PHYSICAL REVIEW VOLUME 95, NUMBER 1 JULY 1, 1954

# Photovoltaic Effect in *p*-*n* Junctions

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(Received March 1, 1954)

The relations between the incoming radiant energy and the outgoing electrical energy are developed in terms of the experimentally measurable constants of the semiconducting material. These results are applied to germanium by making use of constants found in the literature. The high efficiencies calculated for power conversion are strong indication that the *p*-*n* junction may be a practical device for the direct utilization of solar energy.

## I. INTRODUCTION

A *p*-*n* junction exists in a semiconducting material in the region where the impurity content changes from an acceptor type (*p* type) to a donor type (*n* type). These junctions may be formed, for example, by the diffusion of impurity atoms into the surface of a crystal[1] or the segregation of impurities during crystal growth.[2] Single-crystal germanium, the most common material used for such junctions, contains two electronic bands which are involved in conduction processes. These are the valence band which is almost filled with electrons and the almost empty conduction band, which lies about 0.72 electron volt above the valence band. The Fermi energy for the intrinsic material is about in the center of the gap or forbidden region between these bands. For *p* material it lies within the gap, but below the center; for *n* material, above the center.[3]

Figure 1 shows the energy levels in the junction region at equilibrium. At equilibrium, the Fermi energy throughout the material must be the same. In order to fulfill this requirement in the junction region, a charge double layer and accompanying electrostatic potential are set up. The height of this electrostatic barrier is equal to the difference between the position of the gap in the *n* material and the *p* material. The Fermi energy and hence the barrier height vary with the temperature and the impurity concentration.[3]

A hole or unoccupied level in the valence band may diffuse for some distance in *n* material before it combines with an electron. The average distance it travels before combining is called the diffusion length for holes in *n* material. An analogous quantity is defined for electrons in *p* material.

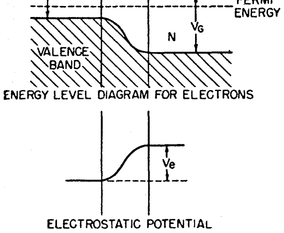

FIG. 1. Energy levels for electrons and the electrostatic potential in the transition region of a *p*-*n* junction.

## II. MODEL OF *p*-*n* JUNCTION TO BE USED

The junction model which we shall use in discussing the photovoltaic effect is the one on which the usual theory is based. We define it precisely by the following assumptions:

(1) The junction or transition region itself is negligibly small compared with the extent of the *p* or *n* material and the diffusion lengths of holes in *n* material or electrons in *p* material. (We consider here the one-dimensional problem only.) Consequently, there is negligible recombination or generation of holes and electrons in the junction region.

(2) The electrostatic field is confined entirely to the narrow junction region. Even under nonequilibrium, steady-state conditions, we assume that there is no field outside this region. The rate-controlling process in current flow is, therefore, the diffusion of holes in the *n* material and electrons in *p* material. Consequently, in order to insure this field-free diffusion process, the nonequilibrium concentration of holes in *n* material or electrons in *p* material must always be much smaller than the equilibrium concentration of electrons or holes.

(3) The donor or acceptor impurity concentrations are always small enough so that Boltzmann statistics may be used instead of Fermi statistics.[4]

## III. THE JUNCTION EQUATIONS

In accordance with our model defined above, we represent the junction as a narrow region of width $2\delta$ at $x=0$ (Fig. 2). The distance $2\delta$ is negligible compared with any other dimension of the junction and the figure is not to scale. As we traverse this region in the $x$ direction (from $p$ material to $n$ material), the electrostatic potential increases by an amount $V_e$.

The difference in electrostatic energy in electron volts between the $p$ and $n$ material is then $eV_e$, where $e$ is the electronic charge and $V_e$ is the equilibrium electrostatic potential difference between the $n$ and $p$

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

[1] R. N. Hall and W. C. Dunlap, Jr., Phys. Rev. **80**, 467 (1950).

[2] Teal, Sparks, and Buehler, Phys. Rev. **81**, 637 (1951).

[3] W. Shockley, *Electrons and Holes in Semiconductors* (D. Van Nostrand Company, Inc., New York, 1950), Chap. 10.

