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Authors
Jackson, CM
Grüner, G
Fisk, Z
et al.

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Microwave conductivity of SmB_6

C. M. Jackson and G. Grüner
Department of Physics, University of California, Los Angles, California 90024

Z. Fisk
Los Alamos National Laboratories, Los Alamos, New Mexico 87545

S. von Molnar
IBM Thomas J. Watson Research Center, Yorktown Heights, New York 10598
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Microwave (9-GHz) conductivity measurements are reported in the intermediate-valence compound SmB_6. The absence of a frequency-dependent conductivity strongly suggests that a gap develops in the density of states at low temperatures, in agreement with earlier transport and optical studies.

Many studies of the energy gap in the intermediate-valence (I-V) compound SmB_6 at E_F, the Fermi energy, have appeared in the literature recently.[1] The reason for this activity is twofold. SmB_6 is the only I-V material in which an energy gap has been observed[2] and the origin of the gap remains controversial. The existence of the gap in SmB_6 was first postulated on the basis of resistivity and Hall-effect measurements.[3] Subsequent transport[4,5] and thermoelectric power[5] measurements were in substantial agreement with the earlier experimental results. More direct evidence for gap structure comes from NMR,[6,7] point contact,[8] and tunneling[9] spectroscopies, and infrared transmission experiments.[1,10] All of these measurements lead to gaps smaller than $\simeq 10^{-2}$ eV, the most reliable figure being approximately 3×10^{-3} eV from optical measurements.[1] Such measurements have not been able to distinguish between the various alternatives for the origin of the gap, however, which include hybridization[11] of the narrow f and the broader d bands on Sm, and Wigner crystallization of the conduction electrons in a disordered medium,[12,13] where the disorder is produced by defects and impurities. Whereas the hybridization gap would not be expected to be temperature dependent, it is suggested in Ref. 13 that the Wigner gap shrinks with increasing temperature above 20 K. We have consequently reexamined the transport in SmB_6 in an effort to gain additional understanding of the origin of the energy gap in this material.

In this Brief Report we describe our microwave conductivity measurements in SmB_6. We do not find a frequency dependence at temperatures below 50 K where both the dc and the microwave conductivity can be described by an activated behavior. As both a stongly disordered material [where an exponential temperature dependence of $\rho(T)$ is due to carrier excitations above the mobility gap while states below the mobility gap are localized and a Wigner crystal is expected to display strongly frequency-dependent response, we conclude that our microwave measurements strongly suggest a gap in the single-particle excitation spectrum at low temperatures.

The microwave (9.14 GHz) measurements used the contactless cavity perturbation technique of Buravov and Shchegolev.[14] The conductivity of the sample was determined from the normalized frequency shift (δ) and change in $Q(\Delta)$ of a resonant cavity, obtained by inserting the sample into and removing it from the cavity at every temperature. The sample was placed in a node of E-field maximum, oriented with the long axis parallel to the E field in a TE_{011} mode of a cylindrical cavity. An X-band sweeper was used to drive the frequency through the resonance, and a significant signal-to-noise ratio was achieved by taking advantage of the additional frequency stability gained by triggering a signal averager with a tunable reference cavity. The sample cavity was placed in an exchange gas can, located in a standard He cryostat. The sample used for these measurements was also used for the measurements described in Ref. 1. The single crystals were grown by the Al flux method.[15]

In the microwave analysis, when the conductivity of the material or the size of the sample are both so large that the E field only penetrates a fraction of a sample diameter characterized by a classical skin depth, the skin effect analysis[16] is appropriate. In this limit, the shift δ is determined only by the sample dimensions, and

$$\delta = \frac{\alpha}{N} \ , \tag{1}$$

where α is the filling factor, and N is the depolarization factor.

In this limit no information about the dielectric constant can be obtained, and the conductivity is related to the change in $Q(\Delta)$ by

$$\sigma = \frac{\alpha^2}{N^4}\frac{9\pi^2 f_0^3 b^2 \epsilon_0}{28c^2(\Delta/2)^2} \ , \tag{2}$$

where f_0 is the resonant frequency, b is the largest sample diameter, ϵ_0 is the permittivity of free space, and c is the speed of light. Figures 1(a) and 1(b) show the temperature dependence of the cavity shift and absorption, respectively. The shift is independent of temperature and is in agreement with that calculated from the sample size and the conductivity, assuming a highly conducting behavior as shown by the dc conductivity measurements on the same sample.[1] The sample size, $5.33\times0.79\times0.66$ mm^3, is much larger than the classical skin depth of 8×10^{-4} mm, predicted from the dc conductivity at room temperature of 5×10^3 $(\Omega\,\mathrm{cm})^{-1}$. At 4.2 K, when the dc conductivity is about 5 $(\Omega\,\mathrm{cm})^{-1}$, the sample diameter is still greater than the skin depth and the skin effect regime analysis is still appropriate. Both the calculated skin depths and the constant measured shift demonstrate that the skin depth limit is appropriate. Consequently, the dielectric constant cannot be evaluated and the

