EFFECT OF DIMENSIONS ON THE EFFICIENCY OF RADIANT ENERGY CELLS

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ABSTRACT

This work deals with the enhancement of the quantum efficiency and photovoltaic energy conversion efficiency of a P-N semiconducting cell by optimizing the dimensions of the cell. Based on the Shockley-Read statistics a general expression for the quantum efficiency of monochromatic incident radiant energy photons has been derived in terms of the absorption coefficient of the incident photons, the minority carrier diffusion length, the built-in electrostatic field appearing in diffused cells and the surface recombination velocity in the exposed layer of the cell. Although the expressions derived may be used for all semiconducting P-N cells, special efforts have been made in the analysis and computations of the Germanium P-N cell. The Germanium cells show a great potential for photovoltaic energy conversion from radiant sources other than the sun. The results for Germanium indicate that the quantum efficiency strongly depends upon the thicknesses of the exposed and base layers. The built-in electrostatic field and the surface recombination velocity in the exposed layer influence the quantum efficiency greatly. Optimization studies for the thicknesses of the exposed and base layers of a N-P type Germanium for different values of minority carrier diffusion length, built-in electrostatic field and surface recombination velocity have been worked out.

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1. INTRODUCTION

In recent years attempts have been made to convert efficiently the radiant energy from incandescent sources burning fossil or nuclear fuels to electrical energy directly. Semiconductor cells (P-N junctions) are used for solid-state conversion of radiant energy to electrical energy. A P-N junction is formed in a semiconducting material in the region where the impurity content changes from P type to N type. The Shockley equation for an ideal P-N junction in the dark is

$$I = I_o \left(e^{\frac{qV}{kT}} - 1\right) \tag{1}$$

When illuminated with electromagnetic radiation, the portion of the energy contained in the energy interval $\lambda = 0$ to λ_g would produce electron-hole pairs.

$$\lambda_g = \left[\frac{hc}{E_g}\right]$$

where E_g is the forbidden energy gap of the semiconductor. The electrons and holes generated by the radiation are swept by the electric field in the space charge region resulting in an electric current. If Q is the number of photons falling per unit area on the cell and they are in the wave length interval $\lambda = 0$ to λ_g, the radiation current density

$$J_R = q\, Q \cdot \eta_Q \tag{2}$$

where η_Q is the quantum efficiency of the photons. It is the efficiency with which a radiant energy photon produces a useful charge carrier. In his work on the conversion efficiency of radiant energy, Jain (1) has shown that Germanium cells have great potential for radiant energy conversion. Assuming that the penetration of the incident radiation is only confined to the exposed layer and assuming that there is no built-in electrostatic field due to impurity concentration gradient and there are no surface states in the exposed layer, Jain (2) computed the quantum efficiency of the incident radiant photons in a Germanium cell. The assumption made by Jain were only made to simplify computations and to get a preliminary idea about the quantum efficiency.

The following work incorporates a general treatment of the quantum efficiency as well as the photovoltaic conversion efficiency of a semiconductor cell in terms of the minority carrier diffusion length, built-in electrostatic field, surface recombination velocity and the thickness of the cell. The effect of photons penetrating in the base layer has also been taken into account. The effect of dimensions of the cell on the conversion efficiency and quantum efficiency has been discussed for a Germanium N-P cell.

2. QUANTUM EFFICIENCY OF MONOCHROMATIC RADIANT ENERGY PHOTONS IN SEMICONDUCTORS

In radiant energy conversion, one does not deal with monochromatic radiations but on the other hand deals with an arbitrary spectral distribution curve, which may or may not fit in a black or gray body spectral distribution curve at a given source temperature T_s. It is, however, convenient to determine the quantum efficiency η_Q, for various wavelengths in the wave length interval $\lambda = 0$ to $\lambda = \lambda_g$ and carry over the results to radiant energy spectrum. Consider a P-N junction of a semiconducting material with incident radiation of wave length λ in the wave length interval $\lambda_g > \lambda > 0$ falling on the N layer of the material. Referring to figure 1, which we use as a model for the study, we make the following assumptions:

(1) Boltzmann statistics can be used in place of Fermi-Dirac statistics.

(2) The junction region (depletion region) 2δ in Fig. 1 is negligible as compared to the thickness of the P or N layers and as compared to the diffusion lengths of holes in the N layer and electrons in the P layer.

$$2\delta \ll d_P$$
$$2\delta \ll d_N$$
$$2\delta \ll L_P$$
$$2\delta \ll L_n$$

(3) Constant built-in electrostatic field due to concentration gradient of impurity atoms exist only in the exposed layer of the cell, i.e.,

$$\mathcal{E} = \frac{1}{d_N} \cdot \frac{kT}{q} \ln \frac{(N_D-N_A)_{x=dN}}{(N_D-N_A)_{x=0}} = \text{constant}$$

where $(-N_A + N_D)_{x=d_N}$ is the net concentration of impurity atoms at $x = d_N$ and $(N_D - N_A)_{x=0}$ is the net concentration of impurity atoms at the junction.

(4) Surface states exist in the exposed layer and the surface recombination velocity may vary between 0 and 10^6 cm/sec.

(5) Each photon absorbed produces only one pair of electron and hole or the quantum yield is unity. (3)

The assumption that the electrostatic field due to concentration gradient of impurity is constant is far from reality in the vicinity of the junction. This has been correctly pointed out by Lindmayer, Wrigley and Schoeni (4). Since determination of the exact electrostatic field even with an exponential variation of impurity atoms is very involved, constant electrostatic field had to be taken to simplify computations.