[4] V. A. Johnson and K. Lark-Horovitz, *Semiconducting Materials* (Academic Press, Inc., New York, 1951), p. 70.

regions. Then, the concentrations of holes on opposite sides of the barrier are related in the following way:

$$p_n = p_p \exp(-eV_e/kT), \tag{1}$$

where $p_n$ is the equilibrium concentration of holes in the $n$ material, $p_p$ that in the $p$ material, $k$ the Boltzmann constant, and $T$ the absolute temperature. With diffusion rate limiting, we may write the quasi-equilibrium equation

$$p(0) = p_p \exp[-e(V_e - V)/kT], \tag{2}$$

where $p(0)$ is the nonequilibrium value of $p(x_r)$ in the $n$ material at $x=\delta$ or $x_r=0$, where $x_r=x-\delta$, and $V$ is a voltage applied to the junction which changes the height of the equilibrium barrier. (In the following, all variables applying to the material to the right of the barrier are functions of $x_r$; those to the left, of $x_l$.) This voltage change may be accomplished by the use of a battery, or by the generation of nonequilibrium charge concentrations near the barrier by means of radiation. Combining Eqs. (1) and (2), we have

$$p(0) = p_n \exp(eV/kT). \tag{3}$$

We have analogous relations for electrons in $p$ material. We shall continue to develop equations for holes in $n$ material and write the analogous equations for electrons in $p$ material in the appropriate places.

We consider a small volume of $n$ material. Within this volume, holes are being generated thermally or by other means and are recombining with electrons. In addition, holes are entering and leaving this volume by diffusion. Under equilibrium conditions (thermal generation only), holes and electrons recombine at the same rate they are generated within this small volume. Shockley and Read have worked out[5] a theory of recombination of holes and electrons postulating the existence of trapping centers where recombination can occur much more readily than in a direct collision of a hole and an electron. This postulate is necessary to account for the short measured lifetime of holes in $n$ material. Using Eqs. (3.8), (3.9), (4.4), and (5.4) of this reference and assuming that we are dealing with an $n$-type sample with sufficiently high donor concentration, we may write for the equilibrium thermal generation of holes:

$$g_p = p_n/\tau_p, \tag{4}$$

where $\tau_p$ is the lifetime of a hole in seconds in $n$ material. From these same equations in reference 4 we write for the nonequilibrium recombination rate

$$r_p = p/\tau_p, \tag{5}$$

where $p$ is the nonequilibrium concentration of holes. If we have generation of holes because of light quanta or other radiation, we may designate this by $g(x)$. The total net generation is then:

$$g_p + g(x) - (p/\tau_p). \tag{6}$$

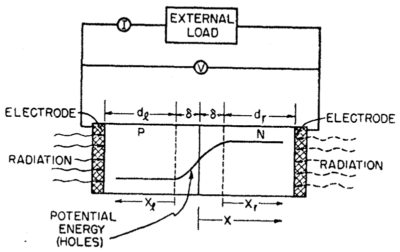

FIG. 2. Model of $p$-$n$ junction used for calculations.

This net generation rate must equal the net rate at which holes leave the small volume. This is just

$$e^{-1} \times \text{divergence of hole current density} = e^{-1}\partial I_p/\partial x.$$

We have then from (6):

$$g_p + g(x) - (p/\tau_p) = e^{-1}\partial I_p/\partial x. \tag{7}$$

Since we are dealing only with diffusion current,

$$I_p = -eD_p(\partial p/\partial x), \tag{8}$$

where $D_p$ is the diffusion constant for holes in $n$ material. Combining with (7),

$$g_p + g(x) - (p/\tau_p) + D_p\partial^2 p/\partial x^2 = 0. \tag{9}$$

The function, $g(x)$ can be written down by referring to Fig. 2. Let us consider first the case in which the light quanta fall on the surface of the $p$ material. We specify that the hole-electron pair generation at the junction due to photons is $g_0$. The generation in the $n$ material (to the right of the junction) is then:

$$g(x_r) = g_0 \exp(-x_r/L_\lambda) \tag{10}$$

where $(L_\lambda)^{-1}$ is the absorption coefficient for photons of wavelength $\lambda$. To the left of the junction,

$$g(x_l) = g_0 \exp(x_l/L_\lambda), \tag{11}$$

where $x_l = -(x+\delta)$ and at the surface on which the photons are incident,

$$g_s = g_0 \exp(d_l/L_\lambda).$$

If we have $H_s$ photons/cm$^2$ sec of wavelength $\lambda$ incident on the surface (after the incident beam has suffered reflection by the electrode or the semiconductor), then, assuming unit quantum efficiency,[6]

$$g_s = H_s/L_\lambda \quad \text{and} \quad g_0 = (H_s/L_\lambda)\exp(-d_l/L_\lambda). \tag{12}$$

