boxes are an average $[\rho=(\rho_\perp+2\rho_\parallel)/3]$ of the single crystal data of Mitchell,[8] and the solid dots are from the polycrystalline data of Reich *et al.*[9] The small diamonds are new measurements of single-crystal Be along the direction perpendicular to the c axis. (On the basis of Mitchell's[8] single-crystal data, we expect the resistivity parallel to the c axis of our crystal to be at most a factor of two larger than that shown in Fig. 1, which would give an average $\rho\simeq 5/3\rho_\perp$.) These samples were grown by G. London and used for *dHvA* studies.[10,11] Note that we plot here the total residual resistivity in all cases, since this is the dissipative resistance seen by any power source. We have used the resistivity at 298 K to normalize all data plotted in Fig. 1. In the interesting temperature range near 77 K, the resistivity increases approximately as T^4. The non-Debye-like phonon spectrum of Be[12] and the possibility of umklapp processes contribution to $\rho(T)$ may explain the lack of a classical T^5 law in this temperature range.

The purity of the sample that showed a RRR $[=\rho(298)/\rho(4)]$ of 1200 (open diamonds in Fig. 1) was examined with particle induced x-ray emission (PIXE) using 3.0 MeV protons and Rutherford backscattering (RBS) using 2.0 MeV alpha particles. The bulk impurity content deduced from these measurements is given in Table I. The impurity content derived from the PIXE measurements assumed that the impurities were uniformly distributed throughout the Be sample. About 95% of the detected x rays were generated in the outermost 45 μm of that sample. The surface RBS measurements were unable to resolve individual fractions in the mass regions spanning the ranges Fe-Zn and Ag-Sn because of the roughness of the sample surface. The relative precision of the PIXE

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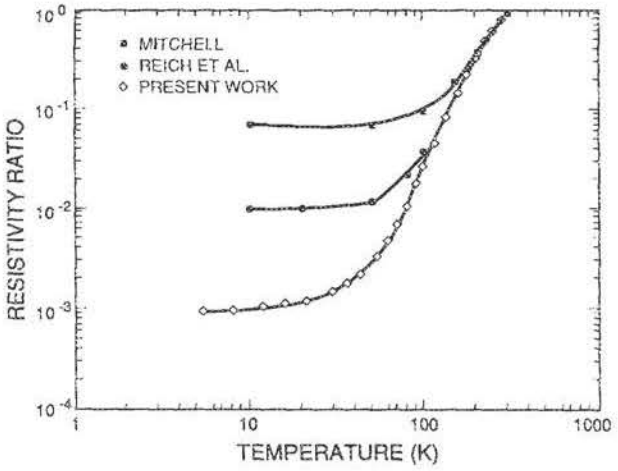

FIG. 1. Normalized resistivity of beryllium metal as a function of temperature. As discussed in the text, the sharp leveling off in the vicinity of 77 K is caused by the freezing out of phonon modes because of Be's high Debye temperature (1481 K).

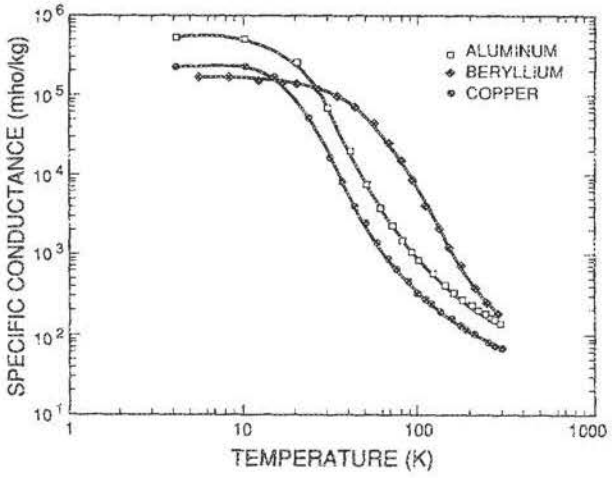

FIG. 2. Figure of merit as a function of temperature. As discussed in the text, we have used the ratio of the conductivity divided by the density for a 10 m wire. Beryllium shows promise in the vicinity of 77 K. Beryllium data correspond to those shown in Fig. 1 as open diamonds.

