N87-26439

CALCULATIONS OF THE DISPLACEMENT DAMAGE AND SHORT-CIRCUIT CURRENT DEGRADATION IN PROTON IRRADIATED (AlGa)As-GaAs SOLAR CELLS

C.S. Yeh and S.S. Li*
University of Florida
Gainesville, Florida

and

R.Y. Loo
Hughes Research Laboratories
Malibu, California

A theoretical model for computing the displacement damage defect density and the short-circuit current (I_{sc}) degradation in proton-irradiated (AlGa)As-GaAs p-n junction solar cells is presented in this paper. Assumptions were made with justification that the radiation induced displacement defects form an effective recombination center which controls the electron and hole lifetimes in the junction space charge region and in the n-GaAs active layer of the irradiated GaAs p-n junction cells. The degradation of I_{sc} in the (AlGa)As layer was found to be negligible compared to the total degradation. In order to determine the I_{sc} degradation, the displacement defect density, path length, range, reduced energy after penetrating a distance x and the average number of displacements formed by one proton scattering event were first calculated. The I_{sc} degradation was calculated by using the electron capture cross section in the p-diffused layer and the hole capture cross section in the n-base layer as well as the wavelength dependent absorption coefficients. Excellent agreement was obtained between our calculated values and the measured I_{sc} in the proton irradiated GaAs solar cells for proton energies of 100 KeV to 10 MeV and fluences from 10^{10} p/cm^2 to 10^{12} p/cm^2.

INTRODUCTION

Although a handful of publications on the study of radiation damage in (AlGa)As-GaAs solar cells have been reported in the literature, there have been no accurate models for computing the short-circuit current (I_{sc}) degradation in the proton irradiated (AlGa)As-GaAs p-n junction solar cells. Wilson et al. [1-3] first proposed a simple model for calculating the I_{sc} degradation in the electron and proton irradiated GaAs solar cell. In their model they assumed that the radiation induced displacements within the solar cells formed recombination centers for the minority carriers produced by photon absorption. Yaung [4] modified Wilson's model

*This work was supported by Air Force Wright Aeronautical Laboratories under subcontract through Universal Energy Systems Inc.

including the wavelength dependent absorption coefficient of the GaAs cell. However, both these models did not consider the reduced energy of an incident proton after penetrating the (AlGa)As window layer, and hence the I_{sc} degradation calculated from these two models was found less satisfactory when compared with the experimental data for the proton irradiated (AlGa)As-GaAs solar cells [5]. The discrepancy found in both models is due primarily to the oversimplified assumptions made by Wilson and Yaung in which the recombination cross sections for both p-type and n-type GaAs were assumed equal and the empirical formulae for the path length (P) and the range (R) of an incident proton in resting in the (AlGa)As and GaAs solar cells were assumed the same. These assumptions are in fact not valid for the proton irradiated GaAs solar cells considered in this paper.

In this paper, we present a more rigorous model for the displacement damage calculations in the (AlGa)As-GaAs solar cells under normal incident conditions, and show the correlation between the defect parameters and the I_{sc} degradation for the proton irradiated (AlGa)As-GaAs solar cells. To facilitate our study, the experimental data on I_{sc} degradation in proton irradiated (AlGa)As-GaAs solar cells fabricated by Hughes Research Laboratories (HRL) were used for comparison with our theoretical calculations.

EXPERIMENTAL DETAILS

Figure 1 shows the physical structure and dimensions of the (AlGa)As-GaAs solar cells used in this study. The wide bandgap Be-doped $Al_{0.85}Ga_{0.15}As$ epi-layer was grown by infinite solution liquid-phase epitaxy (LPE) with dopant density of 3-5 x 10^{18} cm^{-3} and used as a window layer to reduce the surface recombination at the p-GaAs surface. During the window layer growth, a p-n junction was formed by Be diffusion into the n-GaAs buffer layer. The hole density in the p-GaAs layer is around 10^{18} cm^{-3}. The Sn-doped n-GaAs buffer layer was grown on the n+-GaAs substrate by LPE technique, which has an electron density of around 2 x $10^{17} cm^{-3}$. The n-GaAs substrate was doped with tellurium with dopant density of 5 x 10^{17} cm^{-3}. A thin window layer of less than 0.5 μm thick and a diffused junction depth of less than 0.5 μm were used to ensure the low optical absorption loss and to increase radiation hardness [6]. The n-GaAs buffer layer is 10 um thick. No cover glass was used in this cell. AuZn ohmic contacts on the window layer were about 0.3 to 0.4 μm thick with an Ag overlay of about 4 μm. The n-substrate contact is AuGeNi of about 0.5 μm thickness with silver overlay. The anti-reflection coating is Ta_2O_5. The AMO conversion efficiency of around 16 to 17 percent was obtained for (AlGa)As-GaAs solar cells fabricated under these conditions.