Assuming that in Fig. 1, the incident radiation falls on the N type surface, holes which are minority carriers in the N type material would contribute to the diffusion current and hence the radiation current. If the incident radiation penetrates into the P layer across the junction, electrons which are the minority carriers in the P layer will also contribute to the diffusion current. The current density contribution due to holes in N layer is

$$J_p = -q\, D_p \cdot \frac{dp}{dx}\Big|_{x=\delta} \tag{3}$$

and the current density contribution due to electrons in the P layer is

$$J_n = q\, D_n \frac{dn}{dx}\Big|_{x=-\delta} \tag{4}$$

The total current density in the cell is therefore equal to

$$J = J_p + J_n \quad . \tag{5}$$

$\left.\frac{dp}{dx}\right|_{x=\delta}$ and $\left.\frac{dn}{dx}\right|_{x=-\delta}$ can be obtained by solving the continuity equations for minority carriers in the N and P layers respectively. The steady state continuity equation for holes in the exposed layer may be written with the help of Shockley, Read statistics (5).

$$\frac{d^2p}{dx^2} + \frac{\mathcal{E}}{\mathcal{E}_c} \cdot \frac{1}{L_p} \frac{dp}{dx} - \frac{p}{L_p^2} = -\left(\frac{Q_\lambda}{L_\lambda D_p} e^{\frac{x-d_N-\delta}{L_\lambda}} + \frac{p_N}{L_p^2}\right) \tag{6}$$

where $\mathcal{E}_c = \frac{kT}{q} \cdot \frac{1}{L_p}$ is the critical electric field.

Q_λ is the number of photons falling on unit area per second.

$(L_\lambda)^{-1}$ is the absorption coefficient of the radiation in the material.

The general solution of equation (6) is

$$p(x) = A\, e^{\frac{x}{L_1}} + B\, e^{+\frac{x}{L_2}} + \frac{Q_\lambda L_\lambda \tau_p}{(L_\lambda^2 - L_p^2 - \frac{\mathcal{E}}{\mathcal{E}_c} L_\lambda L_p)} e^{\frac{x-d_N-\delta}{L_\lambda}} + p_N \tag{7}$$

In equation (7) A, B are constants of integration and

$$L_1 = -\frac{1}{2L_p}\frac{\mathcal{E}}{\mathcal{E}_c} + \frac{1}{2L_p}\sqrt{\left(\frac{\mathcal{E}}{\mathcal{E}_c}\right)^2 + 4} = \frac{\alpha}{L_p}$$

$$L_2 = -\frac{1}{2L_p}\frac{\mathcal{E}}{\mathcal{E}_c} - \frac{1}{2L_p}\sqrt{\left(\frac{\mathcal{E}}{\mathcal{E}_c}\right)^2 + 4} = -\frac{\beta}{L_p}$$

The boundary conditions for the determination of constants A and B are:

(1) At $x = \delta$ $\qquad p = p_N\, e^{\frac{qV}{kT}}$

(2) At $x = \delta + d_N$ $\qquad J_p = q\left[-D_p \frac{dp}{dx} - \frac{\mathcal{E}}{\mathcal{E}_c} \cdot p \cdot \frac{1}{L_p}\right]_{x=\delta+d_N} = q\, s\, p_{(x=d_N+\delta)}$

or $\left.\frac{dp}{dx}\right|_{x=\delta+d_N} = \left(-\frac{S}{D_p} - \frac{\mathcal{E}}{\mathcal{E}_c} \cdot \frac{1}{L_p}\right) \cdot p_{(x=\delta+d_n)}$

$$\text{or } \left.\frac{dp}{dx}\right|_{x=\delta+d_N} = F_p \cdot p_{(x=\delta+d_n)} \tag{8}$$

where $F_p = -\left(\frac{S}{D_p} + \frac{\mathcal{E}}{\mathcal{E}_c} \cdot \frac{1}{L_p}\right)$

With the help of the above boundary conditions it is possible to determine constants A and B and evaluate J_p by finding out $\frac{dp}{dx}\Big|_{x=\delta}$.

The continuity equation for electrons in the P layer (base layer) with $\mathcal{E} = 0$ is given by

$$\frac{d^2n}{dx^2} - \frac{n}{L_n^2} = -\left[\frac{Q_\lambda}{L_\lambda D_n} e^{\frac{x-d_N-\delta}{L_\lambda}} + \frac{n_p}{L_n^2}\right] \quad (9)$$

The general solution of the above equation is given by

$$n(x) = C\, e^{\frac{-x}{L_n}} + D\, e^{\frac{x}{L_n}} + \frac{Q_\lambda L_\lambda \tau_n}{L_\lambda^2 - L_n^2} e^{\frac{x-d_N-\delta}{L_\lambda}} . \quad (10)$$

The constants C and D can be determined with the help of the following boundary conditions:

(i) At $x = -\delta$ $\quad n = n_p\, e^{\frac{q\vartheta}{k_T}}$

(ii) At $x = -\delta - d_N$ $\quad \frac{dn}{dx} = 0$ (assuming no surface recombination velocity in the base layer).

With the help of the above boundary conditions it is possible to determine constants C and D and evaluate J_n by finding out $\frac{dn}{dx}\Big|_{x=-\delta}$. The quantum efficiency as defined by equation (2) is found to be given by

$$\eta_{Q_\lambda} = \frac{1}{(a_\lambda^2 - 1)}\left[e^{\frac{d_p}{L_p} - \frac{d_p + d_N}{L_p} \cdot \frac{1}{a_\lambda}}\left(1 - \tanh\frac{d_p}{L_p}\right) + e^{\frac{-d_N}{L_p} \cdot \frac{1}{a_\lambda}}\left(a_\lambda \tanh\frac{d_p}{L_p} - 1\right)\right]$$

$$+ \frac{1}{\left(a_\lambda^2 - \frac{\mathcal{E}}{\mathcal{E}_c} \cdot a_\lambda - 1\right)}\left[\frac{(\alpha+\beta)(F_p L_\lambda - 1)\, e^{\frac{-d_N}{L_p}(\alpha-\beta)} + a_\lambda\left[\alpha\beta(1-F_p L_1)\, e^{\frac{d_N}{L_p}\beta} - (1 + F_p L_2)\, e^{-\frac{d_N}{L_p}\alpha}\right] e^{-\frac{d_N}{L_p} \cdot \frac{1}{a_\lambda}}}{\alpha(1-F_p L_1)\, e^{\frac{d_N}{L_p}\beta} + \beta(1 + F_p L_2)\, e^{\frac{d_N}{L_p}\alpha}} + e^{\frac{-d_N}{L_p} \cdot \frac{1}{a_\lambda}}\right] \quad (11)$$

where $a_\lambda = \frac{L_\lambda}{L_p}$.

