

TABLE I. Characteristics of  $\text{CaF}_2$  layers.

Thickness A.u. ( $10^{-7}$ cm)	Time after sput- tering	Capaci- tance $\mu\text{F}$	A.c. re- sistance $k\Omega$	D.c. re- sistance $k\Omega$	Dielectric constant
1000	0	5.0	1.25		550
	30 sec.	1.5	8.5		165
	5 min.	1.2	14.5		130
	24 hr.	1.1	18.0	} >1000	120
	48 hr.	0.22			24
3000	0	3.0	1.75		990
	10 min.	2.7	2.45		895
	2 hr.	1.7	3.10	100	560
	18 hr.	0.03	175	} >1000	9.9
	14 day	0.03	200		9.9
10000	0	4.0	1.35		4400
	1 min.	2.4	2.20		2600
	5 min.	2.0	2.90	70	2200
	15 hr.	0.017	310	700	19
	7 day	0.005	>1000	>1000	5.5

In ten such condensers examined the thickness of the  $\text{CaF}_2$  layer varied between 1000 and 20000 angstrom units. The precision of the measurements is too small to draw any definite conclusions. It seems, however, that the evaluated dielectric constant increases with increasing thickness of the  $\text{CaF}_2$  layer and probably approaches asymptotically a certain limiting value. It is also clearly seen that the a.c. resistance is considerably smaller than the d.c. resistance. This fact may be interpreted by a hysteresis phenomenon. Also the slope of the discharge curve makes this interpretation probable.

Finally it should be pointed out that a  $\text{CaF}_2$  condenser several days or weeks old resumes the anomalous high capacitance when moistened by water.

The experimental work was carried out by Mr. E. Vesa. The investigation continues.

## The Response of the Anthracene Scintillation Counter to Monoenergetic Electrons\*

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IT has been determined previously that the light pulse produced by an electron striking a phosphor substance such as anthracene is approximately proportional to the energy of the impinging electron over limited ranges of energies.<sup>1,2</sup> One desires to know how the pulse height for monoenergetic electrons varies with energy from an energy of a few kev up to an energy of several Mev.

A 180 cm single-lens  $\beta$ -ray spectrometer with an aperture of approximately 0.3 cm was used to supply the monoenergetic electrons. It was equipped with a sliding baffle so that the  $\gamma$ -ray and external background could be determined and the correction of counts made at each pulse height setting. Approximately 50 microcuries of  $\text{Cs}^{137}$  evaporated on to a thin Formvar film served as a source of electrons. The energy of the conversion electrons (630 kev) was used to determine the spectrometer constant. The end plate of the spectrometer at the counter end was made of soft iron and had at its center a mica window having  $\frac{3}{8}$  inch diameter and 1 mg/cm<sup>2</sup> thickness. An anthracene crystal 1.3 cm in thickness was attached with Canada balsam to the photosensitive area of an RCA-5819 photo-multiplier tube. The crystal was then covered with a 0.2-mil light-reflecting aluminum foil and mounted directly in front of the window. A soft iron shield surrounding the scintillation counter, in conjunction with the end plate of the spectrometer, served to prevent variations in magnetic field in the region of the photo-multiplier tube.

The output from the photo-multiplier was fed into a pre-amplifier and linear amplifier<sup>3</sup> combination and counts recorded on a scaler. The output from a pulse generator was used to check the amplifier for linearity and to determine the zero of the pulse height dial.

Counts per second *versus* pulse height data were recorded for each chosen energy and the differential curves plotted to determine the pulse height giving the maximum number of counts per second. Some typical curves are shown in Fig. 1 where the counts per

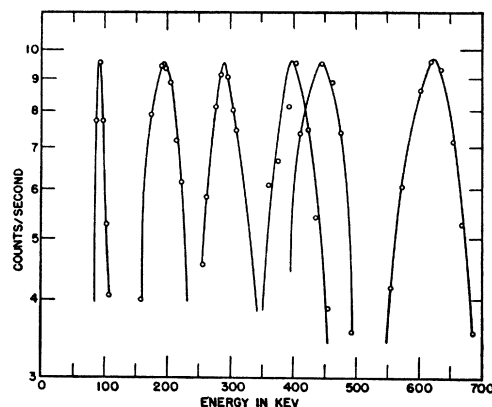


FIG. 1. Counting rate as a function of electron energy.

second have been normalized and plotted against the energy of the electrons in kev. These curves are within the expected statistical variation of the counts per second. It is estimated that the energy corresponding to a maximum number of counts per second for these curves is determined to an accuracy of  $\pm 1.0$  kev near 100 kev and to  $\pm 4.0$  kev from 400 to 665 kev.