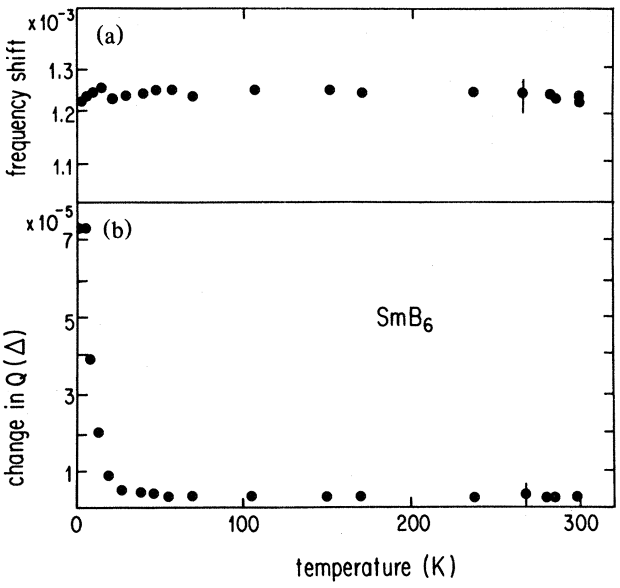

FIG. 1. Temperature dependence of cavity shift and absorption for SmB_6 measured at 9.1 GHz. The filling factor $\alpha = 1.01 \times 10^{-4}$ and the sample size was $5.33 \times 0.79 \times 0.66$ mm^3. The room-temperature microwave conductivity was found to be 3×10^3 $(\Omega\ \mathrm{cm})^{-1}$.

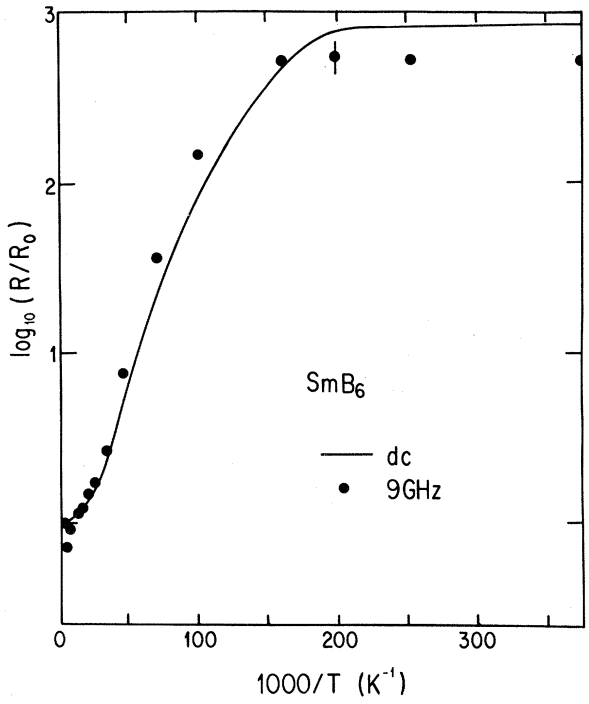

FIG. 2. Temperature dependence of the dc and microwave resistivity (solid line from Ref. 1) and the 9-GHz resistivity (solid circles). The data were normalized at room temperature. The microwave data were calculated from the shift and the change in Q (Fig. 1) and Eq. (2).

conductivity is given by Eq. (2). In Fig. 2, we show both the dc resistivity (solid line from Ref. 1, sample from the same preparation batch) and the microwave resistivity (solid circles) in a $\log_{10}\rho$ vs $1/T$ representation.

We do not observe any frequency dependence down to about 5 K where the dc conductivity flattens off and the microwave conductivity is slightly (only a factor of about 2) larger than the dc conductivity. This difference below 5 K is likewise outside the error of the microwave conductivity measurements. The overall temperature dependence of the conductivity between 5 and 50 K is well described by the expression

$$\sigma = \sigma_0 \exp(-\Delta/kT) + \sigma_1 \ , \tag{3}$$

where σ_0 and σ_1 are the high- and low-temperature limits of the conductivity and $\Delta = 5 \times 10^{-3}$ eV. This may be interpreted as a gap in the density of states[3,4] or as a mobility gap;[17] both assumptions are in agreement with an exponentially temperature-dependent conductivity. In the case of a mobility gap, localized electron states exist in the gap region.[17] While they do not contribute to the dc conductivity, they lead to a strongly frequency-dependent response. Indeed, frequency-dependent studies are the most clearcut evidence for localized states in the gap region. From the absence of any strong frequency dependence found in SmB_6, above 5 K, and a weak frequency dependence below 5 K, we conclude, therefore, that only a very small fraction of the states can be localized in the gap region in SmB_6. This small number of states is most probably responsible for the flattening of the dc conductivity at very low temperatures where σ is most probably dominated by either phonon-assisted hopping between localized (impurity) states in the gap region or by a small activation energy associated with these states. The observation of a small frequency-dependent conductivity in this low-temperature region is in full accord with a model of phonon-assisted hopping. We note that for variable range hopping the temperature dependence of the dc conductivity is expected to be of the form