Equation (11) shows that the quantum efficiency of incident photons depends upon $\frac{d_p}{L_p}$, $\frac{d_N}{L_p}$, a_λ, $\mathcal{E}$ and S. If there is no built-in electrostatic field and there are no surface states, equation (11) may be reduced to:

$$\eta_{Q_\lambda} = \frac{1}{a_\lambda^2 - 1}\left[\left(e^{\left(\frac{d_p}{L_p} - \frac{d_p + d_N}{L_p}\cdot\frac{1}{a_\lambda}\right)} - e^{\frac{d_N}{L_p}}\right) + \left(e^{\frac{d_N}{L_p}}\tanh\frac{d_N}{L_p} - e^{\frac{d_p}{L_p} - \frac{d_p + d_N}{L_p}\cdot\frac{1}{a_\lambda}}\tanh\frac{d_p}{L_p}\right) + a_\lambda\left(\tanh\frac{d_p}{L_p} + \tanh\frac{d_N}{L_p}\right)e^{-\frac{d_N}{L_p}\cdot\frac{1}{a_\lambda}}\right] \qquad (12)$$

Equation (12) reduces to Jain's (2) equation for quantum efficiency if $d_p = 0$. The reverse saturation current density for this case is given by

$$J_o = \left[\frac{p_N D_p q}{L_p}\tanh\frac{d_N}{L_p} + \frac{n_p D_n q}{L_n}\tanh\frac{d_p}{L_n}\right] \qquad (13)$$

Equation (13) shows that J_o depends upon $\frac{d_N}{L_p}$ and $\frac{d_p}{L_n}$.

3. COMPUTATIONS AND DISCUSSION OF THE QUANTUM EFFICIENCY OF A GERMANIUM P-N CELL

Since Germanium cells show a great potential for use in radiant energy conversion, an analysis of the Germanium cell has been carried out with the help of equations (11) and (12). From the data published by Dash and Newmann (6) the absorption coefficients of Germanium for various wave lengths are given in table 1.

TABLE 1.

Wave length λ (microns)	Absorption Coefficient $(L_\lambda)^{-1}$ cm^{-1}
0.4	7.5×10^5
0.6	1.8×10^5
0.8	4.3×10^4
1.0	1.7×10^4
1.2	$9. \times 10^3$
1.4	$7. \times 10^3$
1.6	$2. \times 10^2$
1.66	6.1×10
1.73	3.5×10
1.8	1.2×10
1.87	0.7×10

The following data has been assumed for Germanium:

$L_p = 0.05$ cm $\qquad D_p = 25\ cm^2/sec.$

In order to study the effect of surface recombination velocity S and built-in electrostatic field $\mathcal{E}$, the following intervals for values of $\mathcal{E}$ and S have been selected.

$$\mathcal{E} = 0 \text{ to } 500 \text{ V/cm}$$
$$S = 0 \text{ to } 10^6 \text{ cm/sec}$$

3.1. Optimization of the Cell-dimensions:

With the help of the data given above, quantum efficiency was computed for various wave length photons for different values of d_p and d_N in the model of Figure 1 for Germanium cells. Figure 2 shows $\frac{d_p}{L_p}$ $\frac{d_N}{L_p}$ that for wavelengths in the interval 0.4 to 1.5 microns the quantum efficiency is independent of the thickness of the base layer (P layer) so long as d lies between 0.1 to 1.8, but decreases with increasing thickness of the $\frac{p}{L_p}$ exposed layer. In order to explain this behavior of the quantum efficiency a dotted curve has been drawn from the computations of reference (2), which assumes $d_p = 0$. For the dotted curve it may be said that when the exposed layer is very thin, it is transparent to the incident radiation and the quantum efficiency is low. As the thickness of the exposed layer increases, the layer starts getting opaque, the quantum efficiency rises to a maximum and then gradually decreases. The gradual decrease results from the fact that the rate of recombination of the minority carriers increases with the thickness of the exposed layer. With $\frac{d_p}{L_p}$ lying between 0.1 to 1.8, the solid curve of Figure 2 is obtained. For the case when the exposed layer is thin and is transparent to the radiation, the radiation is absorbed within a small thickness of the base layer because the absorption coefficient of Germanium for the wavelength interval under consideration is very large. The absorption by the base layer boosts the quantum efficiency and no distinct maximum value of quantum efficiency is obtained. (Solid curve Fig. 2). For larger thickness of the exposed layer or for larger values of $\frac{d_N}{L_p}$ the thickness of the base layer has no effect on the quantum efficiency since most of the radiation is absorbed in the exposed layer.

For incident photons with wave lengths greater than 1.5μ, the absorption coefficient is not large and all the radiation is not absorbed in the exposed layer. The thickness of the base layer would, therefore, affect the quantum efficiency. Figure 3 shows the variation of quantum efficiency with the thickness of the exposed layer for various values of $\frac{d_p}{L_p}$ for photons of wave length $\lambda = 1.66\mu$. The quantum efficiency increases with increasing values of $\frac{d_p}{L_p}$ up to $\frac{d_p}{L_p} = 0.9$ and decreases for larger values of the ratio.

