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**Research Article**

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# Static Mode Study of the Magnetic Field Effect on Series Resistance of a Parallel Vertical Junction Silicon Solar Cell under Monochromatic Illumination and Under Irradiation

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**Abstract** In this paper, we have made a theoretical study of a parallel vertical junction solar cell under monochromatic illumination, in static mode, under irradiation and under magnetic field. The resolution of the continuity equation which governs the generation, the recombinations and the electron scattering process in the base, allowed us to establish the expression of the electrons density in the base and deduce expressions of photocurrent density and the phototension depending on the wavelength λ, the recombination velocity at the junction Sf, magnetic field and irradiation parameters.

The expression of the series resistance are obtained from phototension and photocurrent density. We studied the influence of a magnetic field on the minority carriers density in the base, the photocurrent density, phototension and finally on the series resistance.

**Keywords** silicon vertical junction - magnetic field - irradiation - series resistance- recombination velocity

## 1. Introduction

We will effectuate,through this paper, a theoretical study of parallel vertical junction solar cell under monochromatic illumination, in static mode, under irradiation and under magnetic field.

The resolution of the continuity equation will enable us to establish the expression of the density of minority charge carriers in the base and deduct expressions the photocurrent density and phototension.

The expression of the resistance will be subsequently obtained.

We will study, in this paper, the impact of a change in applied magnetic field on the minority carriers density in the base, the photocurrent density, phototension and finally on the series resistance.

## 2. Theory

We consider a solar cell type of parallel vertical junction n + -p-p whose structure may be represented as follows:

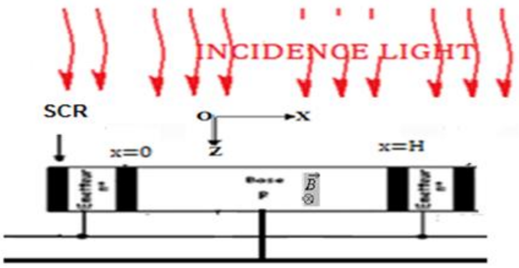


*Figure 1: Parallel vertical junctions of a solar cell*

When the solar cell is illuminated, there is creation of electron-hole pairs in the base.
The behavior of the minority carriers in the base (the electrons) is governed by the continuity equation integrating the generation, diffusion and recombination phenomena which cause the variation of the electrons density according to the width x of the base, its depth z , the recombination velocity at the junction, of the wavelength, applied magnetic field and irradiation parameters.
Solving this equation will allow us subsequently to have initially expressed the minority carrier density of the base and deduce those of the quantities and other solar cell electrical parameters.
The continuity equation in static mode is presented under the form:

$$D(B)\cdot\frac{\partial^2\delta(x,kl,\phi,\lambda,z,B)}{\partial x^2}-\frac{\delta(x,kl,\phi,\lambda,z,B)}{\tau(kl,\phi)}=-G(z,\lambda)$$

$\delta(x,kl,\phi,\lambda,z,B))$ describes the photogenerated minoritycharge carriers.

$D(B)=\frac{D_o}{\sqrt{1+(\mu B)^2}}$ [1] is the diffusion coefficient according to the magnetic field. B, the magnetic field,

$D_o$, the diffusion coefficient with the absence of magnetic field, μ denotes the mobility of the charge carriers.
τ(kl, φ) is the average lifetime of carriers.

We have the relationship: $\frac{1}{\tau(kl,\phi)}=\frac{1}{\tau_0}+kl\phi$ [2]

(H. W. Kraner et al, 1983), k1 and φ respectively denote the damage coefficient and the irradiation energy. $\tau_o$ is the average lifetime of carriers with the absence of irradiation.
G (z, λ) is the overall generation rate of the minority charge carriers according to the depth z of the base and wavelength λ.
The continuity equation can still be written as follows:

$$\frac{\partial^2\delta(x,kl,\phi,\lambda,z,B))}{\partial x^2}-\frac{\delta(x,kl,\phi,\lambda,z,B))}{L(kl,\phi)^2}+\frac{G(z,\lambda)}{D(B)}=0$$

$L(kl,\phi,B))=\sqrt{D(B)\times\tau(kl,\phi)}$ is the diffusion length.

The expression of the overall generation rate of the minority charge carriers is of the form [3]:

$$G(z,\lambda)=\alpha_t(1-R(\lambda))\cdot F\cdot\exp(-\alpha_t\cdot z)$$

R (λ) is the coefficient monochromatic reflection; F is the incident photons flux from a monochromatic radiation.
α is the coefficient of monochromatic absorption.

