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RESEARCH ARTICLE

MINORITY CARRIER'S MOBILITY DETERMINATION IN THE BASE REGION OF N^+-P-P^+ SILICON SOLAR CELL UNDER EFFECTS OF IRRADIATION FLUX, TEMPERATURE AND MAGNETIC FIELD

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Abstract

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The aim of this study is to show the influence of temperature on the relative value of the short-circuit photocurrent density obtained from an **n^+-p-p^+**silicon solar cell front illuminated with modulated polychromatic light. The solar cell was already subjected to charged particules irradiation flux (Φp) and intensity (kl,) and remained under both magnetic field (B) and temperature (T). Thus, the graphical representation of the relative value of the short-circuit photocurrent density as a function of the square of the magnetic field (B) yields to determine the slope, which is related to the mobility of minority carriers in the base. It is obtained for a back surface field silicon solar cellunder both temperature and irradiation flux of charged particules.

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Introduction:-

Phenomelogical parameters such as, lifetime, diffusion length and coefficient, mobility and surfaces recombination velocity, are important in determining the performance of (n+/p/p+) silicon solar cell [1, 2, 3, 4, 5]. The excess minority carrier's mobility is linked by Einstein's relationship to the diffusion coefficient and the operating temperature of the solar cell.Theexcess minority carrier'srecombination velocity (Sf) at the junction (n+/p) [6, 7], (Sb) at the back contact (p/p+) [8,9, 10, 11, 12, 13]and (Sgb) at the grain joints (in the 3D model)[14, 15, 19, 17, 18],appear in the collection of photogenerated carriers through boundaries conditions, while solving diffusion equation related toexcess minority carriers in differents regions in the solar cell.

The phenomelogical parameters are influenced by the manufacturing conditions (doping rate and grain size), the thicknesses of the different [12, 19] that make up the solar cell[20, 21, 22, 23, 24, 25, 26, 27] as well as it operating conditions, which are:

1. Operating regimes as dynamic, i.e. transient[28, 29, 30]and ac[5, 31, 32, 33],and steady state regime[34, 35]
2. The operating point at short-circuit and open circuit[6, 7] and between both.
3. External factors i.e., temperature [36, 37, 38], electromagnetic field (E, B)[39, 40, 41, 42, 43, 44],flow ofirradiationandintensity (□ p, Kl))[21, 45] of charged particules.

Thus theoretical and experimental studies of the expressions of the photocurrent either of the photovoltage,lead to the phenomelogical parameters determination in the characterization of the solar cell [1, 5, 43, 44, 46].

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Our study aims at determining the excess minority carrier'smobilityby the technique of the relativeshort-circuit photocurrent according to the intensity of the magnetic field, in a solar cell initially irradiated by charged particles (□ p, Kl) and placed under a variable temperature (T) and under polychromatic illumination in frequency modulation (□). Our study takes into account the surface recombination velocity (Sb) at the rear of the base of the solar cell.

This article deals with the impact of temperature on the relative value of the short-circuit photocurrent density in order to determine the minority carriers mobility in the (p) base of a silicon solar cell. We will first identify all the mathematical equations concerning this work. Next, the variation of the relative value of the short-circuit photocurrent density as a function of the square of the magnetic field (B) for different temperature values is presented. Finally, a method for determining minority carrier's mobility, temperature (T) dependent is proposed in silicon solar cell with back surface field.

Theory

Presentation of solar cell

We present in **figure 1** the diagram of an(n^+-p-p^+) polycrystalline silicon solar cell [8, 12] under irradiated with charged particules(kl, ϕp) and remained under magnetic field (B) and temperature (T), it is then illuminad with polychromatic light in frequency modulation.