Curves similar to Figure 3 were computed for all wave lengths in the interval 1.5 to 1.87μ. The results show that $\frac{d_p}{L_p} = 0.9$ is an optimum value of the ratio for the maximum quantum efficiency. This is exhibited by Figure 4, which shows the maximum values of the quantum efficiency as obtained by varying $\frac{d_N}{L_p}$ and plotted against $\frac{d_p}{L_p}$. Fig. 5 shows the variation of quantum efficiency with wave length as obtained with the optimum value of $\frac{d_p}{L_p} = 0.9$ and plotted against $\frac{d_N}{L_p}$.

For the wave length interval 0.4 to 1.6μ it is desirable to have $\frac{d_N}{L_p}$ small, but for photons of larger wave lengths $\frac{d_N}{L_p}$ should be larger. This could be explained by the fact that photons of larger wave lengths would need larger layers to be absorbed, because of their comparatively lower values of absorption coefficients.

The effects of built-in electrostatic field and surface recombination velocity are shown in Figure 6. With zero built-in electrostatic field the quantum efficiency decreases sharply with increasing surface recombination velocity. A built-in electrostatic field of 500 V/cm in Fig. 6 compensates for the detrimental effects of the surface recombination velocity. It may, therefore, be concluded that it is advantageous to have diffused cells for radiant energy conversion.

Figure 7 shows the variation of quantum efficiency with wave length for various thicknesses of the exposed layer for typical values of S and $\mathcal{E}$. It can be seen from the figure that $\eta_{Q\lambda} \sim 1$ for $\lambda < 1.6\mu$. For wave lengths $\lambda > 1.6\mu$, the larger the value of $\frac{d_n}{L_p}$, the greater the quantum efficiency. For reasons evident $\frac{d_N}{L_p}$ must be less than 1.

3.2 <u>Average Quantum Efficiency for Sources of Radiation Energy with Different Temperatures</u>:

In the previous section, the quantum efficiency has been computed for monochromatic incident radiations in Germanium cells. A black body or gray body source emits electromagnetic radiation covering the entire wave length range from $\lambda = 0$ to $\lambda = \infty$. The spectral radiancy of a source at temperature T_s is given by

$$W_\lambda = \epsilon C_1 \lambda^{-5} \cdot \frac{1}{e^{\frac{C_2}{\lambda T_s}} - 1} \quad \text{watts/cm}^2\text{-cm}$$

where C_1 and C_2 are constants
ϵ is the emissivity of the emitter

Only the part of the radiation lying between $\lambda = 0$ and $\lambda = \lambda_g = \frac{hc}{Eg}$, the cut off wave length of the material of the junction would produce electron-hole pairs. The number of photons lying between $\lambda = 0$ and $\lambda = \lambda_g$ is different for different source temperature and the photons of different wave lengths have different quantum efficiency. The average quantum efficiency may be defined by

$$\overline{\eta_Q} = \frac{\int_{\lambda=0}^{\lambda_g} W_\lambda \cdot d\lambda \cdot \frac{\lambda}{hc} \cdot \eta_{Q\lambda}}{\int_{\lambda=0}^{\lambda_g} W_\lambda \cdot d\lambda \cdot \frac{\lambda}{hc}} = \frac{\int_{\lambda=0}^{\lambda_g} \eta_{Q\lambda} \cdot \frac{C_1 \lambda^{-4} \cdot d\lambda}{e^{C_2/\lambda T_s} - 1}}{\int_{\lambda=0}^{\lambda=g} \frac{C_1 \lambda^{-4} . d\lambda}{e^{\frac{C_2}{\lambda T_s}} - 1}}$$

It is very difficult to solve the above expression of average quantum efficiency as in a given spectrum it is not possible to determine the number of photons at one discrete wave length. As an alternative, the whole spectrum of the black or gray body radiation was divided into small intervals. The quantum efficiency of the average wave length in that interval was multiplied by the number of photons in that interval. A summation was carried out for wave length interval $\lambda = 0$ to $\lambda = \lambda_g$. As such

$$\overline{\eta_Q} = \frac{\sum_{1}^{N} \eta_{Q_n}(\lambda) \cdot \lambda \cdot W_{\lambda_n} \cdot \Delta\lambda_n}{\sum_{1}^{N} W_{\lambda_n} \cdot \Delta\lambda_n \cdot \lambda},$$

where N is the total number of intervals.

For typical values of $\mathcal{E}$, S and for optimum value $\frac{d_p}{L_p} = 0.9$, the average quantum efficiency is plotted against $\frac{d_N}{L_p}$ for a Germanium cell with different black body sources in Fig. 8. The higher the temperature of the source, the lesser the energy in wave length interval 1.5 to 1.87μ and therefore the higher the efficiency.

3.3. Photovoltaic Energy Conversion Efficiency:

With the help of average quantum efficiency, the short circuit current density J_R can be computed

$$J_R = q\, Q\, \overline{\eta_Q}$$

where Q is the number of photons in the wave length interval $\lambda = 0$ to $\lambda = \lambda_g$. The maximum power load voltage V_{mp} is obtained by the following relationship

$$\left(\frac{q\, V_{mp}}{kT} + 1\right) e^{\frac{qV_{mp}}{kT}} = e^{\frac{qV_{oc}}{kT}}$$

where $$V_{oc} = \frac{kT}{q} \ln\left(\frac{J_R}{J_o} + 1\right)$$ (reference 7)

J_o is the reverse saturation current density.
Knowing V_{mp}, the maximum power output per unit area p_{mp} can be computed. The total input power per unit area p_{input} is given by

$$p_{input} = \int_0^\infty W_\lambda \cdot d\lambda\ .$$

The photovoltaic energy conversion efficiency of the cell is, therefore, given by

$$\eta_{cell} = \frac{p_{mp}}{p_{input}}$$

Figure 9 shows the per unit cell efficiency of a Germanium with typical values of $\mathcal{E}$ and S and as a function of $\frac{d_N}{L_p}$ for various sources.

