GALVANOMAGNETIC PROPERTIES OF GRAPHITE FROM 10 TO 23T*

W.H. Lowrey[+]
Naval Research Laboratory & I.L. Spain
Washington, D.C.
University of Maryland
College Park, Md.

1. Introduction

Measurements of the magnetoresistance ($\rho xx(Bz)$ and $\rho zz(B_z)$) and Hall resistivity ($\rho yx(B_z)$) of highly oriented pyrolytic graphite have been made in steady magnetic fields up to 23T. The starting material (supplied by Dr. A.W. Moore of Union Carbide) is the best quality pyrolytic graphite reported to date, as evidenced by the similarity of its electronic properties to those of natural single crystals. Details of measurements on the material for $B<10T$ will be found elsewhere (1,2). We report here the first work on graphite in the field range at 300K, and the first at 77K other than pulsed-field work (3). Also, new results at 4.2K and 1.1K are reported.

While the experimentally measured quantities are resistivities, the conductivities are needed for comparison with theory. We use the standard transformation and calculate $\sigma xx(B_z)$, $\sigma yx(B_z)$ and $\sigma zz(B_z)$.

2. $\sigma xx(B_z)$.

Classical theory predicts σxxB^2 saturates in the high field limit. However McClure and Spry (4) found $\sigma xx \propto B^{-1}$ at 4.2K in (pulsed) fields up to 16T. Later, Woollam et al(5,6) showed ρxx increases more slowly than B in the high-field region. Our results are shown in Fig. 1 in the form σxxB vs. B. At 298K σxxB decreases and seems to have reached a constant value of ~160kT/Ωm at 23T. The data at 4.2K and 77K are remarkably similar, both showing a minimum at ~13-14T and the 4.2K data shows some structure at higher fields. The data at 4.2K agree with Woollam's observation, and we see a continuing approach to saturation in ρxx at high fields. We also note $\sigma xx(B,T=4.2K) < \sigma xx(BT=1.1K)$, in accord with earlier results below 12T (7).

3. σxy

In simple theory $\sigma xyB =$ (P-N)$|e|$ in the high-field limit. McClure and Spry [4] found σxyB to be constant above about 8T. We find (Fig. 2) that $\sigma xyB(T=4.2K)$ shows a maximum at ~12T then decreases with decreasing slope out to 23T. Deviations from a smooth curve are seen at this temperature and at 1.1K. The curve at 1.1K has pronounced "bumps" at ~18T and ~20.5T. A maximum is also seen at ~11.5T but it is much weaker. At 77K, σxyB shows a general increase with a large "bump" at ~15.5T, and possibly a smaller one at ~21T. At 298K, σxyB increases uniformly with decreasing slope.

4. ρzz

Earlier work on longitudinal magnetoristance in graphite up to 8T [8] indicated saturation for temperature of 77K and below. Our results show not saturation, but a maximum in ρzz(Fig. 3). At 298K this maximum occurs at 16.5T. At 77K, the maximum occurs below 10T. At this temperature ρzz falls linearly with B above 15T. The data at 1.1K show a weak maximum at ~20T. No maximum is seen in the 4.2K data up to 23T.

5. Anisotropy

In measuring the conductivity anisotropy $\sigma xx/\sigma zz$ as a function of field, we have used the approximation $\sigma zz = \rho zz^{-1}$, which is a good approximation in this field range. The results at 298K and 77K (Fig. 4) are remarkably similar in light of the vast difference between σxx(298K) and σxx(77K) and between σzz(77K);note that at 23T the anisotropy changes by less than 5% in going from 298K to 77K. The results for 4.2K and 1.1K are qualitively similar, both showing anisotropy which is decreasing with decreasing slope. The anisotropy at 1.1K is larger than at 4.2K (~50% larger at 22T). This increase in anisotropy as the temperature is lowered from 4.2K to 1.1K follows from our observation that while $\sigma xx(B,T=4.2K) < \sigma xx(B,T=1.1K)$, $\sigma zz(B,T=4.2K) > \sigma(B,T=1.1K)$.

Conclusions

The present results show structure in the galvanomagnetic properties above the quantum limit. It is possible that this is related to magnetophonon oscillations. A measurement of the variation of the amplitude of oscillation with temperature would be helpful in determining if this surmise is correct. This would require an A-C technique.

The behavior of σxx and σxy in very high fields is of great interest, particularly the approximately linear dependence at 1.1 and 4.2K. A revised calculation of the conductivity in this regime is called for.

Finally, the conductivity anisotropies reported here are smaller than any reported for highly oriented graphite (either natural or synthetic) and suggest that defects are not responsible for the high values of $\sigma xx/\sigma zz$ found at low field in pyrolytic materials (The anisotropy of the present samples was ~ 3,000 at 298K rising to ~10^5 at 1.1K.).