$$\sigma = \sigma_0 \exp(-T_0/T)^{1/4} \ . \tag{4}$$

However, over the limited range of temperatures available, the temperature-independent conductivity observed in SmB_6 below 6 K remains unresolvable, as shown by Kasuya *et al.*[12]

It has also been suggested that a disordered Wigner crystal[13] is formed at low temperatures due to strong electron-electron correlations. Such states are similar to those observed in spin-density-wave or charge-density-wave ground states. Such collective states which do not contribute to the dc conductivity because they are pinned by impurities also lead to strongly frequency-dependent response,[18] and, furthermore, lead to dielectric constants often in excess of $\epsilon = 10^8$. Both the absence of a frequency-dependent conductivity in the temperature region where σ shows an activated behavior and the absence of a giant dielectric constant then demonstrate that such collective modes do not exist, or are so strongly pinned that the pinning energy is comparable with or larger than the particle gap.

In conclusion, our microwave conductivity results strongly favor an interpretation in terms of a gap in the density of states, i.e., a hybridization gap. With a small amount of impurity states in the gap region no evidence for strong disorder or a collective Wigner crystal was found by our measurements.

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[1]See, for example, S. von Molnar, T. Theiss, A. Benoit, A. Briggs, J. Flouquet, J. Ravex, and Z. Fisk, in *Valence Instabilities,* edited by P. Wachter and H. Boppart (North-Holland, Amsterdam, 1982), p. 389.

[2]SmS has to be pressurized and TmSe orders magnetically.

[3]J. C. Nickerson, R. M. White, K. N. Lee, R. Bachmann, T. H. Geballe, and G. W. Hull, Jr., Phys. Rev. B 3, 2030 (1971).

[4]J. W. Allen, B. Battlog, and P. Watcher, Phys. Rev. B 20, 4807 (1979).

[5]M. Kasaya, H. Kimura, Y. Isikawa, T. Fujita, and T. Kasuya, in *Valence Fluctuations in Solids,* edited by L. M. Falicov, W. Hanke, and M. B. Maple (North-Holland, Amsterdam, 1981), p. 251.

[6]O. Pena, M. Lysak, and D. E. MacLoughlin, Solid State Commun. 40, 539 (1981).

[7]M. Takigawa, H. Yasuoka, Y. Kitaoka, T. Tanaka, H. Nozaki, and Y. Ishizawa, J. Phys. Soc. Jpn. 50, 2525 (1981).

[8]I. Frankowski and P. Wachter, in Ref. 1 , p. 309.

[9]G. Güntherodt, W. A. Thompson, F. Holtzberg, and Z. Fisk, Phys. Rev. Lett. 49, 1030 (1982).

[10]B. Battlog, P. H. Schmidt, and R. M. Rowell, in Ref. 5, p. 267.

[11]For a recent summary, see the section on the ground-state properties in Ref. 1, pp. 11–61, and N. F. Mott, p. 403.

[12]T. Kasuya, K. Takegehara, T. Fujita, T. Tanaka, and E. Bannai, J. Phys. (Paris) Colloq. 40, C5-308 (1979).

[13]T. Kasuya, M. Kasaya, K. Takegehara, T. Fujita, T. Goto, A. Tamaki, M. Takigawa, and H. Yasuoka, J. Magn. Magn. Mater. 31–34, 447 (1983).

[14]L. I. Buravov and I. F. Shchegolev, Prib. Tekh. Eksp. 4, 171 (1971) [Instrum. Exp. Tech. (USSR) 14(2), 171 (1971].

[15]D. Fisk, A. S. Cooper, P. H. Schmidt, and R. W. Castellano, Mat. Res. Bull. 7, 283 (1972).

[16]N. P. Ong, J. Appl. Phys. 48, 2935 (1977).

[17]N. F. Mott and E. A. Davis, *Electronic Process in Non-Crystalline Materials* (Clarendon, Oxford, 1971).

[18]G. Grüner, L. C. Tippie, J. Sanny, W. G. Clark, and N. P. Ong, Phys. Rev. Lett. 45, 935 (1980); P. A. Lee, T. M. Rice, and P. W. Anderson, Solid State Commun. 14, 703 (1974).