4. CONCLUSIONS

Several conclusions can be drawn from the study of effect of dimensions on the efficiency of radiant energy cells:

(1) For field free and no surface states in the cells, an optimum average quantum efficiency of 85% and optimum cell's conversion efficiency of 15% can be obtained, provided the dimensions of the cells are chosen such that $d_N = 0.1\ L_p = 0.005$ cm, and $d_p = 0.9\ L_p = 0.045$ cm and the radiant energy source is a black body at $T_s = 2000°K$ (for Germanium cell).

(2) With a typical value of built-in electric field of 500 volt/cm and surface recombination velocity of 10,000 cm/sec in the exposed layer of Germanium P-N cells, an optimum average quantum efficiency of 93% and optimum cell conversion efficiency of 17% can be achieved, if the dimension of the cells are chosen such that $d_p = 0.9\ L_p = 0.045$ cm, $d_N = 0.9\ L_p = 0.045$ cm and the radiant energy source is a black body at $T_s = 2000°K$.

(3) It is suggested that photons of wave length in the interval 1.6μ to 1.87μ for the case of Germanium cells should be reflected and conserved so that the average quantum efficiency may be further improved.

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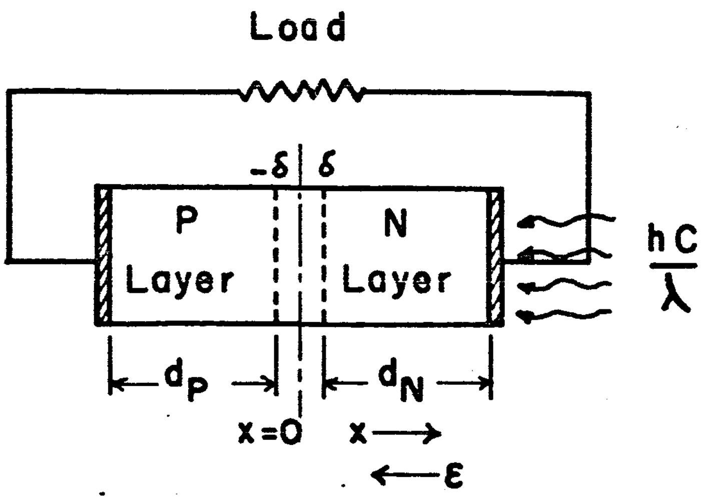

Fig. 1 Model of the P-N Junction

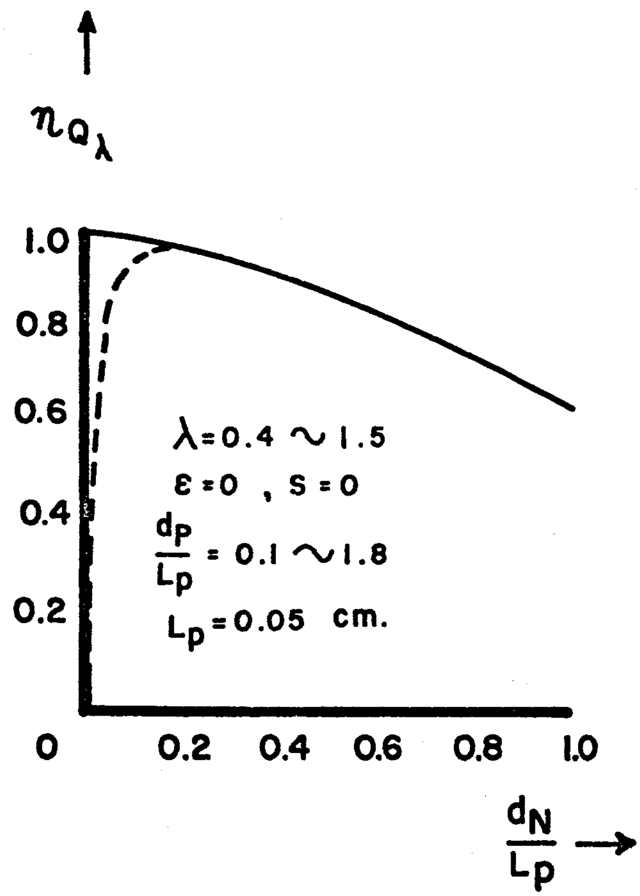

Fig. 2 Quantum Efficiency vs. Thickness of exposed layer of a Ge cell.

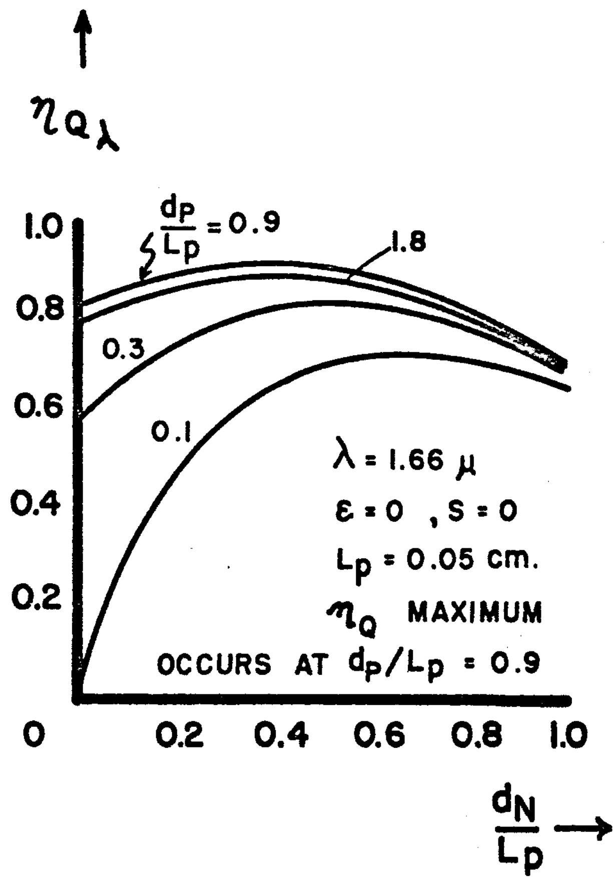

Fig. 3 Quantum Efficiency vs. thickness of the exposed layer of a Ge cell with base layer thickness as parameters.