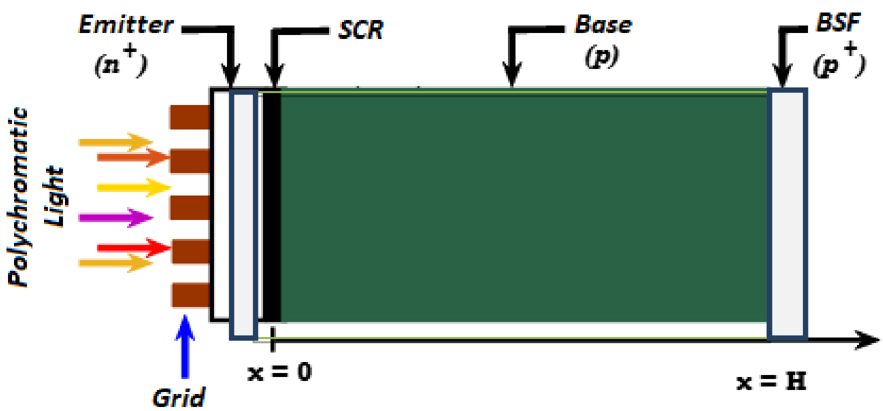

Figure 1:-Structure of n^+-p-p^+ silicon solar cell.

Continuity equation and boundary conditions

Continuity equation

The continuity equation of the minority charge carriersdensity in the (p) base at the abscissa (x) in frequency dynamic regime is written as:

$$D_{\omega}^{*}(\omega, B, T, kl, \Phi p)\frac{\partial^2\delta(x,t)}{\partial x^2} - \frac{\delta(x,t)}{\tau}. = -G(x,t) + \frac{\partial\delta(x,t)}{\partial t} \quad (1)$$

$G(x,t)$and$\delta(x,t)$are respectively the overall generation rate and the density of minority charge carriers in the base as a function of depth (x) and time (t):

$$\delta(x,t) = \delta(x) \times e^{i\omega t} et G(x,t) = g(x) \times e^{i\omega t} \quad (2)$$

Where $\delta(x)$ and $g(x)$characterize the spatial part and$e^{i\omega t}$ the time part

The spatial component of the minority carrier's generation rate[47] is given by following expression:

$$g(x) = n. \sum_{k=1}^{3} a_i . e^{(-b_i x)} \quad (3)$$

aiand **bi**are tabulated coefficients of solar radiation and dependent on the absorption coefficient of silicon with the wavelength at AM 1.5

n: is a parameter called (number of suns) level of solar radiation. It allows to correlate the level of experimental lighting to the level of reference lighting taken under AM 1.5.

By inserting equation (2) into equation (1), we obtain the following relation:

$$\frac{\partial^2 \delta(x)}{\partial x^2} - \frac{1}{L_\omega^*(\omega, B, T, kl, \Phi p)^2} . \delta(x) = -\frac{g(x)}{D_\omega^*(\omega, B, T, kl, \Phi p)} \quad (4)$$

$D_\omega^*(\omega, B, T, kl, \Phi)$ represents the complex diffusion coefficient of minority charge carriers in the base (p) of a solar cell in frequency modulation[48, 49]subjected to irradiation (kl, Φ)[45, 50] under magnetic field (B)[43, 44]and under temperature (T) [51]and is given by the following relationship

$$D_\omega^*(\omega, B, T, kl, \Phi_P) = D(B,T) \cdot \frac{\left[1 + \tau^2(\omega_c(B)^2 + \omega^2) + j\omega\tau[\tau^2(\omega_c(B)^2 - \omega^2) - 1]\right]}{[1 + \tau^2(\omega_c(B)^2 - \omega^2)]^2 + 4\omega^2\tau^2} \cdot D(kl, \Phi_P) \quad (5)$$

With

$$D(B,T) = \frac{D(T)}{1 + [\mu(T)B]^2} \quad (6)$$

D(B,T) is the minority carrier diffusion coefficient under influence temperature T and applied magnetic field B [51].
With:

$$D(T) = \mu(T) \times \frac{kb.T}{q} \quad (7)$$

*D(T)*is the diffusion coefficient versus temperature T, in the solar cell without magnetic field [2, 38].

μ(T) is the minority carrier's mobilityin the base, temperature dependent and expresses as[38]:

$$\mu(T) = 1.43.10^9 . T^{-2.43} cm^2 V^{-1} s^{-1} \quad (8)$$

$q = 1{,}6 \cdot 10^{-19} C$iselementary charge of the electron
$K_b = 1{,}38 \cdot 10^{-23} m^2 kg s^{-2} K^{-1}$ isBoltzmann constant

$$\omega_c(B) = \frac{qB}{m_e} \quad (9)$$

$\omega_c(B)$iscyclotronic frequency of electron [48], while:

$$D(kl, \Phi_P) = \frac{L(kl, \Phi p)^2}{\tau} \quad (10)$$

$$L(kl, \Phi_P) = \frac{1}{\sqrt{\frac{1}{L_0{}^2} + kl\Phi_P}} \quad (11)$$

$D(\Phi_P, kl)$is the diffusion coefficient of the electrons in the base under irradiation$L(kl, \Phi_P)$is the diffusion length of the excess minority carriers in the base as a function of the irradiation energy flux (Φp) and the damage coefficient intensity (kl) [50].