The boundary conditions to be used with Eq. (9) are

$$(1) \text{ at } x_r = 0,\ p = p_n \exp(eV/kT); \tag{13}$$

$$(2) \text{ at } x_r = d_r,\ \partial p/\partial x = 0; \tag{14}$$

$$(3) \text{ as } d_r \to \infty,\ p \to p_n \text{ for all large } x_r. \tag{15}$$

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[5] W. Shockley and W. T. Read, Jr., Phys. Rev. 87, 835 (1952).

[6] F. S. Goucher, Phys. Rev. 78, 816 (1950).

Boundary condition No. (2) is that attained by putting a donor electrode on $n$ material (or an acceptor electrode on $p$ material). Such an electrode provides a reflecting barrier for the minority carrier, but no barrier for the majority carrier.[7] When the electrode is many diffusion lengths away, boundary condition No. (3) is used.

When we consider the differential equation and the pair generation functions for the $n$ material along with the analogous equations for $p$ material, we find that there are four cases of practical interest: (1) Irradiation of $p$ material with junction near the surface; $n$ material extends to infinity. (2) Same as 1, except $n$ material is finite. (3) Irradiation of $n$ material with junction near the surface; $p$ material extends to infinity. (4) Same as 3, except $p$ material is finite. The solutions corresponding to case 1 are

$$\begin{aligned} p=\tau_p g_p[\exp(eV/kT)-1]\exp(-x_r/L_p)& \\ +\frac{\tau_p g_0}{a_p^2-1}[\exp(-x_r/L_p)-\exp(-x_r/L_\lambda)]+\tau_p g_p,& \qquad (16)\end{aligned}$$

$$\begin{aligned} n=\tau_n\left\{g_n[\exp(eV/kT)-1]+\frac{g_0}{a_n^2-1}\right\}& \\ \times\frac{\cosh[(d_l-x_l)/L_n]}{\cosh(d_l/L_n)}+\frac{\tau_n g_0}{a_n^2-1}\bigg[a_n\exp(d_l/L_\lambda)& \\ \times\frac{\sinh(x_l/L_n)}{\cosh(d_l/L_n)}-\exp(x_l/L_\lambda)\bigg]+\tau_n g_n,& \qquad (17)\end{aligned}$$

where $a_p=L_p/L_\lambda$, $a_n=L_n/L_\lambda$ and $L_p$ is the diffusion length for holes in $n$ material $[L_p=(D_p\tau_p)^{\frac{1}{2}}]$ and $L_n$ is the analogous quantity for electrons in $p$ material. The electron current density and the hole current density at the junction constitute the total current density. For Case (1),

$$\begin{aligned} I_p(0)=-eD_p(\partial p/\partial x)_0=eg_pL_p& \\ \times[\exp(eV/kT)-1]-eg_0L_p/(a_p+1),& \qquad (18)\end{aligned}$$

$$\begin{aligned} I_n(0)=-eD_n(\partial p/\partial x)_0=eg_nL_n[\exp(eV/kT)-1]& \\ \times\tanh(d_l/L_n)-\frac{eg_0L_n}{a_n^2-1}[a_n\exp(d_l/L_\lambda)& \\ \times\operatorname{sech}(d_l/L_n)-a_n-\tanh(d_l/L_n)].& \qquad (19)\end{aligned}$$

For Case (2),

$$\begin{aligned} p=\tau_p\left\{g_p[\exp(eV/kT)-1]+\frac{g_0}{a_p^2-1}\right\}& \\ \times\frac{\cosh[(d_r-x_r)/L_p]}{\cosh d_r/L_p}-\frac{\tau_p g_0}{a_p^2-1}\bigg[a_p\exp(-d_r/L_\lambda)& \\ \times\frac{\sinh(x_r/L_p)}{\cosh(d_r/L_p)}+\exp(-x_r/L_\lambda)\bigg]+\tau_p g_p.& \qquad (20)\end{aligned}$$