### 2.1. Solution of the continuity equation

**- Special solution:**

$$\delta_1(x)=\frac{L^2}{D}\alpha_t(1-R(\lambda)).F.\exp(-\alpha_t.z)$$

**-Solution of the equation with second member:**

$$\delta_2(x)=A\cosh\left(\frac{x}{L}\right)+B\sinh\left(\frac{x}{L}\right)$$

**-As the general solution is:**

$$\delta(x,z,\lambda,Sf,kl,\phi,B)=\left[A\cosh\left(\frac{x}{L(kl,\phi)}\right)+B\sinh\left(\frac{x}{L(kl,\phi)}\right)+\frac{L(kl,\phi)^2}{D(B)}\cdot\alpha_t(1-R(\lambda)).F.\exp(-\alpha_t z)\right]$$

**2.2. Search for coefficients A and B:**

**- The boundary conditions:**

**-As at the junction (x = 0) we have:**

$$D \cdot \frac{\partial \delta(x_t, z_t, \lambda, kl, \phi)}{\partial x}\bigg|_{x=0} = Sf \cdot \delta(x_t, z_t, \lambda_t, kl, \phi)\big|_{x=0}$$

$Sf$ is the recombination velocity at the junction. This is a phenomenological parameter that describes how the base minority carriers cross the junction. It can be split in two terms [4].

We have: $Sf = Sf_O + Sf_j$

$Sf_O$ induced by shunt resistance, is the intrinsic recombination velocity. It depends solely on the intrinsic parameters of the solar cell.

$Sf_j$ reflects the current flow imposed by an external charge and defines the operating point of the solar cell

**-In the middle of the base** $(x = \frac{H}{2})$ .The structure of the solar cell, with two identical junctions on both sides of the base, suggests equation below:

$$D \cdot \frac{\partial \delta(x)}{\partial x}\bigg|_{x=H/2} = 0$$

H is the thickness of the solar cell's base.

**3. Results and Discussion**

**3.1. Density profile minority charge carriers in the base**

Figure 2 below shows the profile of the electron density in the base according to its width x for different values of an applied magnetic field.

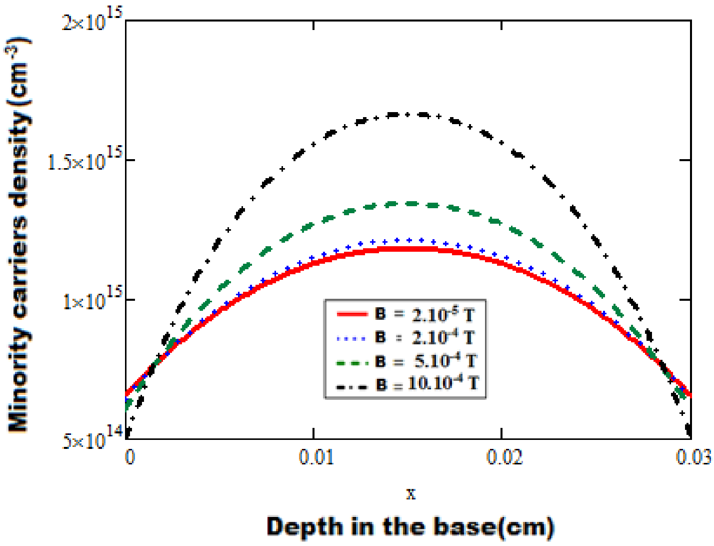


*Figure 2: Variation of the minority charge carriers according to the thickness of the base for different values of the magnetic field*

H=0, 03cm, Z =0, 0001cm, $L_o$=0, 01cm, λ = 0, 5 µm, kl = 10 $cm^2/s$,ϕ=50Mev, µ = 1000 $cm^2.V^{-1}.s^{-1}$

For a given magnetic field value, the analysis of the curve shows that the electrons density in the base is minimal at the levels of the junctions x = 0 and x = H and is maximum in the middle of the base.

We observe a symmetry of the density profile with respect to the axis x = $\frac{H}{2}$.

Moreover, in the middle of the base, the density increases according to the applied magnetic field and it decreases at the levels of junctions when the magnetic field increases.
Indeed the illumination of the base is homogeneous and we have two identical junctions on both sides of the base. The photogenered electrons diffuse toward the junctions which are passingzones but also thru high recombinations rate, which explains the aspect of the density profile.
When a magnetic field is applied to moving charge carriers, they are subjected to the action of the Lorentz magnetic force ($\vec{F} = q\vec{v} \wedge \vec{B}$) whose dynamic effect is manifested by a deviation of the charge carriers trajectory.
The presence of a magnetic field hampers the electrons diffusion toward the junctions, which explains the decrease of the density at the level of junctions, but also the accumulation of these carriers in the vicinity of the middle base.
More the magnetic field increases, more the dynamic effect of the magnetic force is important.