τ isaverage minority carrier'slifetime
$l_\omega^*(\omega, B, T, kl, \Phi p)$: represents the complex diffusion length [31,32, 33] subjected to irradiation (kl, Φp) under magnetic field (B) and under temperature (T). It is given by the following relation:

$$L_\omega^*(\omega, B, T, kl, \Phi p) = L(B, T, kl, \Phi). \sqrt{\frac{1 - j.\omega.\tau}{1 + (\tau.\omega)^2}} \quad (6)$$

$$L(B, T, kl, \Phi p) = \frac{1}{\sqrt{\frac{q \cdot [1 + \mu(T)^2 \cdot B^2]}{\mu(T) \cdot K_b \cdot T \cdot \tau} \cdot kl.\Phi}} \quad (7)$$

$L(B, T, kl, \Phi$p)represents the minority carrier diffusion length the base under steady state and submitted t irradiation (Φ, kl), magnetic field (B) and under temperature (T).

The general solution of the continuity equation is given by the following relation:

$$\delta(x,\omega,B,T,kl,\Phi p) = \left[Ach\left(\frac{x}{L_\omega^*(\omega,B,T,kl,\Phi p)}\right) + Ash\left(\frac{x}{L_\omega^*(\omega,B,T,kl,\Phi p)}\right) - \sum_{i=1}^{3}\beta_i.e^{-b_i x}\right]e^{-j\omega t} \quad (8)$$

$$\beta_i(\omega,B,T,kl,\Phi p) = n.\frac{a_i.{L_\omega^*}^2}{D_\omega^*[(b_i.L_\omega^*)^2-1]} \quad (9)$$

$$with D_\omega^*[(b_i.L_\omega^*)^2-1] \neq 0 \quad (10)$$

The constants A and B are determined from the boundary conditions at the junction and at the rear face.

Boundary Conditions
At the junction: x = 0

$$\left.\frac{\delta(x,\omega,B,T,kl,\Phi p)}{\partial x}\right|_{x=0} = \frac{Sf}{D_\omega^*(\omega,B,T,kl,\Phi p)}\delta(0,\omega,B,T,kl,\Phi p) \quad (11)$$

At the rear face: x = H

$$\left.\frac{\delta(x,\omega,B,T,kl,\Phi p)}{\partial x}\right|_{x=H} = -\frac{Sb}{D_\omega^*(\omega,B,T,kl,\Phi p)}\delta(H,\omega,B,T,kl,\Phi p) \quad (12)$$

The parameters Sf and Sb represent the recombination velocity at the junction[6, 7, 11,14] and at the rear face [8, 10, 13, 34]. The recombination velocity **Sf** is equal to the sum of the recombination velocity **Sj**due to the external load and the intrinsic recombination velocity **Sf0** which is an effective recombination velocity at the emitter-base interface[52, 53, 54] related to the losses by shunt resistance.

Graphic determination of cyclotronic frequency
The maximum minority carrier diffusion coefficient in solar cell is obtained when the modulation frequency is equal to cyclotronic frequency[48, 55].

