between RRS and hot luminescence has been recently elucidated by Shen.[24]

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*Present address: Thomas J. Watson Research Center, P. O. Box 218, Yorktown Heights, N.Y. 10598.

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Pseudo-One-Dimensional Conductor—Plastically Deformed CdS†

C. Elbaum

Department of Physics and Metals Research Laboratory, Brown University, Providence, Rhode Island 02912

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Extraordinary anisotropy (10^8) and unusual temperature dependence of the electrical conductivity have been observed in plastically deformed CdS. These features are attributed to metallic-type conductivity along a pseudo-one-dimensional system consisting of arrays of dislocations. The observed temperature dependence of the conductivity is consistent with a Peierls-type metal-semiconductor transition at 125 K.

Extraordinary anisotropy and unusual temperature dependence of the electrical conductivity of plastically deformed single crystals of CdS (hexagonal) are reported. The observed features are attributed to metallic-type conductivity in a pseudo-one-dimensional system consisting of arrays of dislocations. This interpretation of the experimental results is related to earlier work[1] in which the general problem of electronic energy states of dislocations in compound semiconductors was discussed in some detail.

The experiments are carried out on single crystals of CdS with a room-temperature (298 K) electrical conductivity (in the dark) of $\sim 10^{-6}$ $(\Omega\ \mathrm{cm})^{-1}$; the concentration and type of impurities are not known. Specimens in the shape of rectangular parallelepipeds are prepared with approximate dimensions $3\times4\times5$ mm^3 along directions designated respectively by x, y, and z. The longest (z) and intermediate (y) directions are parallel, respectively, to the $[21\bar{3}0]$ and $[0001]$ crystallographic directions. These specimens are deformed plastically by means of a static compressive load parallel to the x (shortest) dimension. The deformation is carried out at ~600°C for about 20 min, under an atmosphere of helium.[1] The samples used for the conductivity measurements described below were deformed to a total strain of 25%. The deformation (compression) along the x direction resulted in an elongation parallel to the z ([$2\bar{1}\bar{3}0$]) direction, with no measurable change along the y ([0001]) direction. These features, and evidence obtained from x-ray diffraction studies following deformation, are consistent with glide on the ($\bar{1}100$) plane along the [$11\bar{2}0$] direction. It follows from these crystallographic characteristics that the deformation process is expected to result in an increase in the density of screw dislocations parallel to a direction within ~10° of the z direction, and an increase in the density of edge dislocations parallel to the y direction.

After deformation the dc electrical conductivity of the specimens was measured as a function of temperature, along all three directions x, y, z, using indium contacts and a Keithley electrometer, model 610A. The minimum and maximum resistances that could be conveniently measured with this arrangement are ~1 and ~10^{10} Ω, respectively. Many of the measurements were checked over a range 10^2 of applied current and for possible effects of reversing the current direction—no measurable dependence of the resistance on current or on polarity was found. The temperature range covered in these measurements is ~20 to 298 K. A total of three samples prepared in the manner described above were tested. As far as the magnitude of the conductivities is concerned, the results are reproducible to within better than a factor of 2, which is essentially the uncertainty in the actual area of the indium contacts. The general features of the temperature dependence of the conductivity along the z direction (see further details below) are reproducible to within a few percent.

The main features of the experimentally observed conductivity, following plastic deformation, are as follows:

(1) The conductivity along the z (longest) direction has changed to ~3 $(\Omega\ \mathrm{cm})^{-1}$ at room temperature.

(2) The conductivity, at room temperature, along the x and y directions is ~10^{-6} $(\Omega\ \mathrm{cm})^{-1}$.

(3) The effect of the deformation has thus brought about an anisotropy in excess of 10^6, at room temperature.