The solar cells used in this study were irradiated at room temperature by protons with energies of 0.1, 0.2, 0.29, 2, 5 and 10 MeV and fluences varying from 10^{10} to 10^{12} p/cm^2.

THEORETICAL MODEL FOR I_{sc} DEGRADATION

Displacement Damage

A solid may be affected in two ways by the energetic particle bombardments as follows: [7]

(1) Lattice atoms are removed from their regular lattice sites, producing displacement damage.

(2) The irradiating particle causes change in the chemical properties of the solid via ion implantation or transmutation.

In the displacement model, it is assumed that the dominant defect produced by incident protons is due to lattice displacement. Under this assumption, an atom will be invariably displaced from its lattice site during collisions if its kinetic energy exceeds the threshold energy (T_d) for the atomic displacement to take place, and conversely will not be displaced if its kinetic energy is less than T_d [8]. We assume that the transferred energy (T) to the atom which was struck is transformed to the kinetic energy only. If T is sufficiently large (i.e., $T >> T_d$), then additional displacement can be produced by the recoiling nucleus before coming to rest at an interstitial site. Therefore, for $T > T_d$, the total number of displacements produced by a normal incident proton to the solar cell can be calculated by using the expression

$$D(E_0) = \int_0^R N \sigma \overline{V} \, dR \qquad (1)$$

where $D(E_0)$ = number of displacement/incident proton,

E_o = initial energy of an incident proton,

N = number of atoms per unit volume of the solar cell,

σ = displacement cross section for energetic protons,

$\overline{V}$ = average number of displacements formed by one proton-scattering event,

R = range of the proton of energy E_0.

Since the mass of the proton is heavy, it is necessary to consider the multiple scattering effect of the proton. Therefore, $D(E_0)$ with multiple scattering effect is obtained by replacing R with path length P in Eq. (1). The difference however, between the path length and range of a proton coming to rest in the GaAs cell is less than 5 percent for those protons with energies greater than one MeV. Thus, the multiple scattering effect is important only for low energetic protons. The empirical formulae for the path length, range and reduced energy (E_{re}) after penetrating a distance x were obtained by fitting the data of Janni [9] as shown in Appendix.

CALCULATIONS OF I_{sc} DDGRADATION

The total I_{sc} in an (AlGa)As-GaAs solar cell is equal to the sum of I_{sc} in the (AlGa)As window layer, p-GaAs layer and n-GaAs layer as well as in the depletion region of the junction. Since the spectral response of the window layer is much less than that of the whole solar cells [10] and the thickness of the window layer is less than 0.5 μm, it is reasonable to assume that I_{sc} degradation of the window layer is negligible compared with the total I_{sc} degradation.

To derive an expression for the I_{sc} in a proton-irradiated GaAs p-n junction solar cell, the following assumptions are made: [1,11-13]

(1) radiation-induced defects do not alter the internal electric field,

(2) radiation-induced defects alter the cell performance mainly through change of minority-carrier lifetimes in the bulk, and

(3) radiation-induced displacements within the solar cell form recombination centers for the minority carriers of electron-hole pairs produced by photon absorption.

The short circuit current, I_{sco} for the unirradiated solar cell is given by:

$$I_{sco}(\lambda) = \int_0^t \eta_c(x)\, \rho\, (x,\lambda)\, dx \tag{2}$$

and for the damaged cell, the I_{sc} can be expressed by [1, 4]

$$I_{sc}(\lambda) = \int_0^t \eta_c(x)\, [1 - F\,(x)]\, \rho\, (x,\lambda)\, dx \tag{3}$$

The normalized I_{sc} degradation can thus be calculated by using the expression:

$$I_{sc}/I_{sco} = \int_{\lambda_1}^{\lambda_2} I_{sc}(\lambda)\, d\lambda \Big/ \int_{\lambda_1}^{\lambda_2} I_{sc,o}(\lambda)\, d\lambda \tag{4}$$

where

$F(x)$ = $1 - E_2\, [\sqrt{6}\, \sigma_r\, \Phi\, |D(E_x) - D(E_{xj})|]$, the recombination loss coefficient