$n$ is the same as Case (1).

$$\begin{aligned} I_p(0)=eg_pL_p[\exp(eV/kT)-1]& \\ \times\tanh(d_r/L_p)-\frac{eg_0L_p}{a_p^2-1}[a_p-a_p& \\ \times\exp(-d_r/L_\lambda)\operatorname{sech}(d_r/L_p)-\tanh(d_r/L_p)].& \qquad (21)\end{aligned}$$

$I_n(0)$ is the same as Case (1). Case (3) is obtained by interchanging the letters $n$ and $p$ in Case (1). Case (4) is obtained by interchanging the letters $n$ and $p$ in Case (2). For any of these cases, the total current density is $I=I_p(0)+I_n(0)$. We may write this expression

$$\begin{aligned} I=e[\exp(eV/kT)-1]& \\ \times(g_pL_p'+g_nL_n'-eg_0(L_1+L_2),& \qquad (22)\end{aligned}$$

where $L_p'$, $L_n'$, $L_1$, and $L_2$ are the appropriate coefficients of the corresponding terms in such expressions as Eq. (21). This current is in the direction conventionally called "reverse" in rectifier nomenclature. For convenience, we shall change the signs in the right-hand side of Eq. (22) so that we have

$$I=eg_0L-egL'[\exp(eV/kT)-1], \qquad (23)$$

where $L=L_1+L_2$ and $gL'=g_pL_p'+g_nL_n'$. Solving Eq. (23) for $V$, we obtain

$$V=\frac{kT}{e}\log\left(1+\frac{eg_0L-I}{egL'}\right). \qquad (24)$$

The power delivered to an external resistor $R$ connected to the electrodes is

$$P=IV=I\frac{kT}{e}\log\left(1+\frac{eg_0L-I}{egL'}\right). \qquad (25)$$

TABLE I. Values of constants used in the calculation of power conversion efficiency for germanium $p$-$n$ junctions.

| Resistivity $\rho$(ohm-cm) | $D_p$ (cm²/sec)[a] | $D_n$ (cm²/sec)[a] | $\tau_p$ ($\mu$sec)[b] | $\tau_n$ ($\mu$sec) | $L_p$ (cm) | $L_n$ (cm) | $p_p$ (cm$^{-3}$)[c] | $p_n$ (cm$^{-3}$) | $n_n$ (cm$^{-3}$)[c] | $n_p$ (cm$^{-3}$) | $L_\lambda$ (cm) | $\lambda$ (cm) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.4 | 44 | 94 | 80 | 500 | 0.059 | 0.22 | $1.5\times10^{15}$ | $6.3\times10^{11}$ | $1\times10^{15}$ | $4.2\times10^{11}$ | $1.7\times10^{-3}$ | $1.5\times10^{-4}$ |
| 0.014 | 44 | 94 | 50 | 500 | 0.047 | 0.22 | $1.5\times10^{17}$ | $6.3\times10^{9}$ | $1\times10^{17}$ | $4.2\times10^{9}$ | $1.7\times10^{-3}$ | $1.5\times10^{-4}$ |

[a] Pearson, Haynes, and Shockley, Phys. Rev. **78**, 295 (1950).
[b] See reference 9.
[c] Reference 3, pp. 16–17.

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[7] R. N. Hall (private communication).

Setting $dP/dI=0$, we find that the current for maximum power output is

$$I_m=\frac{egL^1(1+g_0L/gL')eV_n/kT}{1+eV_m/kT}, \tag{26}$$

and $V_m$, the voltage for maximum power is given by

$$\exp(eV_m/kT)=\frac{1+g_oL/gL'}{1+eV_m/kT} \tag{27}$$

Hence, the maximum power $P_m$ is

$$P_m=I_mV_m=\frac{egL'(1+g_0L/gL')eV_m/kT}{1+eV_m/kT}V_m. \tag{28}$$

The load resistance for maximum power is

$$R_m=V_m/I_m. \tag{29}$$

The open-circuit voltage is

$$V_0=(kT/e)\log(1+g_0L/gL'). \tag{30}$$

The short-circuit current is

$$I_s=eg_0L. \tag{31}$$

Equations (30) and (31) are useful in determining the quantities $gL'$ and $g_0L$ experimentally from which the maximum power output to be expected can be calculated.