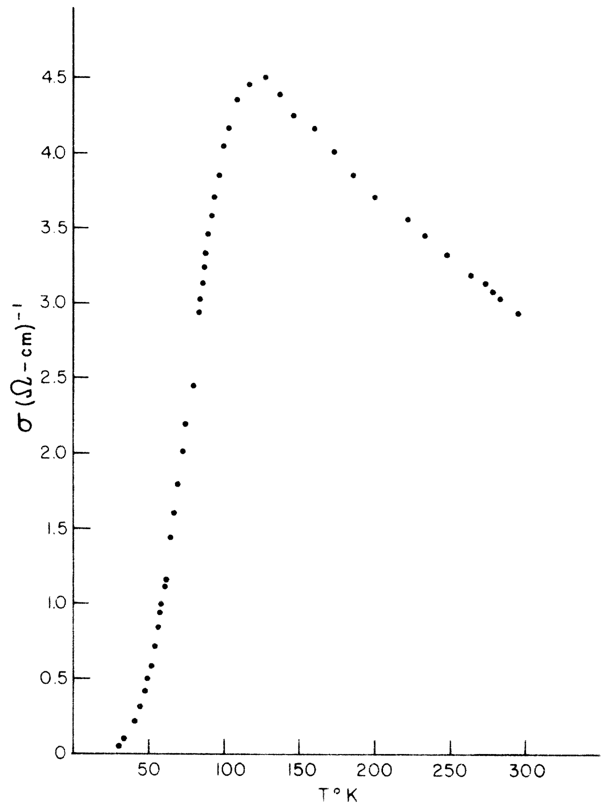

FIG. 1. Electrical conductivity along the z direction (see text) of plastically deformed CdS (25% plastic strain), as a function of temperature.

(4) In the z direction, the conductivity displays the temperature dependence shown in Fig. 1. The conductivity first increases with decreasing temperature, reaches a maximum at 125 K, then decreases exponentially (see Fig. 2).

(5) In the x and y directions the conductivity *decreases* monotonically and at 125 K (the temperature of the conductivity maximum along the z direction) it reaches a value of ~10^{-8} $(\Omega\ \mathrm{cm})^{-1}$. Thus, at 125 K the anisotropy is in excess of 10^8.

(6) Along the z direction, the conductivity σ varies with temperature, in the range 298 to 125 K, as T^{-n} with $n = 0.315 \pm 0.01$. Below ~100 K the conductivity decreases exponentially with decreasing temperature [$\sigma = \sigma_0 \exp(-\Delta/k_B T)$] with $\Delta = 210 \pm 5$ K in units of k_B ($\Delta = 0.018$ eV) (Fig. 2).

Among the observations listed above, the high conductivity [3–5 $(\Omega\ \mathrm{cm})^{-1}$], by itself, could be accounted for in terms of a high concentration of impurities; however, the extraordinary anisotropy in the conductivity seems to rule out this interpretation. It is proposed, therefore, that CdS deformed in the manner described acquires

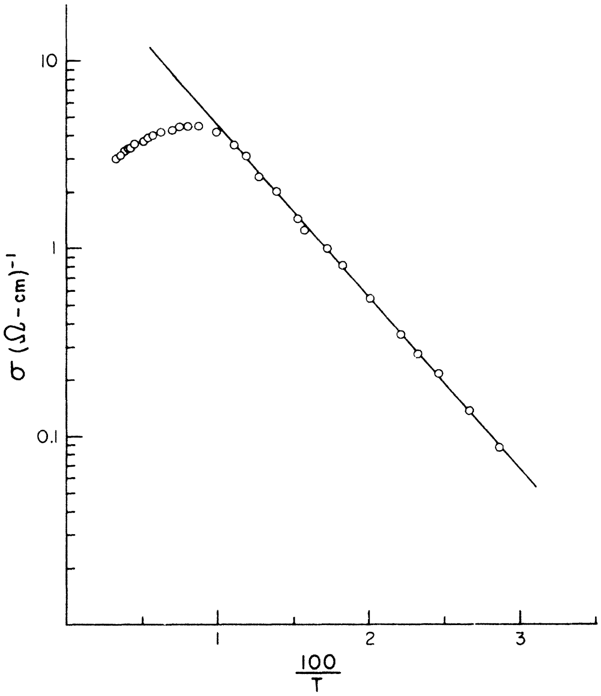

FIG. 2. Log conductivity as a function of $100/T$ for the data of Fig. 1. The slope of the straight line corresponds to an energy in units of k_B of 210 K (0.018 eV).

the characteristics of a pseudo-one-dimensional system. From the geometric features discussed, a high density of screw-type dislocations is expected to occur in a direction nearly parallel to the z direction, while edge-type dislocations are expected to be parallel to the y (low-conductivity) direction. The high conductivity is attributed, therefore, to conduction along screw dislocations thought of as pseudolinear chains with partially filled electronic energy bands.[1] Although no mechanism is suggested for the observed $\sigma \propto T^{-0.3}$ for $T > 125$ K, the temperature dependence of the conductivity σ is not inconsistent with the above interpretation. In particular, the exponential decrease of σ with temperature below ~100 K is suggestive of a Peierls-type transition.[2] It may be noted, in this connection, that if the temperature at which the maximum in conductivity occurs, i.e., 125 K, is identified as the transition temperature T_c, its relation to the observed gap Δ of 210 K is

$$k_B T_c \sim 0.6\Delta.$$

A theoretical relation between T_c and the gap parameter Δ_0 at $T = 0$ K, for the Peierls transition, is[3]

