

samples containing As, ionized impurity concentration was changed by a factor of ten by adding Ga. This resulted in an increase in the apparent ionization energy as determined from the slope of the carrier concentration curve. This effect is in the right direction but somewhat too large to be entirely accounted for by predictions of theory (based on spherical energy surfaces)<sup>5</sup> regarding the dependence of  $\mu_H/\mu$  upon ionized impurity scattering. The experimental results thus suggest that the ionization energies determined are somewhat too high, particularly for those samples having  $10^{18}$  or more ionized impurities at low temperatures. However, since most of the samples have about the same ionized impurity concentration at low temperatures the calculated ionization energies are comparable on a relative basis and the variations found should be significant.

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<sup>1</sup> Morin, Maita, Shulman, and Hannay, *Bull. Am. Phys. Soc.* **29**, No. 5, 22 (1954).

<sup>2</sup> C. S. Hung and J. R. Gliessman, *Phys. Rev.* **79**, 726 (1950); H. Fritzsche, *Phys. Rev.* **94**, 1415 (1954).

<sup>3</sup> F. J. Morin, *Phys. Rev.* **93**, 62 (1954).

<sup>4</sup> For the method used, see Sec. 16.4, W. Shockley, *Electrons and Holes in Semi-conductors* (D. Van Nostrand and Company Inc., New York, 1950).

<sup>5</sup> H. Jones, *Phys. Rev.* **81**, 149 (1951).

## Low-Temperature Luminescence of Cadmium Sulfide

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THIS is to report the existence of six emission bands in the wavelength range 5100–5400Å at 4°K for single crystal hexagonal cadmium sulfide grown by M. E. Bishop.<sup>1</sup>

These bands were obtained by exciting the cadmium sulfide with 3650Å radiation produced by a high-pressure Cenco mercury arc filtered with a 7–37 Corning filter. The luminescence was photographed with a Hilger medium glass spectrograph. The microphotometer trace of the spectrogram is shown in Fig. 1.

TABLE I. Observed and calculated values of  $\nu$ .

Observed $\lambda$ (Å)	Observed $\nu$ ( $\text{cm}^{-1}$ )	( $v'$ , $v''$ )	Calculated $\nu$ ( $\text{cm}^{-1}$ )
5133	19482	(1,0)	19488
5182	19298	(0,0)	19288
5212	19186	(1,1)	19192
5267	18986	(0,1)	18992
5290	18904	(1,2)	18896
5350	18692	(0,2)	18696

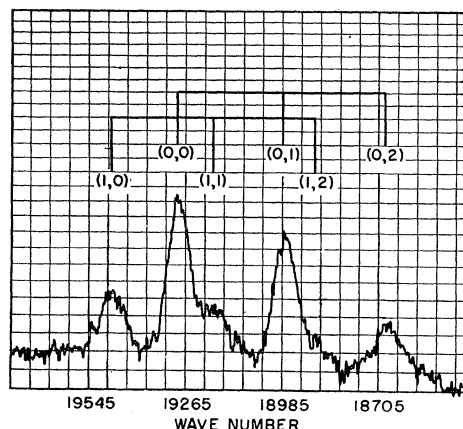


Fig. 1. Microphotometer trace of the emission of cadmium sulfide at 4°K from 5100 to 5400Å.

The spacing and relative intensities of these six bands together with the absence of photoconductivity<sup>2</sup> at this temperature suggested that the concept of localized complexes, or centers, might be applicable in this case. The center might consist, for example, of a group of ions surrounding a sulfur vacancy or surrounding a foreign ion which has replaced the sulfur. It was found that a molecular-type wave number equation for these bands,

$$\nu = \nu_e + \omega'(v' + \frac{1}{2}) - \omega''(v'' + \frac{1}{2}),$$

gave a reasonable fit where  $\nu_e$  is the electronic jump;  $\omega'$  and  $\omega''$  are the vibrational wave numbers for the first excited and ground states, respectively; and  $v'$  and  $v''$  are the corresponding vibrational quantum numbers. By using the observed values of  $\nu$  shown in the table below and quantum numbers selected according to the relative positions and intensities of the bands, the appropriate wave-number equation was calculated to be

$$\nu = 19336 + 199(v' + \frac{1}{2}) - 296(v'' + \frac{1}{2});$$

and from this the calculated values of  $\nu$  corresponding to the observed values were obtained as shown in Table I, where the transition associated with 19298  $\text{cm}^{-1}$  has been assigned the quantum numbers (0,0). It should be pointed out, however, that although a molecular-type calculation has been made, the intensity distribution, as shown in Fig. 1, differs from typical molecular spectra intensity distributions. These centers are characterized by an electronic jump of 19336  $\text{cm}^{-1}$  (5172Å), a vibrational wave number of 199  $\text{cm}^{-1}$  (50 $\mu$ ) in the first excited state and a vibrational wave number of 296  $\text{cm}^{-1}$  (34 $\mu$ ) in the ground state. It is noteworthy that Plyler found a weak absorption band in the vicinity of 34 $\mu$  at room temperature as reported by Klick.

<sup>1</sup> M. E. Bishop and S. H. Liebson, *J. Appl. Phys.* **24**, 660 (1953).

<sup>2</sup> C. C. Klick, *Phys. Rev.* **89**, 274 (1953).

<sup>3</sup> C. C. Klick, *J. Opt. Soc. Am.* **41**, 816 (1951).