

The factor N gives the number of minima in the energy surfaces of the conduction band, of which, according to recent cyclotron resonance experiments,⁴ there are either eight as illustrated in Fig. 1, or four if the energy minima occur at the band edges. In the above expressions the first factor in the curly brackets expresses,

through the delta function, the conservation of energy requirement; the second factor is the square of the matrix element for the transition, the third factor gives the density of photon states, and the final factor the appropriate density of electron states. These expressions can be reduced to

$$W_d(\omega)d\omega = C_1 \frac{2m_v}{\hbar} (E_v - E_0)^{\frac{3}{2}} \omega d\omega, \quad (3)$$

$$W_i(\omega)d\omega = C_1 C_2 \left\{ \left[k_c^2 + \left(\frac{m_c + m_v}{\hbar^2} \right) (E_v + \hbar\omega - E_c) \right] B + \frac{2(m_v - m_c)}{3\hbar^2} [(E_{c0} - E_c)(E_v + \hbar\omega - E_{c0})]^{\frac{3}{2}} \right\} \frac{d\omega}{\omega} \quad (4a)$$

$$B = \frac{1}{4} \left\{ [3(E_v + \hbar\omega) - 2E_{c0} - E_c] [(E_{c0} - E_c)(E_v + \hbar\omega - E_{c0})]^{\frac{3}{2}} + (E_v + \hbar\omega - E_c)^2 \tan^{-1} \left(\frac{E_{c0} - E_c}{E_v + \hbar\omega - E_{c0}} \right)^{\frac{1}{2}} \right\}; \lambda \leq \lambda_d,$$

$$W_i(\omega)d\omega = C_1 C_2 \frac{\pi}{8} \left\{ k_c^2 + \left(\frac{m_c + m_v}{\hbar^2} \right) (E_v + \hbar\omega - E_c) \right\} (E_v + \hbar\omega - E_c)^2 \frac{d\omega}{\omega}; \lambda \geq \lambda_d. \quad (4b)$$

The constant C_1 involves only known physical constants; C_2 contains a factor characterizing the strength of the electron-phonon interaction in the conduction band and also the quantity N already referred to above. Free electron wave functions have been used throughout.

By using Eqs. (3) and (4) and the following parametric values²⁻⁴: $E_{c0} - E_c = 0.75$ eV, $E_{c0} - E_v = 1.45$ eV, $m_v = 0.3m_e$, $m_c = 0.2m_e$, the shapes of the absorption spectra for the direct and indirect transitions have been obtained, and these curves are shown in Fig. 2. An estimate for the ratio of the absorption coefficients for the direct and indirect transitions at wavelength

$\lambda_d - \Delta\lambda$ and $\lambda_i - \Delta\lambda$, respectively, gives

$$A_d(\lambda_d - \Delta\lambda) / A_i(\lambda_i - \Delta\lambda) \sim 10.$$

These results appear to be in qualitative agreement with experimental observations of absorption in thin films of germanium by Brattain and Briggs.⁵ Details of the calculation will soon be published in this journal.

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† On leave from the University of California at Santa Barbara, California.

¹ F. Herman, Phys. Rev. **88**, 1210 (1952).

² F. Herman and J. Callaway, Phys. Rev. **89**, 518 (1953).

³ Dresselhaus, Kip, and Kittel, Phys. Rev. **92**, 827 (1953).

⁴ Dexter, Zeiger, Lax, and Rasenblum, Phys. Rev. **95**, 597 (1954).

⁵ W. H. Brattain and H. B. Briggs, Phys. Rev. **75**, 1705 (1949).

Some Properties of Germanium-Silicon Alloys

EVERETT R. JOHNSON AND SCHUYLER M. CHRISTIAN
RCA Laboratories, Princeton, New Jersey

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PREPARATION of homogeneous alloys of germanium-silicon has been reported by Stöhr and Klemm¹ and by Wang and Alexander.² We have prepared a series of germanium-silicon alloys by a process of homogenization at high temperatures and have determined composition, density, lattice constant, and forbidden band gap. All alloys were homogeneous within the precision of the x-ray measurements. Absolute values of composition of the material were determined by analyzing for germanium polarographically.³ This method of analysis, with silicon as the sole chemical impurity, is believed to be accurate to better than

± 1 percent. Forbidden band widths were determined optically, on samples normalized to 0.020-in. thickness. The band width was taken as the energy corresponding to the value of the absorption which is exhibited by germanium at its accepted band width (0.72 eV). At this point the absorption coefficient was 22.7 cm⁻¹. All absorption curves had slopes which were similar to that of pure germanium.⁴

In Table I is summarized the data obtained on these alloys. Figure 1 shows the variation of lattice constant with composition and agrees within experimental error with that obtained by Stöhr and Klemm.¹ Lattice constant measurements indicate that one should observe a nonlinear variation of density with composition due to the small volume difference between germanium and silicon. However, our measurements of density and composition are not sufficiently sensitive to detect this. Consequently, a plot of density *versus* composition