$$k_B T_c = 0.57\Delta.$$

An evaluation of the proposed conductivity along screw dislocations, σ_D, is difficult because of the large uncertainty in the dislocation density. An order-of-magnitude estimate, based on an assumed screw dislocation density of 10^{10} lines/cm^2 of cross section and an effective dislocation radius of 5×10^{-8} cm, gives

$$\sigma_D \sim 10^5\ (\Omega\ \mathrm{cm})^{-1},$$

which is comparable to "good" metallic conductors. Furthermore, on the assumption that there is an electron concentration in the dislocations of $\sim 10^{20}/\mathrm{cm}^3$, one obtains an electron mean free path along the dislocations of $l \sim 10^{-5}$ cm. This is the average spacing of edge dislocations intersecting the screw dislocations, on the assumption that the density of both types of dislocations in the deformed crystal is the same. These intersections can be thought of, therefore, as the dominant scattering centers for the moving electrons. While these estimates of σ_D and l do not constitute any more than supporting evidence for the proposed model, it is emphasized that they are based on highly plausible features of the physical system.

With regard to what might constitute a suitable, periodic "lattice" distortion required for the proposed Peierls transition, it is noted that screw dislocations with the Burgers vector along the $\langle 11\bar{2}0\rangle$ direction in CdS can split into pairs of partial dislocations. The periodicities along the dislocation lines characteristic of the partial dislocations are different from that corresponding to the whole dislocation. In particular, a transition from partial dislocations at high temperature to whole dislocations at low temperatures would be accompanied by an *increase* of the period along the dislocations, with a corresponding *decrease* of the period in reciprocal space. The details of the energetics of such a change, with particular reference to the temperature dependence of the energy of stacking faults involved in dislocation splitting, are now being examined.

Finally, it is noted that the temperature dependence of the conductivity along the z direction (Fig. 1) is qualitatively similar to that usually observed in tetrathiofulvalinium tetracyanoquinodimethane (TTF-TCNQ) (i.e., in the absence of the occasionally observed divergence) and identified with pseudo-one-dimensional transport.[4] Whether dislocations in semiconductors are candidates for pseudo-one-dimensional superconductors is not clear, but it is a tempting, if remote, possibility.

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Critical Exponents of the Eight-Vertex Model in Any Dimension

Bill Sutherland
Physics Department, University of Utah, Salt Lake City, Utah 84112
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Results on the critical temperature of the eight-vertex model in any dimension are combined with the Griffiths inequalities for correlations in Ising ferromagnets to yield relations between critical exponents of eight-vertex models of differing dimensionality. Then Baxter's exact results for the two-dimensional, eight-vertex model are able to yield information on the three-dimensional exponents of these models. As in the planar eight-vertex models, the exponents in all dimensions probably vary continuously with the energy parameters.

Within recent years, there has been a renewed and intensive study of lattice models for hydrogen-bonded crystals. This sudden interest has several explanations: realization of the need both experimentally and theoretically to study more diverse behavior than that of magnetic systems and Ising models, and recent spectacular advances in producing exact solutions to nontrivial models. Exact solutions began with Lieb's calculation of the entropy of two-dimensional (2D) ice[1]; then there followed solutions by Lieb and by the author for 2D ferroelectrics constrained by the "ice rule,"[2] and culminated in Baxter's solution for the 2D, eight-vertex problem.[3] The state of the art is now such that these hydrogen-bonded models include as a special case Onsager's original solution of the 2D Ising problem.[4] A separate line of development has produced the solution of the 2D ice-rule model in an arbitrary 2D electric field.[5]

Undoubtedly the full implication of these exact solutions for our general understanding of critical phenomena is not yet understood. The original peculiar properties of the 2D ice-rule models were dismissed as artefacts of the ice rule itself. Then Baxter was able to violate the ice rule with the 2D, eight-vertex model, and he found the critical exponents to vary continuously with the interaction strengths. This was quite unexpected and, on the face of it, would seem to contradict "universality,"[6] or "naive universality" as one would now say. Kadanoff and Wegner[7] offered an explanation for the 2D, eight-vertex model, within the context of scaling theory, which allowed for variation of critical exponents, and it is the author's understanding that the modern renormalization-group approach is able to encompass such previously exotic behavior; however, such behavior is not expected to be the norm.

In a recent Letter[8] I determined the critical temperature T_c for the eight-vertex model in any dimension. In this Letter I combine these results with certain powerful inequalities first due to Griffiths,[9] and then generalized by Kelly and Sherman,[10] to yield rigorous inequalities relating critical exponents of eight-vertex models of differing dimensionality. The results are strong evidence for continuously varying exponents for the eight-vertex model in any dimension; this is discussed at the end of the Letter.