**Photocurrent density profile**
The expression of the photocurrent density of the solar cell is obtained from the gradient of the minority carriers density in the base according to Fick's law. We have:

$$J_{Ph} = 2q \cdot D \cdot \left. \frac{\partial \delta(x, z, Sf, \lambda, kl, \phi, B)}{\partial x} \right|_{x=0}$$

Where q is the elementary charge of electricity. From where:

$$J_{ph} = 2q \frac{S_f L^3 . \alpha_t (1-R).F.\exp(-\alpha_t . z).\tanh(\frac{H}{2L})}{S_f . L + D \tanh(\frac{H}{2L})}$$

Figure 3 below shows the profile of the photocurrent density according to the recombination velocity at the junction for different values of the applied magnetic field

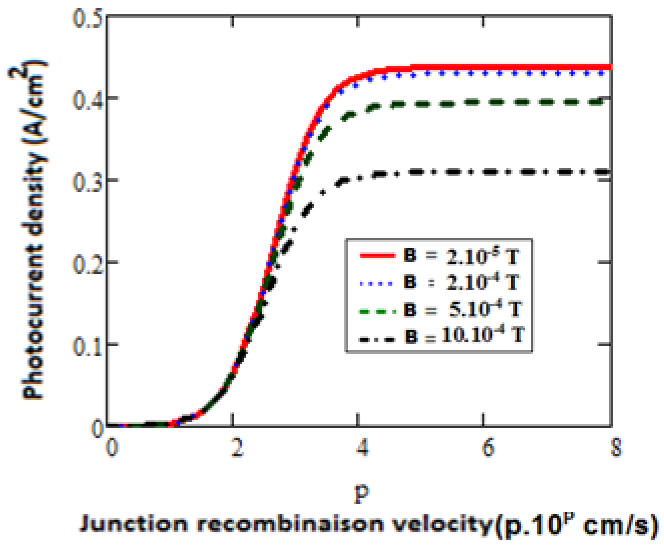


*Figure 3: Variation of the photocurrent density versus recombination velocity at the junction for different values of the applied magnetic field*

H=0, 03cm, Z =0, 0001cm, $L_o$=0, 01cm, λ = 0, 5 µm, kl = 10 $cm^2/s$,ϕ=50Mev, µ = 1000 $cm^2.V^{-1}.s^{-1}$
The photocurrent density is almost zero for the low values of the recombination velocity at the junction reflecting operation of the solar cell in open circuit.
The open-circuit’s situation corresponds to a blocking of the minority charge at the junction.

The photocurrent density gradually increases to an asymptotic value corresponding to the short-circuit photocurrent when the recombination velocity at the junction becomes larger.
The shortcircuit statecorresponds to a massive transfer of the electrons which arrive at the junction toward the emitter.
The photocurrent of short-circuit decreases when the value of the magnetic field increases because the electrons density in the base decreases at the levels of the junctions.

**Phototension Profile**

The phototension created by the accumulation of charge carriers at the junction is obtained from Boltzmann's relationship:

$$V = V_T \cdot \ln\left[1 + \frac{N_b}{n_0^2} \cdot \delta(0, z, \lambda, kl, \phi, Sf, B)\right]$$

$V_T = \frac{KT}{e}$ is the thermal tension
Nb: doping rate of acceptor atoms in the base
n0: intrinsic density of carriers at thermal equilibrium. From where:

$$V_{Ph} = \frac{KT}{q} \ln\left\{1 + \frac{N_b}{n_0^2}\left[\frac{D(B)\tanh(\frac{H}{2L})}{S_f L + D(B)\tanh(\frac{H}{2L})}\right] \cdot \frac{L^2}{D(B)} \cdot \alpha_t (1-R) \cdot F \cdot \exp(-\alpha_t \cdot z)\right\}$$

Figure 4 below shows the profile of the phototension according to the recombination velocity at the junction for different values of the applied magnetic field.

