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:

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

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

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

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.

[1] D. M. Chapin, Am. Inst. Mining Met. Engrs., Symposium on Semiconductors, February 15, 1954 (unpublished).

[2] R. L. Cummerow, Phys. Rev. **95**, 16 (1954).

[3] T. S. Moss, *Photoconductivity in the Elements* (Academic Press, Inc., New York, 1952), p. 113.

[4] F. E. Benford, Gen. Elec. Rev. **46**, 377, 433 (1943).

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.

A disk-shaped germanium crystal,[2] approximately six mm in diameter and slightly less than one mm thick, was cut from an ingot with the grown junction parallel to the faces and approximately 0.1 mm from the *n* face. The resistivity of the *n* material was in excess of 20 ohm-cm and that of the *p* material was less than one ohm-cm. The radiation was incident normal to the *n* face of the crystal; this surface was etched for these experiments. Fine wire leads were soldered to the centers of the parallel faces; each electrode covered less than one tenth of the area of the face. Observations were made both with the continuous spectrum supplied by a 3200°K photoflood lamp and with the exit beam of a quartz monochromator. Intensity variation with the continuous spectrum was obtained by changing the lamp-to-crystal distance. A shutter in front of the crystal permitted observations to be made immediately upon exposure of the crystal to the radiation; all observations described here were made with the crystal at room temperature. For both types of observation a vacuum thermopile was used to determine the appropriate radiation intensities at the crystal surface. For a given incident intensity the external current and voltage were measured as functions of the load resistance; the photocurrent was measured with a low-resistance galvanometer and the photovoltage with a high-impedance vacuum-tube voltmeter. The point of maximum power was selected by inspection of the resulting power-*vs*-load resistance curve.

Figure 1 shows the observed efficiency of conversion of incident power into maximum delivered power as a function of the incident radiation intensity for radiation of four different compositions. The inset is the low-intensity portion of the figure with the vertical scale expanded. The dependence for the white radiation from the tungsten lamp is given by curve *A*. Curve *B* is for the part of this radiation beyond 0.9 μ as transmitted by an infrared filter. Curve *C* shows the relationship for the tungsten lamp radiation between 0.7 μ and 1.1 μ as transmitted by a glass color filter. Curve *D*, which appears only in the inset, represents the efficiency data for low intensities of wavelength 1.65μ as obtained with the monochromator. It is seen that, in all four cases, the power efficiency increases with incident intensity over a large range of intensities. The dependence is nearly linear for low intensities (i.e., below about 0.005 watt/cm²) and becomes approximately logarithmic for larger intensities. This is similar to the manner in which the open-circuit photovoltage varies with the incident intensity.[1] As would be expected from a consideration of the current-voltage characteristic of a *p-n* junction, it was found that the load resistance for maximum power remained approximately the same (200 to 300 ohms for this crystal) for low intensities but decreased with increasing incident radiation intensity to about 25 ohms for the highest intensity used.[3] It will be noted that for white radiation (curve *A*) an efficiency maximum of nearly ½ percent is indicated for an incident intensity of approximately 0.1 watt/cm² (nearly the magnitude of the solar constant); for larger intensities the observed power efficiency decreases. This occurs in the same high-intensity region in which the beginning of a current saturation effect was observed for both the short-circuit and the maximum-power conditions. No efficiency maximum is indicated for any of the other data.

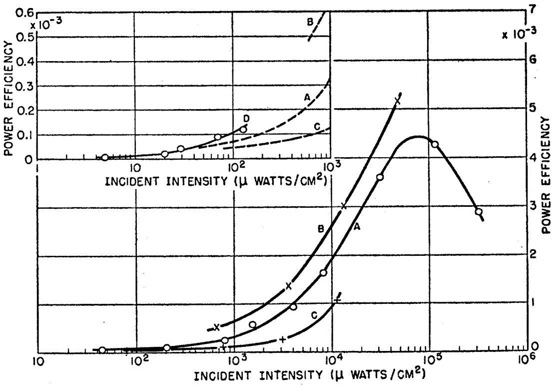

FIG. 1. Efficiency of germanium grown junction in converting power received in incident radiation into maximum power in external resistive load. *A*. White radiation from incandescent tungsten source. *B*. Radiation of *A* beyond 0.9 μ. *C*. Radiation of *A* between 0.7 μ and 1.1 μ. *D*. Radiation of wavelength 1.65 μ.

The curves shown in Fig. 1 represent lower limits for the power efficiencies, since the data presented are given in terms of incident power and not in terms of the power absorbed by the germanium crystal at its surface. As the reflecting power of germanium in the wavelength regions involved here is the order of 0.5,[4] it follows that the efficiencies of conversion of *absorbed* power are roughly twice those shown in Fig. 1.