$E_2(z)$ = exponential integral of order 2,

σ_r = capture cross section; for electrons and holes σ_r is different,

Φ = proton fluence,

D(E) = total number of displacements calculated from equation (1),

E_x = reduced proton energy after penetrating a distance, x.

x_j = junction depth,

$\rho(x,\lambda)$ = photo-absorption rate at depth x, $\rho(x,\lambda) = K\,\alpha\,\exp(-\alpha\,x)$,

K = integrated photon flux in the absorption band,

α = the absorption coefficient,

$\eta_c(x)$ = current collection efficiency,

Note that t is the thickness of the cell and λ_1 and λ_2 denote the short-wave and long-wave limits of the total useful solar spectra for the GaAs cell (i.e. λ_1 = 0.35 um and λ_2 = 0.9 um).

RESULTS AND DISCUSSION

The parameters involved in the I_{sc} degradation calculations are absorption coefficients of GaAs, current collection efficiency, electron and hole capture cross sections, total number of displacement defects formed and fluences and energy of protons. In order to calculate the total number of displacement defects, parameters such as P, R and E_{re} of incident protons should also be calculated. In our computer simulation, we have assumed that the absorption coefficient and current collection efficiency of the GaAs cell remain constant after irradiation. Thus, according to Eq. (3) it is obvious that the larger the recombination loss F(x), the smaller the I_{sc}, and the smaller the F(x), the larger the value of $E_2(z)$. Since the fluence of protons through the entire GaAs is constant, and the total number of displacement is bound to the initial energy of incident protons, the values selected for electron and hole capture cross sections are critical to the I_{sc} degradation calculations. The values of parameters used in our simulation are listed in Table 1.

Since the I_{sc} degradation in the (AlGa)As window layer is negligible, it is reasonable to calculate the I_{sc} degradation in the GaAs solar cell only. In our simulation we first calculated E_{re} after penetrating the window layer. If the E_{re} is equal to zero, then there is no damage to the GaAs solar cell. Otherwise, the E_{re} would be applied as the initial energy of the proton for the GaAs solar cell. According to our calculations, the proton would lose 50 KeV after penetrating a 0.34 μm thick window layer. Therefore, there is no damage to the GaAs solar cell if the incident proton energy is less than 50 KeV. It is appropriate to use two different recombination cross sections (i.e., σ_n in the p-region, and σ_p in the n-region of the solar cell) for our computer simulation since the recombination mechanism in the p-diffused region is controlled by the electron capture cross section and by the hole capture cross section in the n-region. We have chosen the best value of 1.8 x 10^{-14} cm^2 for the electron capture cross section in the p-region and 1.5 x 10^{-13} cm^2

for the hole capture cross section in the n-region in our calculations. These approximations are consistent with the fact that p-GaAs is more radiation hardness than that of n-GaAs, as confirmed by the deep-level transient spectroscopy. [13]

Figure 2 shows the range of proton irradiated $Al_{0.85}Ga_{0.15}As$-GaAs solar cells as a function of proton energy. Since the thickness of the window layer is assumed equal to 0.34 μm, for proton energies less than 50 KeV there will be no damage created by these protons. The 100 KeV protons are stopped at about 0.8 μm below the surface, creating damage close to the junction. The 200 KeV protons penetrate deeper into the GaAs cell and are stopped at about 1.34 μm below the surface, causing most of the damages throughout the junction. The 290 KeV protons are stopped at about 2.0 μm below the surface, producing damages to the bulk of the n-GaAs layer. The one Mev protons are stopped at about 10 μm which is equal to the thickness of the cell. For proton energies higher than one MeV, protons will penetrate the p-n junction cell, and hence create less damages to the cell.

It should be noted that the total number of displacement defects as shown in Fig. 3 are obtained from Eq. (1) by integrating along the path length if the multiple scattering effect is considered, and by integrating along the range if the multiple scattering effect is excluded. Thus, the accurate empirical formulae of path length and range for $Al_{0.85}Ga_{0.15}As$-GaAs solar cells are important for displacement defect density calculations. The reasons for using Janni's data [9] instead of the data given by Andersen and Ziegler [14] are twofold: (1) data of path length and range obtained by Janni are for GaAs instead of Ga and As elements, and (2) data of range included high energy multiple scattering correction, and are therefore applicable for proton energies above 100 KeV [9].

