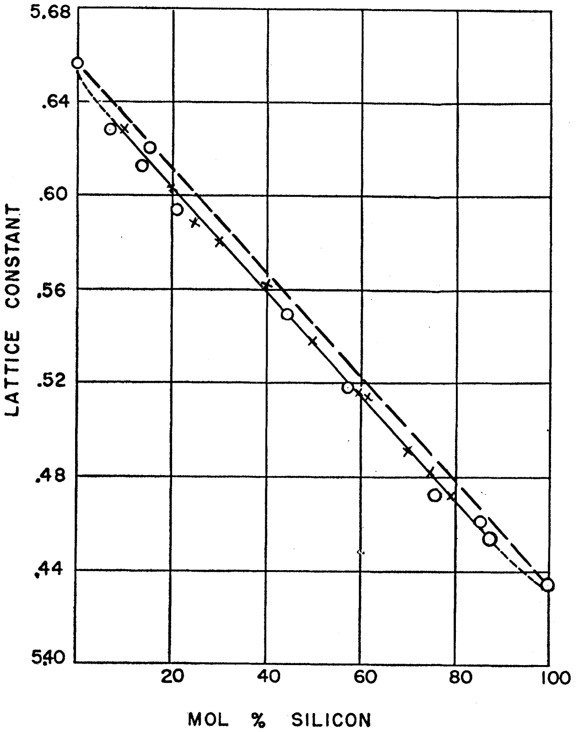

FIG. 1. Variation of lattice constant with mol percent silicon. × = Values given by Stöhr and Klemm corrected to the more modern values of lattice constant for pure Ge and Si. ○ = Values of lattice constant measured and reported herein.

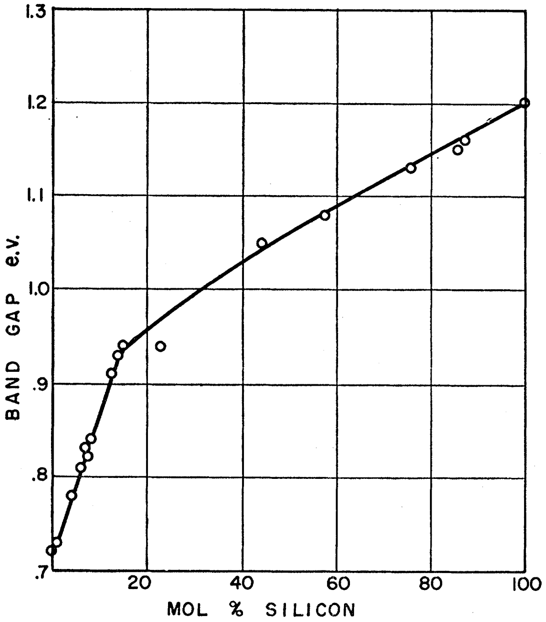

FIG. 2. Variation of energy gap with mol percent silicon.

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 those containing more than 12 mol percent were polycrystalline.

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 $x \pm 0.1x$ mol percent.

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[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

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CHAPIN[1] 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 writer[2] 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.

For this purpose, we consider solar radiation as that characteristic of a black body at a temperature of 5760°K. At the top of the earth's atmosphere energy is received at the rate of 0.135 watt/cm^2 from this black body. We assume that at the earth's surface on a clear day this intensity is reduced by 20 percent in passing through the atmosphere with negligible alteration in the black body spectrum in the range of junction response. Under these conditions, the intensity at the earth's surface is 0.108 watt/cm^2 at normal incidence.