## IV. DISCUSSION AND NUMERICAL EXAMPLES

The equations given above can be used to calculate the efficiency of a $p$-$n$ junction as a power converter. The input power with monochromatic radiation of wavelength $\lambda$ and intensity $H_s$ photons/cm² sec is

$$P_i=H_s(hc\times 10^{-7}/\lambda)\,(\text{watts/cm}^2), \tag{32}$$

where $h$ is Planck's constant in erg-sec, $c$ is the velocity of light in cm/sec and $\lambda$ is the wavelength in cm. The efficiency of the junction as a power converter is

$$\text{Eff.}=P_m/P_i, \tag{33}$$

where $P_m$ is given by Eq. (28). To obtain a curve of the efficiency as a function of any of the quantities in Eq. (28), it is necessary to solve Eq. (27) numerically for a series of values and plot the resulting points.

We consider the efficiency of junctions made of approximately 1 ohm-cm material and those made of approximately 0.01 ohm-cm material. The experimental constants needed for these calculations were taken from the current literature. In the following calculations, we have taken $\lambda=1.5$ microns. We have assumed that the absorption coefficient for 1 ohm-cm material and 0.01 ohm-cm material is the same as that measured[8] in 48 ohm-cm $n$ germanium, since we are dealing for the most part with absorption in the fundamental band which involves the breaking of valence bonds and does not depend on the concentration of holes or electrons. The values of the mean lifetimes of minority carriers for the 1 ohm-cm material have been found by experiment;[9] those for the 0.01 ohm-cm material are extrapolated from the same experimental results. Table I gives the experimentally-determined constants used in the calculations.

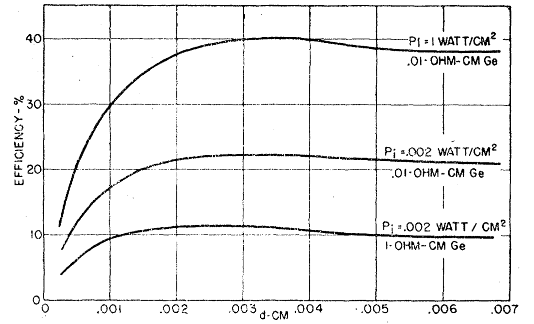

FIG. 3. Efficiency of power conversion as a function of the distance from electrode to junction.

Figure 3 shows the efficiency of power conversion *versus* the thickness $d$ of the $p$ material and that of the $n$ material (the total thickness is $2d$). We have taken $d_r=d_l=d$ and have assumed the $n$ material is irradiated (Case 4). For all regions of the curves, the maximum nonequilibrium concentration of the minority carrier is never greater than one-tenth the equilibrium concentration of the majority carrier in accord with the assumptions listed above under No. (2). It will be noted that all three curves rise rapidly in the region where the material is so thin that it is transparent. This region is probably of little practical importance, since such thin sections would be too difficult to prepare. As the thickness increases and the material becomes opaque, the efficiency rises to a maximum and gradually decreases. This gradual decrease results from the increase in the total recombination rate with thickness. This increase is not very fast since the thickness is in all cases small compared with the diffusion length. Thus it is possible to make the assembly considerably thicker than the optimum without an excessive loss in efficiency. This is an important point, since it means that the thicker, more easily realizable assemblies are useful.

The 0.01 ohm-cm material, because it has a higher equilibrium concentration of majority carriers, can be used with power inputs up to 2 watts/cm² at 300°K before the concentration of minority carriers becomes so great that the theory is not valid. The corresponding limit for the 1 ohm-cm material is 0.004 watt/cm² for the optimum thickness. Figure 4 shows the variation of efficiency for input power in the 1 ohm-cm material and Fig. 5 that for the 0.01 ohm-cm material. It will be

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[8] H. B. Briggs, J. Opt. Soc. Am. **42**, 686 (1952).