As shown in Fig. 4 the maximum I_{sc} degradation was created by the 200 KeV protons. The reason the 200 KeV protons create much more damage than those higher energy protons is that most of the damages caused by 200 KeV protons occurred in the junction and inside the active region of the n-GaAs layer. The solid dots shown in Fig. 4 for proton energies of 100 KeV, 290 KeV, 2 MeV, 5 MeV and 10 MeV are the experimental data for the proton irradiated (AlGa)As-GaAs p-n junction solar cells and the solid curves are calculated from Eq. (4).

SUMMARY AND CONCLUSIONS

A rigorous model for computing the I_{sc} degradations in proton irradiated AlGaAs/GaAs p-n junction solar cells has been developed in this work, and calculations of I_{sc} degradation in proton irradiated (AlGa)As-GaAs solar cells have been carried out for proton energies from 100 KeV to 10 MeV and fluences from 10^{10} to 10^{12} p/cm^2. In addition, the empirical formulae for the path length, range, total number of displacement defects formed and reduced energy after penetrating a distance have also been derived for the proton irradiated (AlGa)As-GaAs solar cells. The result shows that the I_{sc} degradations increases with increasing proton fluences. The results show an excellent agreement between our calculated values and the experimental data for the I_{sc} degradation in (AlGa)As-GaAs p-n junction solar cells.

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APPENDIX

1. Empirical Formulae for Path Length and Range

(i) $Al_{0.85}Ga_{0.15}As$ window layer:

$$P = \begin{cases} 3.300891\ E^{0.550212} & E \leqq 0.15\ \text{MeV} \\ 10.79623\ E^{1.163227} & E \leqq 1.25\ \text{MeV} \\ 9.963561\ E^{1.1565366} & E \leqq 10.0\ \text{MeV} \end{cases}$$

$$R = \begin{cases} 5.010253\ E^{0.865712} & E \leqq 0.175\ \text{MeV} \\ 10.31089\ E^{1.257302} & E \leqq 1.500\ \text{MeV} \\ 9.561796\ E^{1.579760} & E \leqq 10.00\ \text{MeV} \end{cases}$$

where P and R are in μm and E is in MeV. Unless specify otherwise, the unit of length is in μm and that of energy is in MeV.

(ii) GaAs solar cell:

$$P = \begin{cases} 3.859312\ E^{0.545909} & E \leqq 0.150\ \text{MeV} \\ 11.85262\ E^{1.135261} & E \leqq 1.250\ \text{MeV} \\ 10.92040\ E^{1.550638} & E \leqq 10.00\ \text{MeV} \end{cases}$$

$$R = \begin{cases} 5.861370\ E^{0.878671} & E \leqq 0.175\ \text{MeV} \\ 11.23652\ E^{1.243952} & E \leqq 1.500\ \text{MeV} \\ 10.42719\ E^{1.567030} & E \leqq 10.00\ \text{MeV} \end{cases}$$

2. Empirical Formulae for Reduced Energy

(i) $Al_{0.85}Ga_{0.15}As$ window layer:

With Multiple Scattering

$$E_{re} \begin{cases} = 0.00130 - 0.01750x + 0.22468x^2 - 0.10073x^3, & E_0 \leqq 0.1\ \text{MeV.} \\ = -0.01715 + 0.13045x - 0.00424x^2 + 0.000079x^3, & E_0 \leqq 1.75\ \text{MeV} \\ = 0.85196 + 0.04353x - 0.000087x^2 + 0.000000095x^3, & E_0 \leqq 10\ \text{MeV} \end{cases}$$

where E_{re} is in MeV; E_0 is the initial energy in MeV, x is the distance in μm

Without Multiple Scattering:

$$E_{re} \begin{cases} = -0.00031 + 0.09588x + 0.159531x^2 - 0.120901x^3, & E_0 \leqq 0.1 \text{ MeV} \\ = 0.01389 + 0.13373x - 0.00462x^2 + 0.000091x^3, & E_0 \leqq 1.75 \text{ MeV} \\ = 0.67525 + 0.05087x - 0.000014x^2 + 0.000002x^3, & E_0 \leqq 10 \text{ MeV} \end{cases}$$

(ii) GaAs solar cell:

Multiple Scattering:

$$E_{re} \begin{cases} = 0.00131 - 0.014452 + 0.155159x^2 - 0.0557547x^3, & E_0 \leqq 0.1 \text{ MeV} \\ = -0.02554 + 0.11890x - 0.00346x^2 + 0.000059x^3, & E_0 \leqq 1.75 \text{ MeV} \\ = 0.82870 + 0.04092x - 0.000076x^2 + 0.000000078x^3, & E_0 \leqq 10 \text{ MeV} \end{cases}$$

Without Multiple Scatterins:

$$E_{re} \begin{cases} = -0.00027 + 0.08880x + 0.10807x^2 - 0.06943x^3, & E_0 \leqq 0.1 \text{ MeV} \\ = 0.01126 + 0.12242x - 0.00386x^2 + 0.000071x^3, & E_0 \leqq 1.75 \text{ MeV} \\ = 0.85343 + 0.04137x - 0.000078x^2 + 0.000000081x^3, & E_0 \leqq 10 \text{ MeV} \end{cases}$$

Table 1. Input parameters for the calculations of the I_{sc} degradation of the proton irradiated (alGa)As-GaAs Solar Cells.

Cell	d(μm)	x_j(μm)	t(μm)	T_d(eV)	Z_2	M_2	$\sigma_n(cm^2)$	$\sigma_p(cm^2)$
(AlGa)As	0.34	-	-	-	-	-	-	-
GaAs	-	0.5	10	9.5	32	72.5	1.8×10^{-14}	1.5×10^{-13}

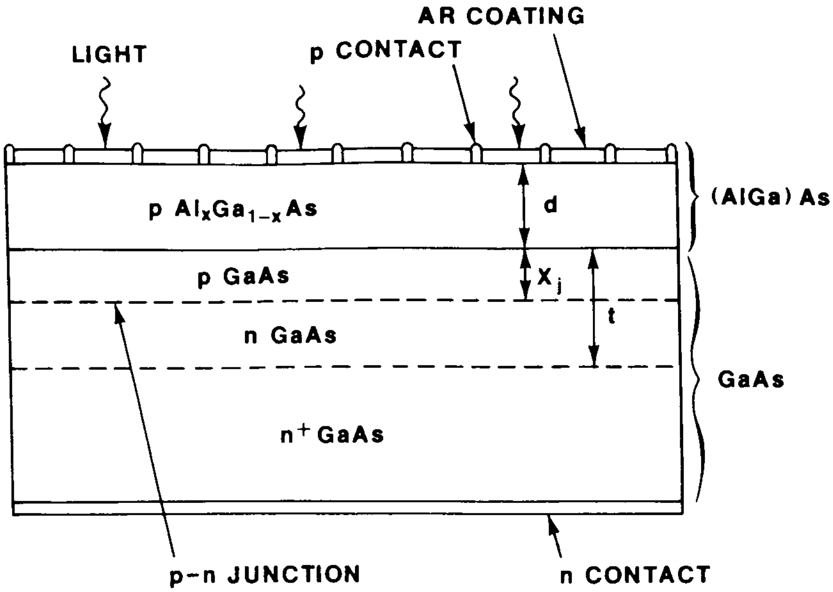

Fig. 1. The cross sectional view of a (AlGa)As-GaAs p-n junction solar cell.

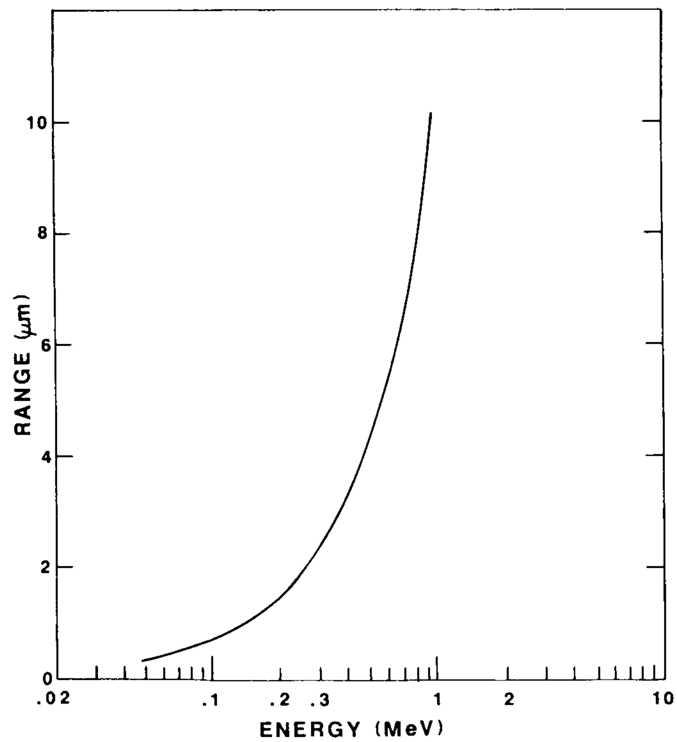

Fig. 2. The range of the $Al_{0.85}Ga_{0.15}As$-GaAs solar cell vs. incident proton energies.