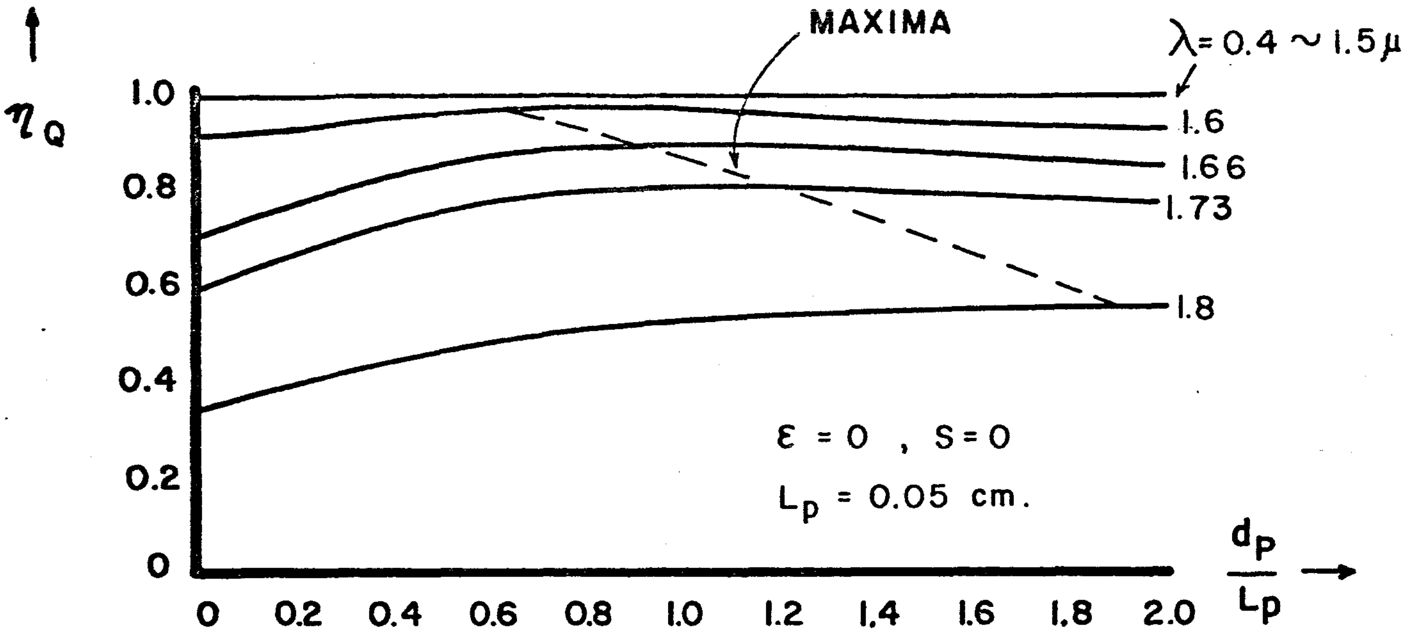

Fig. 4 Maximum quantum efficiency vs. thickness of base layer of a Ge cell with optimized exposed layer.

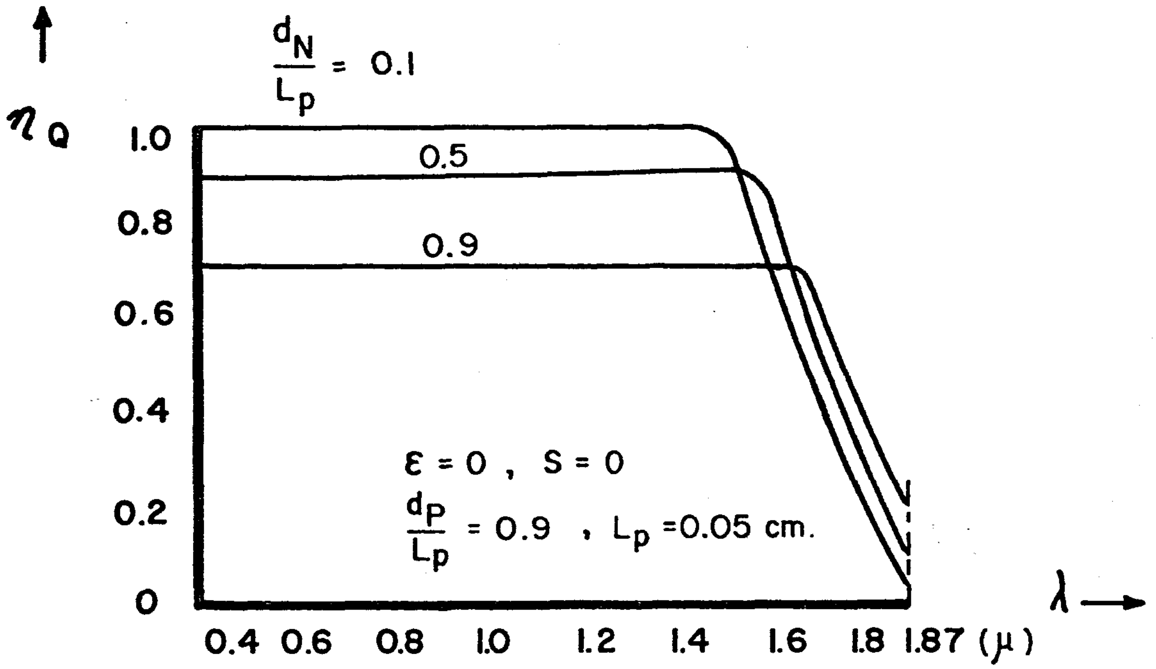

Fig. 5 Quantum efficiency vs. wave length of incident photons for various value of $\frac{d_N}{L_p}$.