[9] Burton, Hull, Morin, and Severiens, J. Phys. Chem. **57**, 853 (1953).

noted that the efficiency rises sharply with the power input and then levels off. By expanding the exponential in Eq. (27) and retaining only the first-order term, we obtain for the low input-power efficiency:

$$\text{Eff.}=\frac{1}{4}\frac{g_0L}{gL'}\frac{L}{L_\lambda}\frac{\exp(-d/L_\lambda)}{hc/\lambda}kT,\quad (g_0L\ll gL'),\tag{34}$$

showing that the efficiency starts from zero and is linear with $g_0$, which is proportional to the input power. Such a variation, of course, follows from the variation of the output power for low intensities:

$$P_m=\tfrac{1}{4}[(g_0L)^2/gL']kT.\tag{35}$$

This variation is obtained because, initially, both the current and the voltage increase linearly with input power. The variation gradually changes from a square law to an almost linear relation at high input power, because, for large $g_0$,

$$I_m\rightarrow eg_0L,\tag{36}$$

$$V_m\rightarrow\frac{kT}{e}\log\frac{g_0L}{gL'},\tag{37}$$

and

$$P_m=I_mV_m\rightarrow kTg_0L\log(g_0L/gL'),\tag{38}$$

giving an approximately linear variation of the output power with input power. The efficiency at high input power is consequently

$$\text{Eff.}=\frac{P_m}{P_i}=\frac{L}{L_\lambda}\frac{\exp(-d/L_\lambda)}{hc/\lambda}kT\log\left(\frac{g_0L}{gL'}\right).\tag{39}$$

It is interesting to consider the effect of temperature on the efficiency of power conversion. We must know the temperature variation of the quantities listed in Table I. Shockley[3] (p. 288) gives results which indicate that the variation of mobility resulting from both temperature and impurity scattering

$$\mu\sim T^{-b},\tag{40}$$

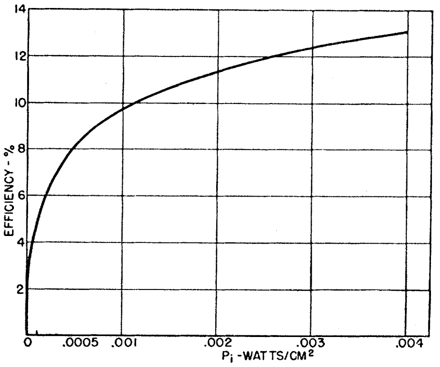

FIG. 4. Efficiency of power conversion as a function of power input for 1 ohm-cm germanium at 300°K, $d=2.5\times10^{-3}$ cm.

where $b$ is between zero and 1. The Einstein relation[3] shows that

$$D=(kT/e)\mu,\tag{41}$$

which makes $D$ almost temperature-independent. The diffusion length $L$ is given by

$$L=(D\tau)^{\frac{1}{2}},\tag{42}$$

where $\tau$ is the mean lifetime of an excess minority carrier. Shockley and Read[4] state that for highly doped material $\tau$ is insensitive to temperature. Therefore, $L$ itself is quite insensitive to temperature.

In the temperature range in which all donor or acceptor impurities are ionized, the concentration of the majority carrier does not change with temperature. The minority carrier concentration, however, changes exponentially with temperature and therefore, in accord with Eq. (4),

$$g_p=p_n/\tau_p,\tag{4}$$

the thermal generation rate does likewise. By using the relation developed by Shockley[3] (p. 245) it is easily shown that

$$gL'=2.33\times10^{31}T^3\exp(-eV_g/kT)\left[\frac{L_p'}{n_n\tau_p}+\frac{L_n'}{p_p\tau_n}\right]\tag{43}$$

so that the thermal generation rate varies exponentially with temperature with an activation energy of $eV_g$, where $V_g$ is the potential difference between the valence band and the conduction band in the semiconductor. Thus, the low-intensity efficiency [Eq. (34)] decreases exponentially as the temperature increases. The limiting high-intensity efficiency [Eq. (39)] does not decrease so rapidly as the low-intensity efficiency, but still has a negative slope. In Fig. 4 curves of efficiency *versus* input power are shown for the 0.01 ohm-cm material for three different temperatures, *viz.*, 200°K, 300°K, and 400°K. These curves were calculated from the exact expression (28) and Eq. (43) and conform in general with our approximate analysis above.