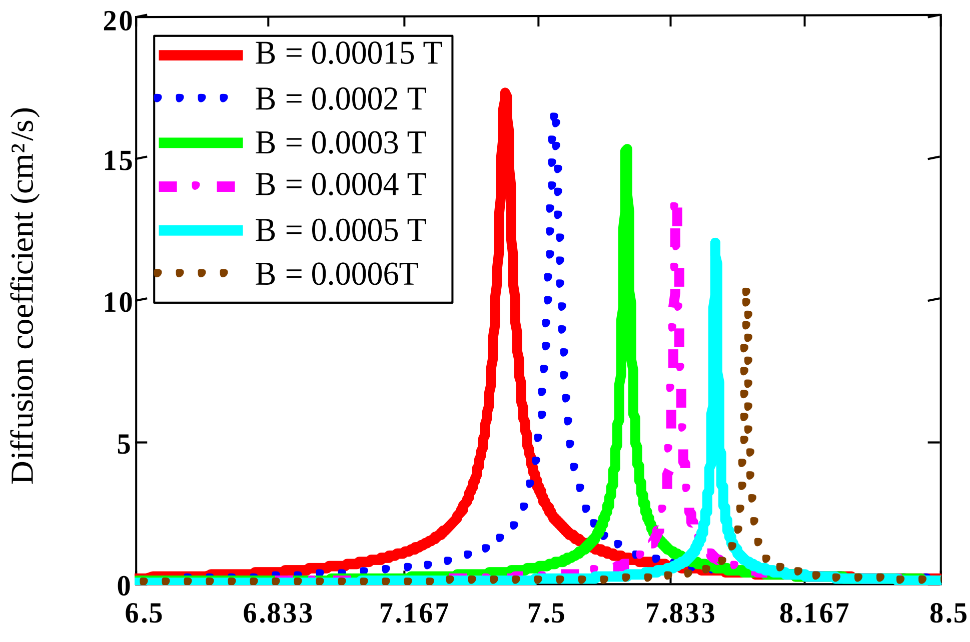

Figure 2:- Represents the minority carrier diffusion coefficient according tofrequency for different values magnetic field at the temperature T = 300 K.

In the **table. 1** we define the value of the magnetic field for each cyclotronic frequency.

Table. 1:-Cyclotronic frequency obtained for different magnetic field values.

B(Tesla)	$1,5 \cdot 10^{-4}$	$2 \cdot 10^{-4}$	$3 \cdot 10^{-4}$	$4 \cdot 10^{-4}$	$5 \cdot 10^{-4}$	$6 \cdot 10^{-4}$
ω_c	$10^{7,42}$	$10^{7,54}$	$10^{7,72}$	$10^{7,847}$	$10^{7.94}$	$10^{8,02}$

Determination of the Optimal Temperature by Graphical Method

We represent in the figure. 3,the minority carrier diffusion coefficient according to temperature for different pairs' values cyclotronic frequency and the magnetic field[49, 51].