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+ NRC Resident Research Associate

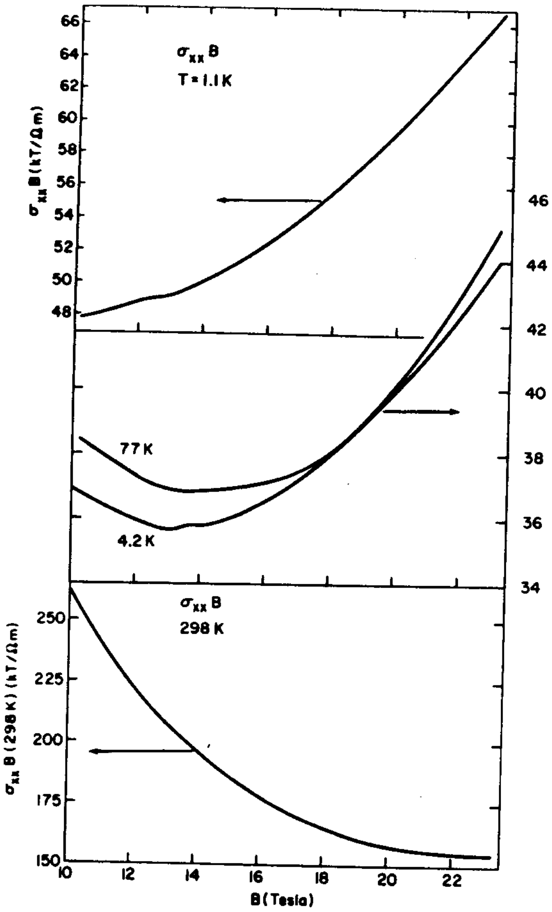

Fig. 1. σxx.B at 1.1, 4.2, 77 and 298K.

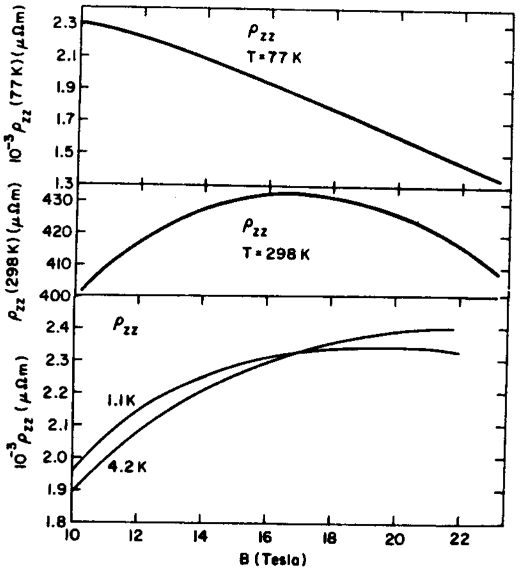

Fig. 3. ρzz at 1.1, 4.2, 77 and 298K.

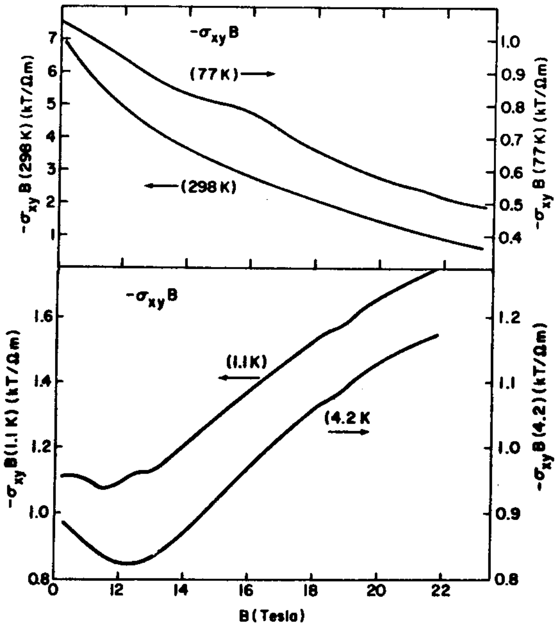

Fig. 2. σxy.B at 1.1, 4.2, 77 and 4.2K.

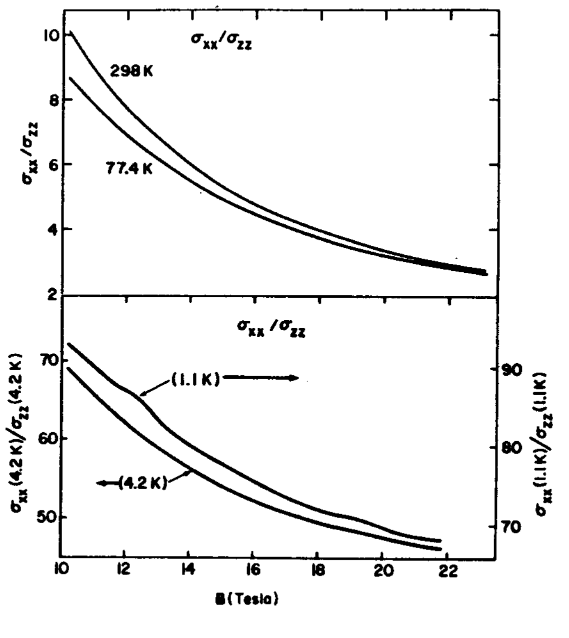

Fig. 4. The conductivity anisotropy ratio as a function of field (σxx/σzz) at 1.1, 4.2, 77 and 298K.