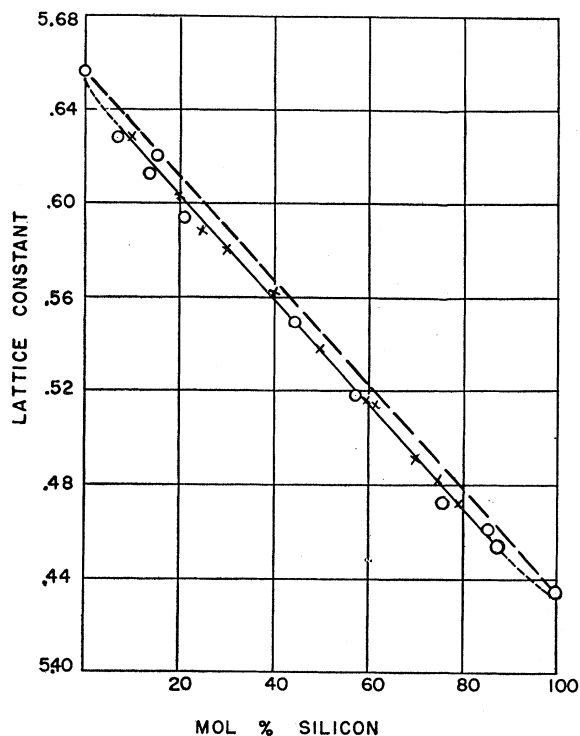


FIG. 1. Variation of lattice constant with mol percent silicon. \times = Values given by Stöhr and Klemm corrected to the more modern values of lattice constant for pure Ge and Si. \circ = Values of lattice constant measured and reported herein.

is linear within experimental error. This indicates that density is adequate for determining composition of homogeneous material, within a few percent. In Fig. 2 is plotted band gap *versus* composition. As can be seen a marked change in slope occurs at approximately 10 mol percent silicon. The alloys containing less than 12 mol percent silicon were single-crystal specimens while

TABLE I. Summary of data obtained in germanium-silicon alloys.

Designation	Density	Lattice constant	Mol percent silicon	Forbidden band width (ev)
GS-23	2.80	5.461	85.8	1.15
GS-25	2.72	5.454	87.4	1.16
GS-26	3.03	5.473	75.7	1.13
GS-29	3.62	5.518	57.5	1.08
GS-30	3.95	5.549	44.3	1.05
GS-31	4.86	5.620	15.0	0.94
GS-34	4.89	5.613	13.5	0.93
GS-37	4.70	5.593	22.9	0.94
D-28	—	—	7.2 ^a	0.83
D-31	—	—	4.3 ^a	0.78
D-39	—	—	6.0 ^a	0.81
D-40-G	—	5.626	12.6 ^a	0.91
D-40-S	—	—	4.2 ^a	0.78
D-40-T	—	—	7.4 ^a	0.82
D-41	—	—	8.2 ^a	0.84
200-S	—	—	0.7 ^a	0.73
Ge	5.323	5.657	—	0.72
Si	2.328	5.434	—	1.20

^a Determined spectrographically as $\pm 0.1\%$ mol percent.

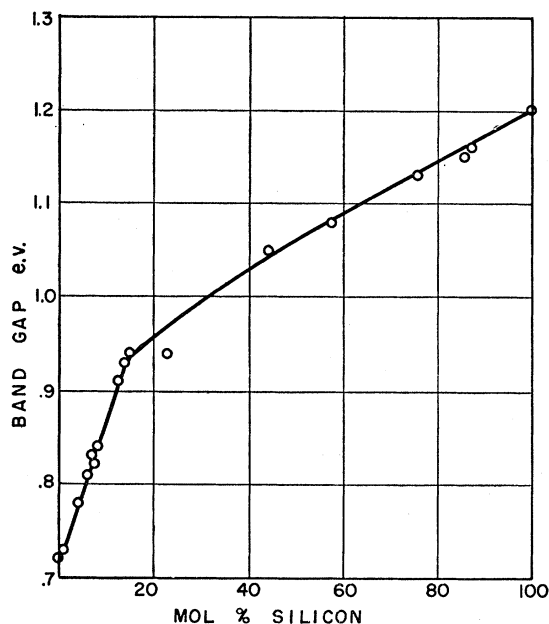


FIG. 2. Variation of energy gap with mol percent silicon.

those containing more than 12 mol percent were polycrystalline.

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¹ Herbert Stöhr and Wilhelm Klemm, *Z. anorg. u. allgem. Chem.* **241**, 4, 305-424 (1939).

² C. C. Wang and B. H. Alexander, *Am. Inst. Mining Met. Engrs., Symposium on Semiconductors*, New York City, February 15-18, 1954 (unpublished).

³ M. C. Gardels (to be published).

⁴ The slopes of those curves obtained on polycrystalline specimens differed slightly from the single crystalline specimens. However, sufficient information on polycrystalline samples was obtained to indicate that the general appearance of the curve shown in Fig. 2 would not change appreciably if all the data had been obtained on single crystalline specimens.

Use of Silicon *p-n* Junctions for Converting Solar Energy to Electrical Energy

R. L. CUMMEROW

Knolls Atomic Power Laboratory, Schenectady, New York*

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CHAPIN¹ has reported experiments using silicon *p-n* junctions to convert solar radiation into electrical energy. He reports attaining an efficiency of 4 percent with such a device. The writer² has recently developed relations for the efficiency of *p-n* junctions as power converters in terms of the fundamental experimentally determined constants of semiconducting materials. These equations are given for monochromatic radiation. It is interesting to extend these calculations to the solar spectrum with a silicon *p-n* junction.