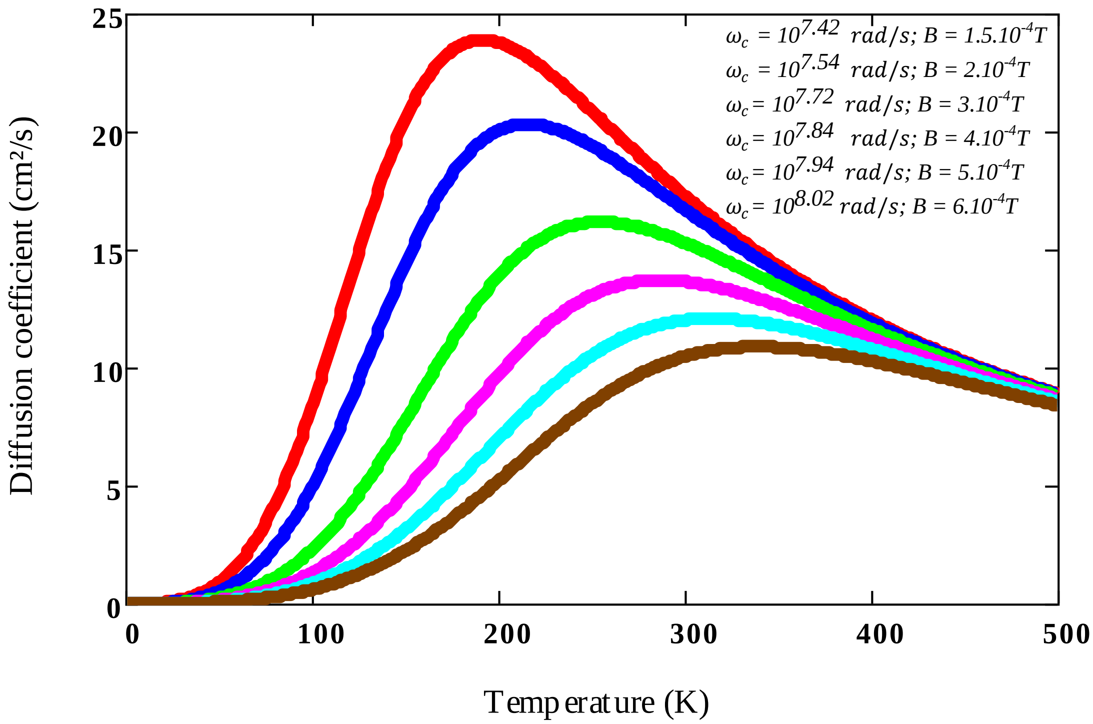

Figure 3:-Diffusion coefficient versus temperature for different values of both cyclotronic frequency and the magnetic field.

Table. 2:-gives, extracted values of Dmax, allowing the calculation of short circuit photocurrent.

B(Tesla)	$1,5 \cdot 10^{-4}$	$2 \cdot 10^{-4}$	$3 \cdot 10^{-4}$	$4 \cdot 10^{-4}$	$5 \cdot 10^{-4}$	$6 \cdot 10^{-4}$
$\omega_c(B) rad/s$	$10^{7,4216}$	$10^{7,5453}$	$10^{7,7218}$	$10^{7,847}$	$10^{7.9435}$	$10^{8,0228}$
$T_{opt}(K)$	191	215	255	287	315	340
$D_{max}(cm^2/s)$	23,861	20,295	16,146	13,691	12,062	10,866

Expression of the short-circuit photocurrent density (Jsc) and the backsurface recombination velocity (Sb).

The short-circuit photocurrent density (Jsc) is obtained from the photocurrent density for large recombination velocity values (Sf$\geq 10^6$ cm/s)at the junctionIt is then given as:

$$J_{SC}(\omega, B, kl, \Phi p, T, H) = \lim_{Sf \geq 10^6 cm/s} J_{ph}(Sf, \omega, B, kl, \Phi p, T) \quad (13)$$

$J_{ph}(Sf, \omega, B, kl, \Phi p, T, H)$: represents the photocurrent density of a solar cell subjected to irradiation (Φp, kl) under magnetic field (B) and under temperature (T) and is given by the following expression.

$$J_{ph}(\omega, B, T, kl, \Phi p, H) = q. D_{\omega}^{*}(\omega, B, T, kl, \Phi p) \left. \frac{\partial \delta(x, \omega, B, T, kl, \Phi p, H)}{\partial x} \right|_{x=0} \quad (14)$$

By calculation, the expression of the short-circuit photocurrent density of a solar cell is given as:

$$J_{SC}(\omega,B,kl,\Phi p,T,H) = q\cdot D_\omega^* \sum_{i=1}^{3} \beta_k \frac{L_\omega^*(D_\omega^* b - Sb)\left[cosh\left(\frac{H}{L_\omega^*}\right) - e^{-bH}\right] + (bSbL_\omega^{*2} - D_\omega^*)\, sinh\left(\frac{H}{L_\omega^*}\right)}{L_\omega^{*2}\cdot Sb\, sinh\left(\frac{H}{L_\omega^*}\right) + D_\omega^* L_\omega^*\, cosh\left(\frac{H}{L_\omega^*}\right)} \quad (15)$$

With $l_\omega^* = l_\omega^*(\omega,B,T,kl,\Phi p)$

The expression of the recombination velocity at the rear face (Sb) is obtained from the resolution of following equation:

$$\frac{\partial Jph(Sf,Sb,\omega,B,kl,\Phi p,T)}{\partial Sf} = 0 \quad (16)$$

This equation is obtained for the large values of the recombination velocity at the junction Sf (Sf $\geq 10^6$ cm/s), where the photocurrent density is asymptotic and constant [7, 11, 13, 14].