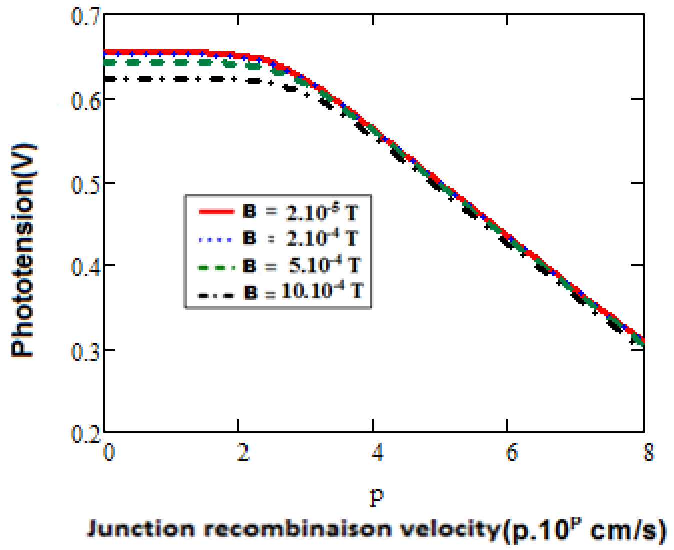


*Figure 4: Variation of the phototension according to the recombination velocity at the junction for different values of the applied magnetic field*

H=0, 03cm, Z =0, 0001cm, $L_o$=0, 01cm, λ = 0, 5 µm,kl = 10 $cm^2/s$,ϕ=50Mev, µ = 1000 $cm^2.V^{-1}.s^{-1}$

The phototension decreases when the recombination velocity at the junction Sf increases. For the large values of Sf, the phototension tends towards zero value, which corresponds to the solar cell's operation in short circuit. For low values of Sf, there is no passage of charge at the junction, the phototension remains constant and its value corresponds to the open-circuit voltage Vco.
This open circuit voltage decreases when the value of the applied magnetic field increases because of the magnetic force whose dynamic effect on the charge carriers increases according to the magnetic field intensity.
The amount of charges stored on either side of the junction decreases as the magnetic field increases.

**Current-voltage Characteristic**

Figure 5 below shows the profile of photocurrent density according to the phototension.

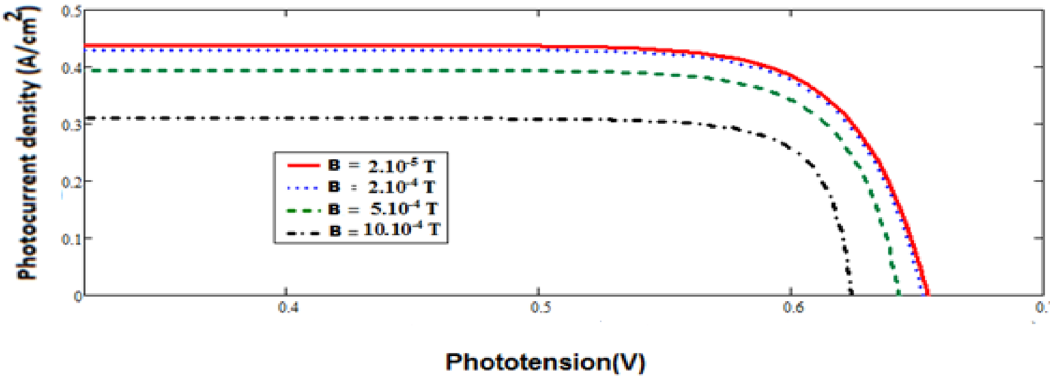


*Figure 5: I-V characteristic of the solar cell*

H=0, 03cm, Z =0, 0001cm, $L_o$=0, 01cm, $\lambda$ = 0, 5 µm,kl = 10 $cm^2/s$,$\phi$=50Mev, $\mu$ = 1000 $cm^2.V^{-1}.s^{-1}$

The characteristic analysis shows that the phototension is not independent from the photocurrent.

The solar cell behaves as a real voltage generator in the vicinity of the open circuit and as a real current generator in the vicinity of the short circuit.

For each mode of operation, an electrical circuit equivalent to the solar cell is proposed.

**Series Resistance**

The electric model equivalent to the photocell when it works as a real voltage generator is as follows:

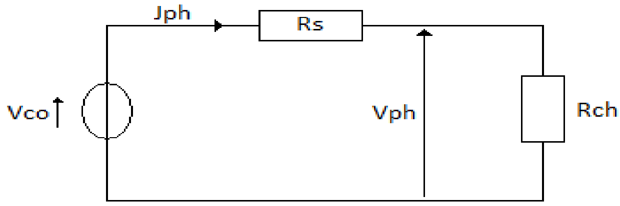


*Figure 6: Equivalent circuit of the photocell (real voltage generator)*

From the study of this electrical circuit, the expression of the series resistance is deduced:

$$R_S\left(S_f,\lambda,kl,\phi,z,B\right)=\frac{V_{CO}(\lambda,kl,\phi,z,B)-V_{PH}\left(S_f,\lambda,kl,\phi,z,B\right)}{J_{PH}\left(S_f,\lambda,kl,\phi,z,B\right)}$$

Figures 7 and 8 below represent the profile of the series resistance according torespectively the irradiation energy and the damage coefficient.