measurements is $\leqslant 5\%$, with an absolute uncertainty of $\pm 20\%$. The RBS surface measurements are accurate to $\pm 5\%$ and the RBS bulk measurements to $\pm 20\%$. The total impurity content of the sample was 6150 ppm (atomic fraction) of which 6000 ppm was oxygen and carbon as found in the outer 8000 A of the surface. It is difficult to extrapolate such a measurement to determine the bulk oxygen or carbon concentration. Nevertheless 6000 ppm is a reasonable upper limit. We have not made a study of which impurities cause the highest resistivity increase in Be, or of what techniques would remove them, although for further work or applications this is surely important. We conclude that the samples used in our investigation were certainly excellent for the time they were grown. However, they may not represent the metallurgical limit of what can be achieved in Be nowadays in terms of either impurity content, microstructure, or RRR.

TABLE I. Impurity analysis of 1200 RRR Be sample.

Element	PIXE (bulk) (ppm wt.)	RBS (surface) ($\times 10^{15}$ at/cm^2)	RBS (bulk) (ppm wt.)
C		260	5300
O		53	3560
Si		1.7	
Cl	4.42	4.5	
K	13.7		
Cr	2.95		
Mn	2.01		
Fe	18.1		
Co	46.7		
Ni	48.8	11.2	
Cu	636		700
Zn	86.3		
Ag	141	0.45	266
Sn	215		
Pb	29.4	0.052	

The noteworthy feature of Fig. 1 is that all three sets of Be data show a substantial leveling off in the resistivity near 77 K. This leveling-off does not happen until nearly 20 K in other good conductors such as Al or Cu. The main reason is not hard to discern: Be has a substantially higher θ by a factor of 3 or 4 than all the others. At and below boiling nitrogen temperature, most phonons of Be are frozen out, exposing the effects of residual impurities on the resistivity.

Based on the results of Fig. 1, we were intrigued to see how well Be compared to other materials near 77 K. To make a useful comparison for conducting materials, we propose a figure of merit (FOM) which is the specific conductance (mhos per kilogram). We envisage a task of making a 10 m conducting bar from 1 kg of material with the maximum conductance. As is clear, such a FOM essentially scales the cross-sectional area A of the bar: the lighter the material, the thicker the cross section and the smaller the bar's resistance. For a fixed length L, this FOM devolves into the ratio of the temperature-dependent conductivity to that of the density:

$$\mathrm{FOM}=\frac{G}{M}=\frac{A\sigma/L}{\delta AL}=\frac{\sigma}{\delta L^2}, \tag{2}$$

where σ is the conductivity and δ is the density.

In Fig. 2 we show the log of the FOM as a function of the log of the temperature for Cu, Al, and Be. For Cu and Al, we have extracted the temperature-dependent part of $\rho(T)$ from the Landolt–Boerstein Tables.[13] The small dots are a FOM for Be derived from Fig. 1. As can be seen, in the vicinity of 77 K, there is about a factor of 10 improvement in the specific conductance of Be of 1200 RRR compared with 3500 RRR Al. Copper of RRR 3400 has a poorer FOM everywhere. Another way of stating the same results: in the vicinity of 77 K, one could save about 90% of the conductive mass by using Be conductors even when compared with Al. If we had used data for extremely pure Cu or Al(RRR > 20 000), the plotted specific conductance

would rise below 20 K by about an order of magnitude. Materials of such high purity are expensive, difficult to fabricate, and difficult to use. But in making plots of such FOMs almost nothing would change in the vicinity of 77 K from that given in Fig. 2. Hyperconducting applications for Be span the range 40–200 K.

The results we have given here are tailored for an actively cooled system. We have not considered more complicated and dynamical system parameters such as the power transfer time, relative cost, refrigeration efficiency, cooling method, load level, and system reliability. Nevertheless, in space-borne applications, Be conductors may have significant benefit compared with Cu or Al. Since the radiant temperature of space is about 80,[14] Be conductors might be useable without any cooling.[15] Similarly Be may have significant impact on advanced naval, land, or air applications where weight savings in power transfer is important. Futhermore, with bulk high-temperature superconductors presently limited to a critical current density of $10^8 A/m^2$, beryllium conductors may be of superior and more immediate utility for many conduction applications near 77 K.

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