In reference 2, expressions are given for g_0L, where g_0 is the rate of generation of hole-electron pairs per unit volume at the transition region in the p-n junction, and L is an effective diffusion length given by Eqs. (19), (21), (22), and (23). To extend these results to the sun's spectrum we consider more conveniently the product $g_0L=G$. We can express G in the following way:

$$G=\frac{r_s^2}{r_0^2}\int_0^{\lambda_c}\frac{N_\lambda}{S_\lambda}\exp(-d/S_\lambda)L(\lambda)d\lambda. \tag{1}$$

In this expression, N_λ is the number of photons per unit wavelength per unit area in the black-body spectrum assumed above, S_λ is the reciprocal absorption coefficient for photons of wavelength λ, d is the depth of the junction below the irradiated surface, $L(\lambda)$ is the effective diffusion length, λ_c is the cutoff wavelength in the semiconductor corresponding to the width of the band gap, and r_s and r_0 are the radii of the sun and the earth's orbit, respectively.

Moss[3] gives a curve of absorption coefficient *versus* wavelength for silicon. For the very high absorption region at the shorter wavelengths, Eq. (1) simplifies to

$$G=\frac{r_s^2}{r_0^2}\operatorname{sech}(d/L_p)\int_0^{\lambda_c}N_\lambda d\lambda, \tag{2}$$

where we use electrodes which reflect the minority carriers at the surfaces of the semiconducting material and assume that we are irradiating n-type material of depth d, and where the diffusion length of the holes (minority carrier) is L_p. The value of the integral in Eq. (2) has been worked out and is given in graphical form by Benford.[4]

For the longer wavelength regions of the spectrum, it is necessary to evaluate the integral [Eq. (1)] numerically or graphically. For silicon, using Moss' absorption coefficient *versus* wavelength, the approximation (2) is good from very short wavelengths up to about 0.87μ. From 0.87μ to 1.1μ a graphical evaluation of Eq. (1) is employed.

Table I shows the constants assumed for the silicon p-n junction. Using the approximation for the sun's spectrum described above, the constants shown in Table I, and the calculated value of $G=2.25\times10^{17}$ cm^{-2}sec^{-1}, we find from Eqs. (27) and (28) of reference 2 that the efficiency of conversion (neglecting reflection loss) of solar energy to electrical is 17 percent. If we increase the intensity by a factor of four by some suitable optical arrangement, the efficiency rises to only 18 percent. From this result we conclude that we are well above the knee of the efficiency curve such as shown for germanium in reference 2, since a large increase in power produces very little increase in efficiency. The calculated efficiency is lower by a factor of two than that calculated for monochromatic radiation of wavelength 0.87μ.

TABLE I. Assumed constants for silicon junction.[a]

Mobilities		Lifetimes		Conductivities	
μ_n	μ_p	τ_n	τ_p	σ_n	σ_p
(cm^2/volt sec)		(sec)		(ohm^{-1} cm^{-1})	
1200	400	10^{-5}	10^{-5}	1.0	1.0

[a] It was also assumed that the square of the concentration for intrinsic material, $n_i^2=2.5\times10^{20}$ cm^{-6}.

These calculated efficiencies are in reasonable agreement with that observed experimentally by Chapin, since we have neglected the surface reflection loss which could reduce the efficiency by a factor as great as two. The other factor of two could be accounted for in differences between the assumed characteristics and those of the silicon actually employed by Chapin.

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* Operated by the General Electric Company for the U. S. Atomic Energy Commission.

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Power Efficiency for the Photovoltaic Effect in a Germanium Grown Junction*

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IT is known that the short-circuit photovoltaic current of an unbiased p-n junction increases linearly with the intensity of the incident radiation except for very large intensities. The open-circuit photovoltage also increases with the incident intensity, but at a rate which decreases for large intensities.[1] A consideration of the current-voltage characteristic of a typical rectifying junction indicates that the photocurrent for maximum power delivered to an external resistive load must vary with incident intensity in much the same way that the short-circuit photocurrent does; the photovoltage for maximum power must follow more closely the dependence of the open-circuit photovoltage. Thus, the efficiency of conversion of incident power into maximum power delivered to the external load should increase with incident intensity in a manner similar to that of the open-circuit photovoltage, provided the intensity is not too large.