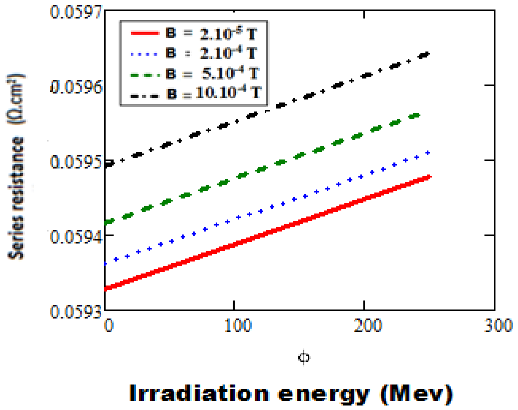


*Figure 7: Variation of the series resistance according to the irradiation energy for different values of the magnetic field*

H=0, 03cm, Z =0, 0001cm, $L_o$=0, 01cm, $\lambda$ = 0, 5 µm, kl = 10 $cm^2/s$,$\phi$=50Mev, $\mu$ = 1000 $cm^2.V^{-1}.s^{-1}$

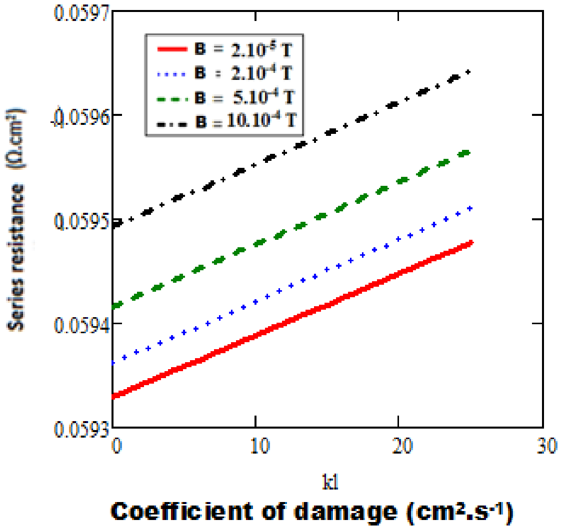


*Figure 8: Variation of the series resistance according to the coefficient of damage for different values of the magnetic field*

H=0, 03cm, Z =0, 0001cm, $L_o$=0, 01cm, λ = 0, 5 µm, kl = 10 $cm^2/s$, ϕ=50Mev, µ = 1000 $cm^2.V^{-1}.s^{-1}$

Series resistance characterizes the resistive effects of the material and the contact device used.

The analysis of figures 7 and 8 shows that the series resistance increases according to the magnetic field but also according to irradiation parameters.

Irradiation increases the resistive effects of electronic components.

We have the linear relation $R_S(kl,\phi,B)=a.X+R_S(B)$ where X denotes either kl or φ.

$R_S(B)$ is the series resistance with the absence of irradiation. We have recorded in the table below the $R_S(B)$ variations according to the magnetic field:

**Table 1:** Variation of the series resistance according to the magnetic field with the absence of irradiation.

| B (T) | $2.10^{-5}$ | $2.10^{-4}$ | $5.10^{-4}$ | $10.10^{-4}$ |
|---|---|---|---|---|
| $R_S(B)$ (mΩ.$cm^2$) | 59,35 | 59,37 | 59,42 | 59,49 |

$R_S(B)$ increases according to the magnetic field. The increase in the intensity of the magnetic field decreases the diffusion current of the solar cell, from where the growth of the series resistance.

## Conclusion

The resolution of the continuity equationallowed us to obtain the expression of the electrons density in the base and we deduced those of the photocurrent density and the phototension.

From the electric model equivalent to the solar cell when operating in the vicinity of the open circuit, we established the expression of the series resistance.

We studied in this paper the impact of the variation of an applied magnetic field on the minoritycarriers densityin the base, on the photocurrent density, on the phototension and finally on the series resistance.

The study showed that the presence of a magnetic field affects theminority carriers density in the base.

The dynamic effect of the Lorentz force reduces the diffusion of the charge carriers towards the emitters, which results in the reduction of the density of these carriers at the junction levels, from where the reduction of the photocurrent density, the phototension and increasing the resistivity of the material.

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