In Fig. 2 is shown the pulse height variation with energy. It is noted that there is a slight deviation from linearity below 125 kev. Absorption data for electrons given by Glendenin<sup>4</sup> were used to

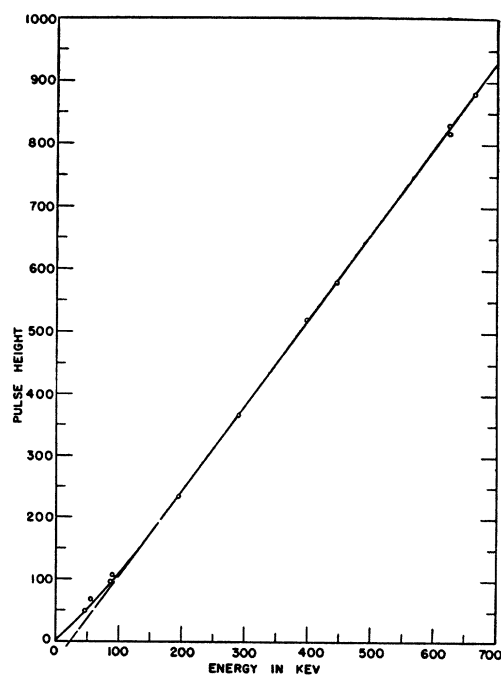


FIG. 2. Pulse height as a function of electron energy.

account for energy losses due to the absorption by the mica window, air space, and aluminum foil. Possible unaccountable errors in this experiment may be due to (1) background variations, since the spectrometer was located in the pile building, (2) magnetic variations near the photo-multiplier tube and (3) generator hash in the magnet current at times.

Work is being continued to further investigate the pulse height-energy variation in the low energy range and in the energy range above 650 kev.

Many thanks are due P. R. Bell for his constant advice and the Oak Ridge National Laboratory for the experimental facilities afforded.

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<sup>1</sup> H. Kallmann, *Natur und Technik* (July, 1947).

<sup>2</sup> M. Deusch, M.I.T. Technical Report No. 3 (December, 1947).

<sup>3</sup> W. H. Jordan and P. R. Bell, *Rev. Sci. Inst.* **18**, 703 (1947).

<sup>4</sup> L. E. Glendenin, *Nucleonics* **2**, 12 (1948).

### Energy Bands and Mobilities in Monatomic Semiconductors

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FOR a cubic crystal subject to a homogeneous strain,  $\epsilon_{ij}$ , the linear shift in energy band with strain may be expressed in the form

$$E = E_0 + \sum \beta_{ij} \epsilon_{ij} = E_0 + E_1 \Delta, \quad (1)$$

where  $\Delta = \epsilon_{11} + \epsilon_{22} + \epsilon_{33}$  is the dilation since all terms containing  $\epsilon_{ij}$  with  $i \neq j$  must vanish by symmetry. The shifts in the energy levels corresponding to the top of the filled band,  $E_f$ , and the bottom of the conduction band,  $E_c$ , produced by a periodic dilation of a lattice wave are shown schematically in Fig. 1(a). As illus-

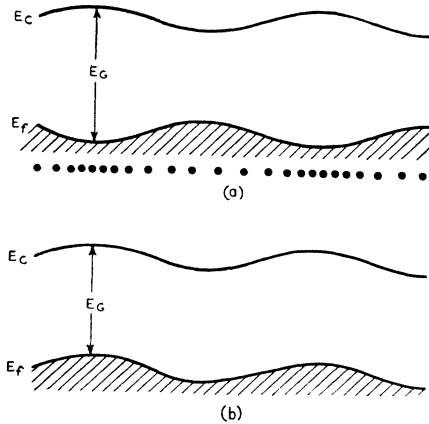


FIG. 1. (a) Shift of energy bands with varying dilation. (b) Shift of energy bands with varying electrostatic potential.

trated, the bands may shift in opposite directions. In crystals with the diamond structure, such as Ge and Si, the energy gap,  $E_G$ , decreases with a positive dilation; in others, such as Te, the shift is in the opposite direction. The difference between the shifts in  $E_c$  and  $E_f$  is equal to the shift in  $E_G$ :

$$E_{1G} = E_{1c} - E_{1f}. \quad (2)$$

On the other hand, a varying electrostatic potential makes the bands move up and down together, as in Fig. 1(b).

The theories of Peckar<sup>1</sup> and of James<sup>2</sup> may be extended to show that the effective mass concept may be applied to gradual shifts in energy bands produced by distortions as well as by a varying electrostatic potential.<sup>3</sup> In both cases, the position of the energy band may be used as an effective potential for the electron provided that the variation is sufficiently gradual. This is the case for shifts caused by lattice vibrations of long wave-length which interact with electrons of thermal velocities in semiconductors.