We see that the *p-n* junction is potentially a useful device for the conversion of light energy to electrical energy. Under our assumption of unit quantum efficiency, we may calculate the total number of charges created per second, the fraction of this total that passes through the external circuit, and hence the fraction that is lost by recombination. For example, at 300°K in the 0.01 ohm-cm material with a power input of 0.1 watt/cm$^2$ we have $7.55\times10^{17}$ photons/cm$^2$ sec incident on the surface. Potentially the charge generation is $7.55\times10^{17}$ charges/sec. However, because a small fraction of the photons is transmitted through the material, the charge generation is $7.43\times10^{17}$ charges/sec. The number per unit time passing through the external resistor is $6.76\times10^{17}$ charges/sec. The number lost by recombination is $0.67\times10^{17}$ charges/sec. Thus, 89.4 percent of the possible charges generated pass through the external resistor; 1.6 percent are not generated because of photon transmission, and 9 percent do not pass through the external circuit because of recombination. The potential energy obtained per charge is 0.305 electron volt. The potential energy expended in creating each charge is 0.825 ev (the energy per photon). Thus, each charge gives up only 37 percent of the energy used to create it giving the power conversion efficiency of 33 percent as plotted on the curve. From this analysis it is apparent that this device would be efficient in using the charges created, but that the potential energy per charge available for useful work is the limiting factor in power conversion efficiency. If we consider the same material with the same power input at 200°K, we find that transmission through the material is still about zero.[10] The number of charges/sec passing through the external resistor is $7.1\times10^{17}$. This is 94 percent of those potentially available or 95.6 percent of those created, leaving only 4.4 percent lost by recombination. The potential energy per charge delivered externally is 0.453 ev. This is 54.8 percent of the energy expended in creating a charge. The power conversion efficiency is thus $0.94\times54.8$ percent$=51.5$ percent as plotted on the curve.

For greatest power conversion efficiency, it is thus apparent that the following conditions must be met: (1) The energy per photon must be nearly equal to the band gap (it must not be less, of course). (2) The potential barrier height in the junction should be as close to the band gap as possible. (3) The whole assembly should be short compared with the diffusion lengths of the minority carriers, but great enough in extent so that the incident radiation will be absorbed.

Condition (1), in the practical case of a fundamental power source, would be applied to the solar spectrum. Since we are not dealing with monochromatic radiation, a semiconductor with a gap energy somewhere near the photon energy characteristic of the peak of the solar spectrum, i.e., 2 ev would be required.

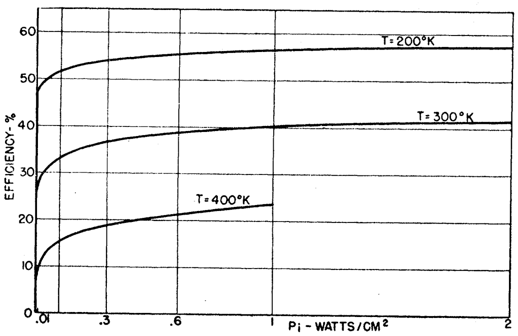

FIG. 5. Efficiency of power conversion as a function of power input for 0.01 ohm-cm germanium for three different temperatures, $d=3.5\times10^{-3}$ cm.

Our analysis shows that Condition (2) can be met by using material with the doping as high as possible and by keeping the temperature as low as possible. In addition, materials with band gaps larger than germanium and the same resistivity have potential barriers greater relative to the band gap.

Condition (3) can be readily met in practice, since the diffusion lengths of the minority carriers are reasonably long.

In practice, some provision for cutting down surface reflection would have to be made. The reflection coefficient for germanium is of the order of 50 percent. Using a germanium junction with a band gap of 0.72 ev and solar radiation and sufficient cooling, one might expect to realize an efficiency of 10 or 12 percent (assuming a reflection loss of $\frac{1}{3}$) for power conversion. The feasibility and engineering details of such a system would have to be determined by examining the over-all economy of this method of power production.

## ACKNOWLEDGMENTS

It is a pleasure to acknowledge many fruitful discussions with Dr. J. W. Moyer. Helpful conversations were also held with Dr. R. P. Ruth. The interest and encouragement of Mr. C. Mannal are greatly appreciated.

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[10] H. Y. Fan and M. Becker, *Semiconducting Materials* (Academic Press, New York, 1951), p. 138.