The obtained expressions ofback surface recombination velocity aregiven by following relations:

$$Sb_1(\omega,B,T,kl,\Phi p,H) = \frac{D_\omega^*(\omega,B,T,kl,\Phi p)}{L_\omega^*} \sum_{i=1}^{3} \frac{\sinh\left(\frac{H}{L_\omega^*}\right) - L_\omega^* b_1\left[cosh\left(\frac{H}{L_\omega^*}\right) - e^{-bH}\right]}{L_\omega^* b_1 \sinh\left(\frac{H}{L_\omega^*}\right) - \left[cosh\left(\frac{H}{L_\omega^*}\right) - e^{-bH}\right]} \quad (17)$$

$$Sb_2(\omega,B,T,kl,\Phi p,H) = -\frac{D_\omega^*(\omega,B,T,kl,\Phi p)\cdot}{L_\omega^*}\tanh\left(\frac{H}{L_\omega^*}\right) \quad (18)$$

The expression of the relative value of the short-circuit photocurrent density is written as:

$$f(\boldsymbol{B},\omega,T,kl,\Phi p,H,Sb) = \frac{J_{SC}(\boldsymbol{B}=\boldsymbol{0},\omega,T,kl,\Phi p,H,Sb) - J_{SC}(\boldsymbol{B},\omega,T,kl,\Phi p,H,Sb)}{J_{SC}(\boldsymbol{B}=\boldsymbol{0},\omega,T,kl,\Phi p,H,Sb)} \quad (19)$$

Study of the relative value of the short-circuit photocurrent density (Jsc)

Respectively otSb expressions, figures **4** and **5**show the profiles of the relative value of the short-circuit photocurrent density of a solar cell as a function of the square of the magnetic field (B) for different values of the temperature. As these graphical representations describe well a straight line, then allow us to determine the square of the slopes, corresponding to the minority carrier's mobility in the (p) base.

Taking into account the first solution (Sb1)

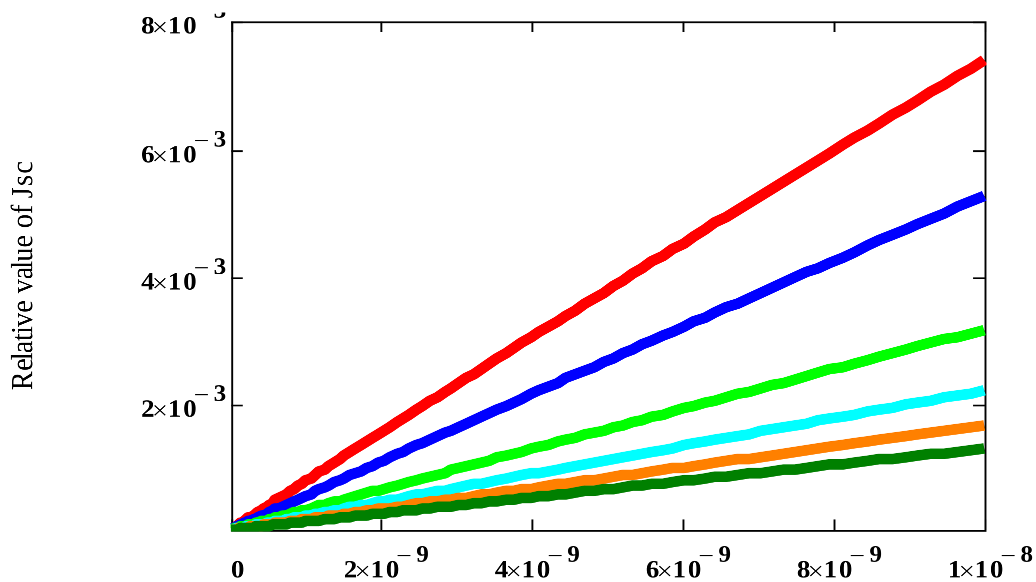

Figure 4:- Relative values of the short-circuit photocurrent density as a function of the square of the magnetic field for different temperature values kl = 10 $cm^2.s^{-1}$, Φp = 100 MeV; Sb1.