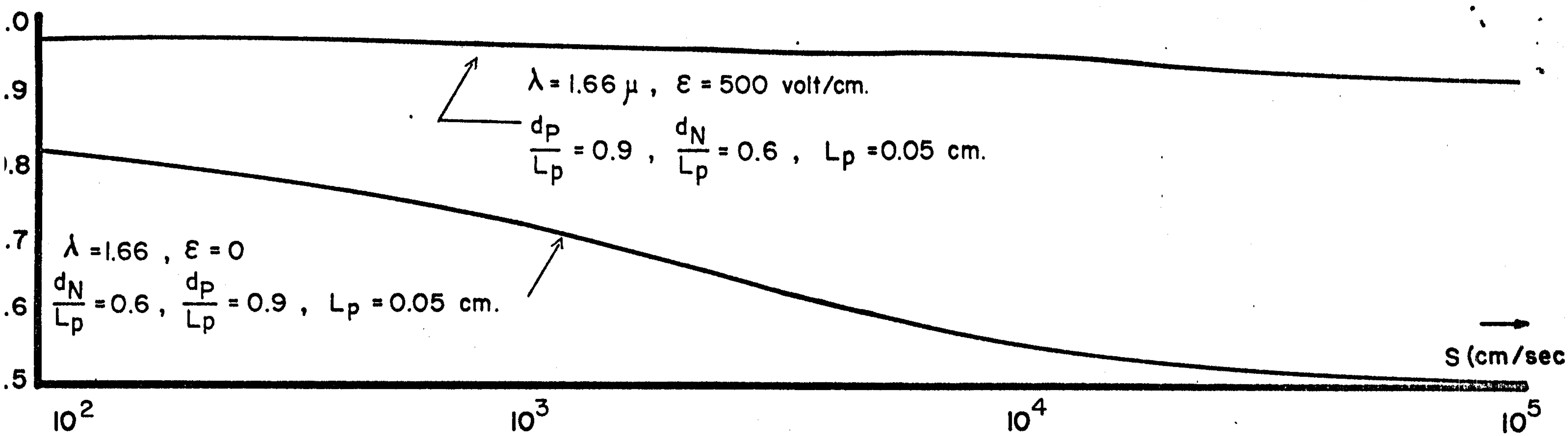

Fig. 6 Effects of surface recombination velocity (in the exposed layer) on the quantum efficiency of a Ge cell with and without built-in electrostatic field.

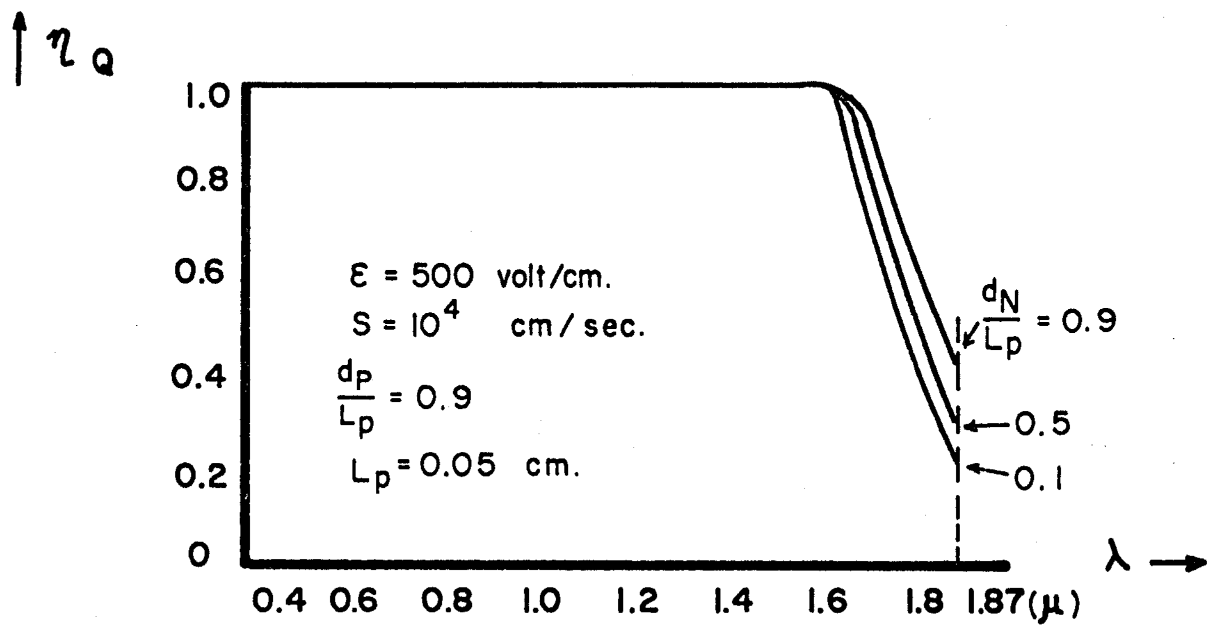

Fig. 7 Quantum efficiency vs. wave length λ → for various values of $\frac{d_N}{L_p}$.