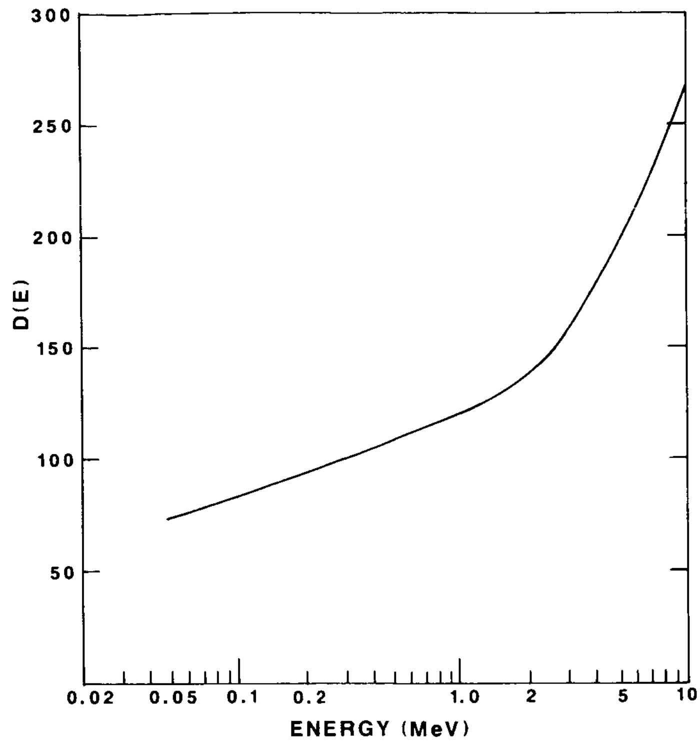

Fig. 3. The total number of displacement defect vs. incident proton energies for a GaAs p-n junction solar cell.

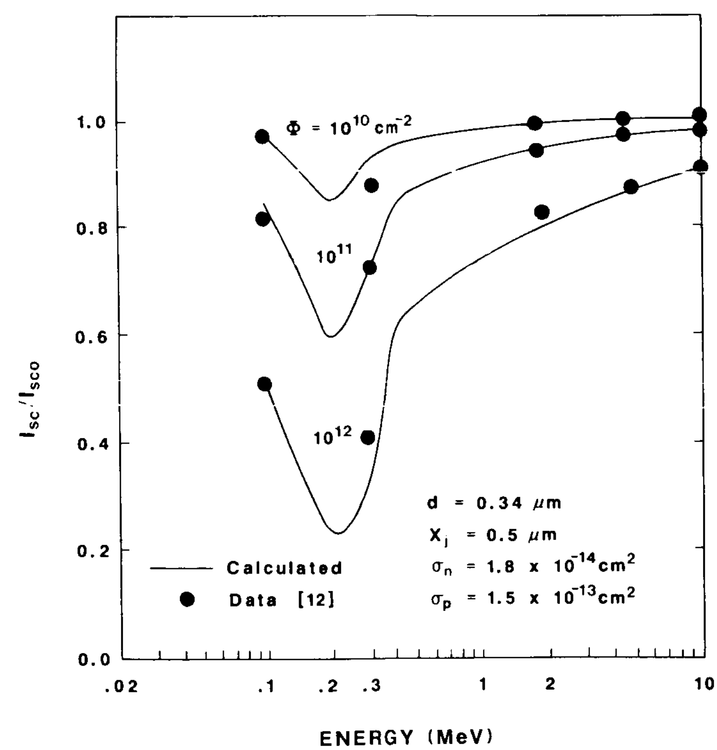

Fig. 4. The calculated I_{SC} degradation ratio in the $Al_{0.85}Ga_{0.15}As$-GaAs p-n junction solar cell. Solid curves are from our calculations, solid dots are the experimental data. The thickness of the window layer is 0.34 μm and the junction depth is 0.5 μm.