An effective quantum efficiency appreciably less than unity was observed for this crystal. The relative photocurrent response of the crystal to an equal-energy spectrum of low intensity is shown in Fig. 2. The energy sensitivity at the peak response point is approximately three times that at 1.0 μ; the sensitivity per incident photon at the peak is nearly twice that at 1.0 μ. The relative responses, for a given incident intensity, in-

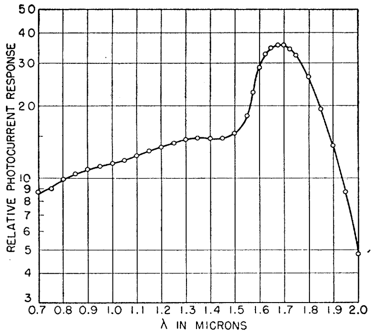

FIG. 2. Relative photocurrent response of germanium grown junction to an equal-energy source.

dicated by the curves of Fig. 1 are consistent with the spectral sensitivity data of Fig. 2. Utilizing the short-circuit photocurrents, found by extrapolation to zero external resistance, and the corresponding measured intensities it was possible to calculate the effective quantum efficiencies for both the monochromator measurements and the direct-radiation measurements. The peak response region between $1.65\ \mu$ and $1.70\ \mu$ corresponds to approximately 0.3 electron-hole pairs produced per incident photon. If approximate values for the optical constants of germanium[4] are applied to the data of Fig. 2 the general shape of the response curve is not appreciably altered, but the peak response then corresponds to an effective quantum efficiency of approximately 0.5 electron-hole pairs per absorbed photon and the $1.0\ \mu$ region to approximately 0.3. These effective quantum efficiencies, although verified on several occasions, are decidedly less than the value of unity generally accepted for the photovoltaic process at a *p-n* junction.[5] The discrepancy can be attributed to excessive recombination of the generated charges at the crystal surfaces and to an effective series ohmic resistance at the electrode contacts on the crystal.

The relatively small effective quantum efficiency does not affect the validity of the results reported; it does, however, restrict the magnitudes of the power efficiencies observed. Had an effective quantum efficiency of approximately unity been observed in the peak response region the curves of Fig. 1 would indicate power efficiencies from $2\frac{1}{2}$ to four times those shown. This would correspond to efficiencies of conversion of *absorbed* power five to eight times those indicated in Fig. 1. For the white radiation of curve *A* this would mean a maximum power efficiency of approximately two percent. For the infrared radiation of curve *B* an efficiency of three percent or more is indicated, since there is no evidence of a maximum in the intensity range shown. It appears not unreasonable to presume that efficiencies of seven or eight percent could be realized with a junction better suited to this application.

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* This investigation was described, in slightly different form, in a paper presented at the Rochester, New York, meeting of the American Physical Society on June 18, 1953. See Ralph P. Ruth and James W. Moyer, Phys. Rev. **92**, 846 (1953).

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

[1] H. Y. Fan, Phys. Rev. **75**, 1631 (1949); M. Becker and H. Y. Fan, Phys. Rev. **75**, 1631 (1949); **78**, 301 (1950).

[2] The junction used for this work was supplied by Dr. R. N. Hall of the General Electric Research Laboratory.

[3] A theoretical development of these empirical relationships is contained in a study of the photovoltaic effect in *p-n* junctions made by R. L. Cummerow of this laboratory [Phys. Rev. **95**, 16 (1954)].

[4] W. H. Brattain and H. B. Briggs, Phys. Rev. **75**, 1705 (1949); K. Lark-Horovitz and K. W. Meissner, Phys. Rev. **76**, 1530 (1949); H. B. Briggs, Phys. Rev. **77**, 287 (1950); M. Becker and H. Y. Fan, Phys. Rev. **76**, 1530 (1949); D. G. Avery and P. L. Clegg, Proc. Phys. Soc. (London) **B66**, 512 (1953); H. B. Briggs, J. Opt. Soc. Am. **42**, 686 (1952).

[5] F. S. Goucher, Phys. Rev. **78**, 816 (1950). See also B. J. Rothlein, Sylvania Technologist **4**, 86 (1951).

Magnetic Domains in Cobalt by the Longitudinal Kerr Effect*

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THE longitudinal Kerr effect was recently employed by the authors to successfully photograph the magnetic domains in a single crystal of silicon iron.[1] The domains in that specimen were unusually large (1–3 mm wide) and the question remained as to how applicable the technique would be for examining the very much smaller domains usually encountered in ordinary ferromagnetic crystals. Partly to answer this question, we have undertaken to photograph the domains in a (10·0) surface of a single crystal of hexagonal cobalt, which was known from powder pattern evidence to contain antiparallel domains lying in the direction of the *c* axis, the direction of easy magnetization.

No data on the longitudinal Kerr effect in cobalt were available, but the normal polar case in cobalt is reported to rotate the plane of polarization by about 20 minutes, which is about the same magnitude as for the normal polar case in iron.[2] The polar effect in cobalt had been employed by Williams, Wood, and Foster to photograph the mottled structure characteristic of the end-on view of domains terminating in a basal plane normal to the *c* axis.[3] We therefore first sought to measure the longitudinal Kerr rotation for the cobalt specimen by using the photoelectric technique previously described.[1] The rotation, a maximum when the light is incident at about 60°, measured 3.5

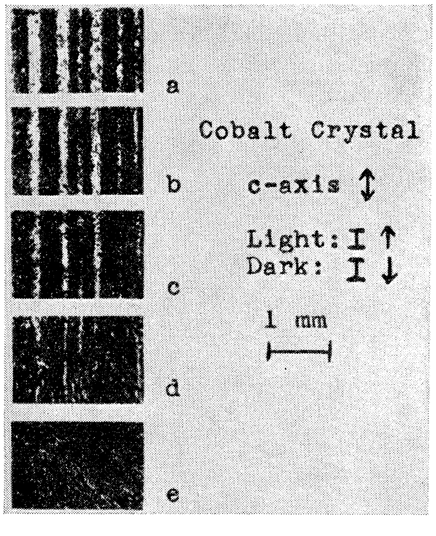

FIG. 1. Photographs of the domain behavior in a (10·0) surface as the applied field is increased from zero in (a) to a value sufficient to produce saturation in (e). The direction of the field is toward the bottom of the page.