Taking into account the second solution (Sb2)

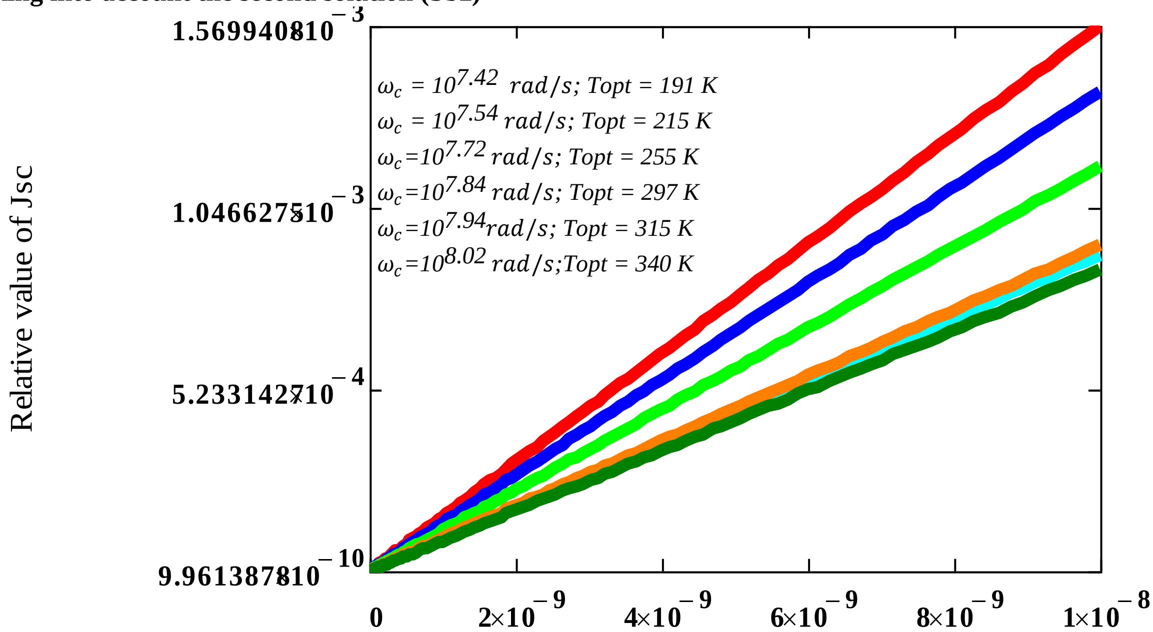

Figure 5:- Relative values of the short-circuit photocurrent density as a function of the square of the magnetic field for different temperature values with $\mathrm{kl} = 10\ \mathrm{cm}^2.\mathrm{s}^{-1}$, $\Phi\mathrm{p} = 100$ MeV, Sb2.

Calculation of the slope (a) and its square root corresponding to the mobility of minority carriers in the base (type p) for different temperature (T) values

The mobility found as a function of the temperature of the base (type p) for each experiment is given in the following table 3.

Table 3:- Values of the slope (a) and the minority carrier'smobility in the base for different temperature values.

	Sb_1		**Sb_2**	
Temperature T (kelvin)	***Slope values (a)***	***Mobility of minority carriers* (cm².V^{-1}.S^{-1})**	***Slope values (a)***	***Mobility of minority carriers* (cm².V^{-1}.S^{-1})**
191	727 883,96	853,16	156994,33	396,22
215	527 943,54	726,59	138041,06	371,5
255	326 214,68	571,15	116499,29	341,31
297	218 822,40	467,78	93747,88	306,18
315	163 182,05	403,96	91272,12	302,11
340	129 100,32	359,30	86690,43	294,43

We note that the mobility of minority carriers in the base decreases when the temperature of the base increases according to different solutions Sb1 and Sb2.

From Table. 3, theexpressions of mobility μ1 and μ2 as a function of temperature (T) are obtained as following equationsunder cyclotron frequency of given magnetic field and constantenergy irradiation.

$$\mu_1(\mathrm{T}) = -3.269 \times \mathrm{T} + 1443 \qquad (20)$$

$$\mu_2(\mathrm{T}) = -0.7243 \times \mathrm{T} + 529 \qquad (21)$$

Conclusion:-

In this paper, the relative value of the short-circuit current density and the mobility of the minority carriers in the (p) basesilicon solar cell, was studied for different temperature values. The mobility of minority carriers in the baseis derived for different temperature values. It has been observed that the increase in temperature yiedsa decrease ofminority carriers mobility. This shows that at high temperature the number of thermally excited phonons increased according to Boltzmann law.Therefore, a strong interaction between phonon and minority carriers induces the increase in resistance and a decrease in the thermal conductivity of the material.

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