It is thus possible to calculate scattering by lattice waves by taking as the interaction potential,  $U(\mathbf{r})$ , the shift in energy band resulting from dilation,  $E_1 \Delta(\mathbf{r})$ :

$$U(\mathbf{r}) = E_1 \Delta(\mathbf{r}). \quad (3)$$

The matrix element involved in scattering,

$$M_{kk'} = \int \psi_{k'}^* U(\mathbf{r}) \psi_k d\tau = \int \exp[i(\mathbf{k} - \mathbf{k}') \cdot \mathbf{r}] E_1 \Delta(\mathbf{r}) d\tau \quad (4)$$

vanishes unless  $\mathbf{k}' = \mathbf{k} \pm \mathbf{q}$ , in which case

$$|M_{kk'}|^2 = E_1^2 |\mathbf{q} \cdot \mathbf{A}_q|^2, \quad (5)$$

where  $\mathbf{A}_q$  is the complex amplitude of the lattice wave of wave vector  $\mathbf{q}$ . The interaction constant  $C$  used by Sommerfeld and Bethe and by Seitz<sup>4</sup> is equal to  $(3/2)E_1$ ; that used by Wilson is equal to  $E_1$ .

The expression for mobility,  $\mu$ , derived in the usual way, may be expressed in the form:

$$\mu = 2(2\pi)^{1/2} e \hbar^4 \rho c_i^2 / 3m_e^{5/2} (k_0 T)^{3/2} E_1^2 \\ = (3.2 \times 10^{-5}) \rho c_i^2 / T^{3/2} E_1^2 \text{ cm}^2/\text{volt sec}. \quad (6)$$

In deriving the numerical factor we have set the effective mass ratio equal to unity and expressed  $E_1$  in ev. The product of the density,  $\rho$ , and the square of longitudinal wave velocity,  $c_i^2$ , can be expressed in terms of the elastic constants.

Equation (6) may be used to derive  $|E_{1c}|$  and  $|E_{1f}|$  from mobilities of conduction electrons and holes, respectively. The calculations for diamond, Si, Ge, and Te, together with relevant data, are given in Table I. The anisotropy of Te has been neglected.

TABLE I. Derivation of shift of energy bands with dilation from mobility data and comparison with shift of energy gap with dilation.

	Diamond	Silicon	Germanium	Tellurium
$\rho c_i^2 \times 10^{-12}$ (c.g.s.)	10.8 <sup>a</sup>	2.0 <sup>c</sup>	1.55 <sup>b</sup>	0.5 <sup>e</sup>
$\mu_n$ (electrons) (cm <sup>2</sup> /volt sec., 295°K)	900 <sup>d</sup>	300 <sup>e</sup>	3500 <sup>f</sup>	530 <sup>g</sup>
$\mu_p$ (holes) (cm <sup>2</sup> /volt sec., 295°K)	>200 <sup>b</sup>	100 <sup>e</sup>	1700 <sup>f</sup>	530 <sup>g</sup>
$\mu_n T^{3/2}$	45 × 10 <sup>5</sup>	15 × 10 <sup>5</sup>	180 × 10 <sup>5</sup>	27 × 10 <sup>5</sup>
$\mu_p T^{3/2}$	>10 × 10 <sup>5</sup>	5 × 10 <sup>5</sup>	86 × 10 <sup>5</sup>	27 × 10 <sup>5</sup>
$ E_{1c} $ (ev)	8.8	6.5	1.7	2.4
$ E_{1f} $ (ev)	<30	11.3	2.4	2.4
$ E_{1c}  +  E_{1f} $	<39	17.8	4.1	4.8
$ E_{1G} $ (ev)	?	~30 <sup>i</sup>	~5 <sup>i</sup>	5.0 <sup>i</sup>

<sup>a</sup> Longitudinal velocity in [110] direction calculated from elastic constants. See R. F. S. Hearmon, *Rev. Mod. Phys.* **18**, 409 (1946).

<sup>b</sup> Calculated from elastic constants measured by McSkimin, Mason, and Bond on single crystal sample prepared by K. M. Olson.

<sup>c</sup> Estimated from compressibility.

<sup>d</sup> C. C. Klick and R. J. Maurer, *Phys. Rev.* **76**, 179 (1949).

<sup>e</sup> Reference 5.

<sup>f</sup> Unpublished data of J. R. Haynes.

<sup>g</sup> Vivian A. Johnson, *Phys. Rev.* **74**, 1255 (1948).

<sup>h</sup> K. G. McKay (private communication).

<sup>i</sup> See text.

If  $E_{1c}$  and  $E_{1f}$  have opposite signs, as in Fig. 1(a), we should have

$$|E_{1G}| = |E_{1c}| + |E_{1f}|. \quad (7)$$

Various independent estimates of  $|E_{1G}|$ , given in the last row of the table, are in reasonable agreement with (7). These estimates were obtained as follows:

**Silicon.** The variation of  $E_G$  with temperature, derived from intrinsic concentration,<sup>5</sup> combined with the thermal expansion coefficient.

**Germanium.** (a) As for Si, (b) change of intrinsic conductivity with pressure,<sup>6</sup> (c) change of resistance of  $n-p$  junction with pressure.<sup>7</sup>