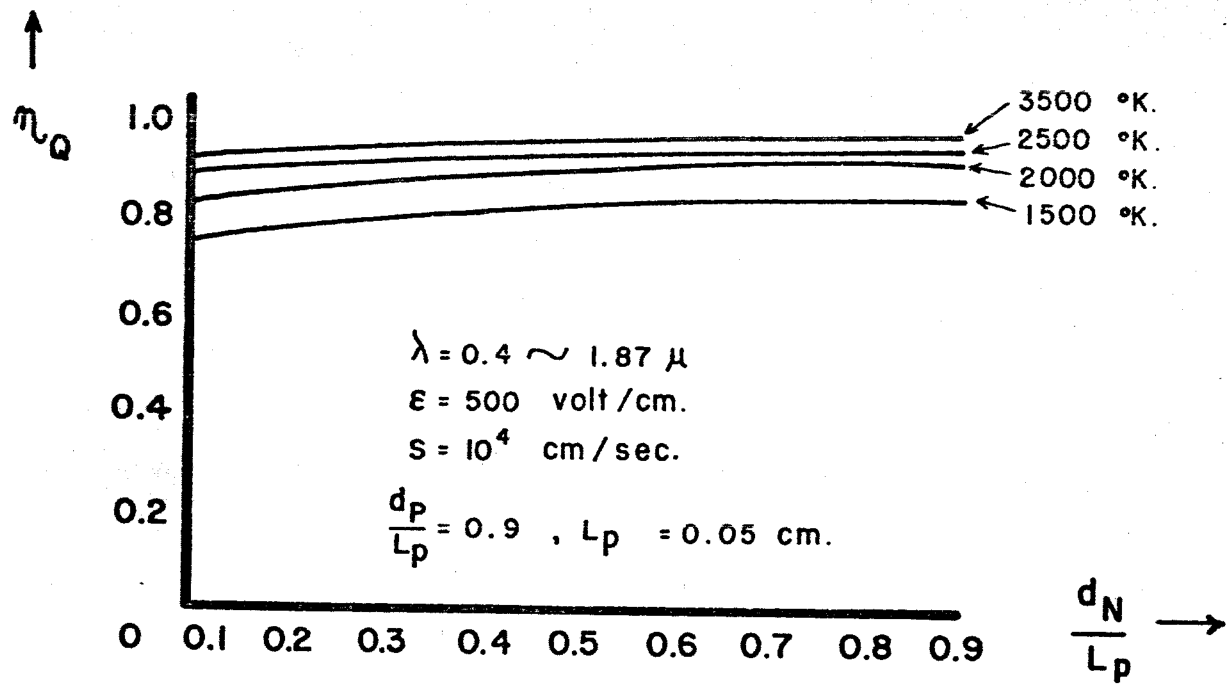

Fig. 8 Variation of average quantum efficiency of a Ge cell with thickness of the exposed layer for various source temperatures.

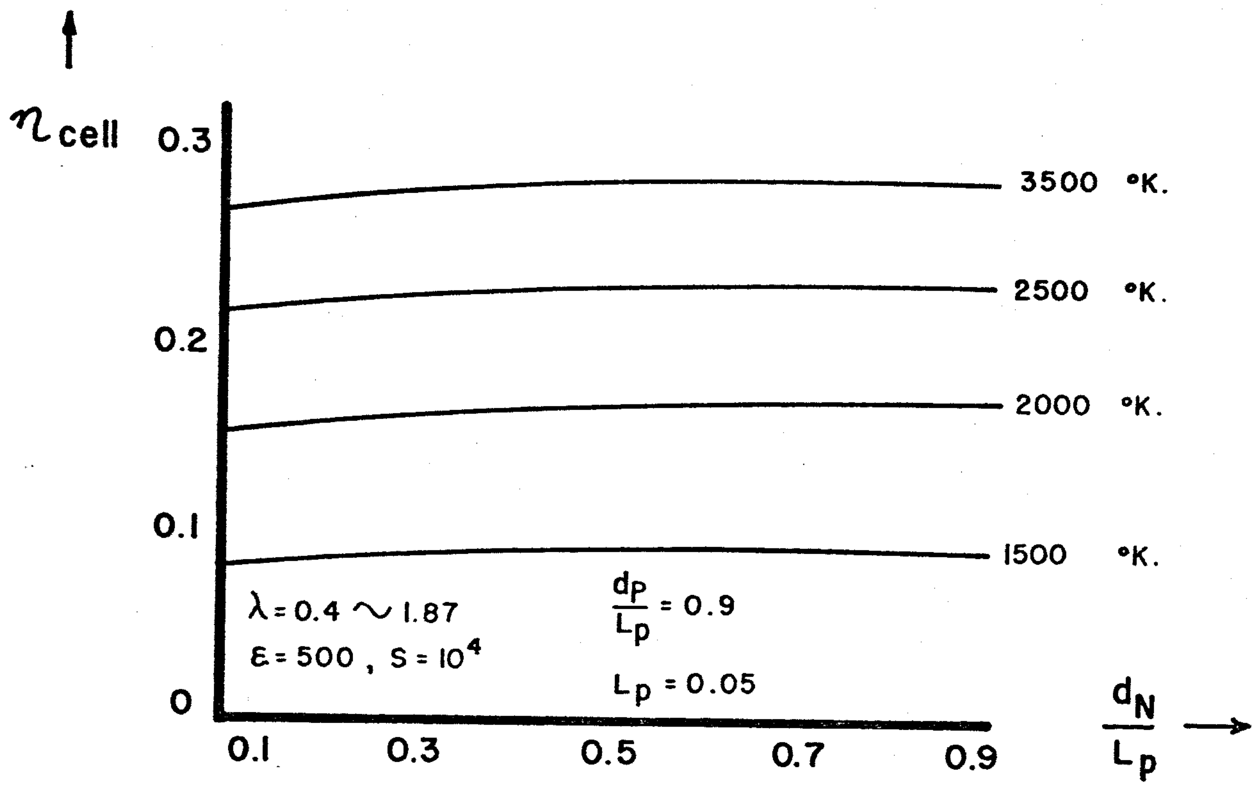

Fig. 9 Variation of photovoltaic conversion efficiency of a Ge cell with thickness of the exposed layer for various source temperatures.