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EFFECT OF MAGNETIC FIELD ON GERMANIUM P-N HOMOJUNCTION

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Abstract

In this study, the effect of magnetic field, which is perpendicular to junction current, on diffusion current has been investigated in Germanium based p-n homojunction diodes, theoretically. The magnetic field dependent diffusion current has been derived analytically. Resulting magnetic field dependent diode equation has been used to produce current – voltage theoretical data. Using this data, current – voltage curves of devices, I(B) - V have been plotted under different magnetic fields and effect of magnetic field on current – voltage characteristics has been investigated. According to these results, it has been observed that increasing magnetic field increases potential barrier V_{th}, decreases junction current and reverse saturation current I_0. Also effect of magnetic field on static and dynamic magnetoresistances, using $R_d(B)$ – V and $R_s(B)$ – V graphs which is plotted using theoretical data, have been analyzed and it has been observed that increasing magnetic field increases static and dynamic magnetoresistance in Germanium based devices.

Keywords: ***Semiconductor, p-n junction, magnetic field, magnetoresistance***

MANYETİK ALANIN GERMANYUM P-N EKLEM ÜZERİNE ETKİSİ

Özet

Bu çalışmada p-n eklem diyotlarında bağlantı akımına dik olan manyetik alanın difüzyon akımına etkisi teorik olarak incelenmiştir. Manyetik alana bağlı difüzyon akımı ifadesi analitik olarak türetilmiştir. Elde edilen manyetik alana bağlı diyot denklemi, Germanyum p-n eklem diyotları için akım-gerilim teorik verilerinin üretilmesinde kullanılmıştır. Bu veriler kullanılarak akım – gerilim grafikleri, I(B) – V farklı manyetik alanlar altında çizilmiş ve manyetik alanın akım – gerilim özelliklerine etkisi araştırılmıştır. Bu grafikler kullanılarak artan manyetik alanın potansiyel bariyeri, V_{th} arttırdığı eklemden geçen akım ve ters doyma akımını, I_0 azalttığı gözlemlenmiştir. Ayrıca teorik veriler kullanılarak çizilen $R_d(B)$ – V ve $R_s(B)$ – V grafikleri kullanılarak manyetik alanın statik ve dinamik manyetodirençler üzerindeki etkisi araştırılmış ve Germanyum p-n eklemlerinde artan manyetik alanin statik ve dinamik manyetodirençleri arttırdığı gözlemlenmiştir.

Anahtar Kelimeler: Yarı iletken, p-n eklem, manyetik alan, manyetodirenç

Cite

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1. Introduction

Study of semiconductors began at the end of the 1940s and has continued. Nowadays, semiconductor materials are used in all electronic devices such as diode, transistor, laser, LED, detector and solar cell devices because of their long lifetime, small size and efficiency [1] Operation principle of many semiconductor devices depends on the nature of the junction between n-type and p-type which is between semiconductor-semiconductor, semiconductor-conductor or conductor-conductor materials [2]. P-n junction diodes are the most important one in circuit elements such as AC-DC circuits, solar cells, LED etc. The non-linear behavior of the p-n junction diodes enables it to be used in information and signal transfer applications, such as rectifying any signal, amplifying the weak signal, and controlling the electron flow [3-4]. In this study, we focused on p-n homojunctions between semiconductor-semiconductor. P-n homojunction can be made of the same crystal which has p and n-type semiconductors. A forward biased p-n junction diode allows the electric current when a voltage is applied across the p-n junction. A reverse biased p-n junction allows almost no current. Here, some electrical properties of p-n junction diodes were theoretically investigated under different magnetic fields to contribute to the technological development process of p-n junctions. In this context, diffusion current in the n and p regions in forward bias of p-n homojunction diodes was analytically derived depending on the variation of magnetic field. Total current equation through the p-n junction was derived by summing the diffusion current for n and p regions and magnetic field dependent diode equation was obtained. As an application of the derived equation, we picked the Germanium as a semiconductor element to simulate the p-n homojunction diode. In the presence of magnetic-field which is varied from 0 T to 1 T, current voltage characteristics have been deeply investigated. Using the theorical data, some electrical properties for example, reverse saturation current, barrier potential and magnetoresistance have been calculated and tried to understand the dependency of the magnetic-field.

2. The Model

Current density equation of a p-n junction consists of diffusion term and drift term in the absence of magnetic field. Under magnetic field, the term which depends on magnetic field, will be added to this current density equation (Equation 1) [5-6].

$$\vec{J}_{n,p} = \vec{J}_{n,p,diffusion} + \vec{J}_{n,p,drift} + \vec{J}_{n,p,magnetic\,field} \tag{1}$$

When magnetic field is perpendicular to junction current, the term in Equation 1 will be following [2]:

$$\boldsymbol{J_{n,p}} = (n,p)e\mu_{n,p}\boldsymbol{E} + eD_{n,p}\boldsymbol{\nabla_{n,p}} + \boldsymbol{J_{n,p\perp}}tan\theta_{n,p} \tag{2}$$

where $\boldsymbol{tan\theta_{n,p}} = \mathbf{q}\boldsymbol{\mu_{n,p}}(\boldsymbol{n},\boldsymbol{p})\boldsymbol{R_H}\boldsymbol{B}$, $\mu_{n,p}$ and $\boldsymbol{D_{n,p}}$ are the electron/hole mobility and diffusivity, **n** and **p** are the electron and hole densities, $\boldsymbol{R_H}$ is the electron/hole Hall Coefficient and $\boldsymbol{J_{n,p\perp}}$ is the component of current density which is perpendicular to magnetic field.
In the presence of a magnetic field in the z direction, x components of the current densities for electrons and holes, are shown in Equation 3 and 4, respectively.[7-8]:

$$J_{nx} = ne\mu_n E_x - ne\mu_n E_y \mu_n B + eD_n \frac{\partial n}{\partial x} - eD_n \mu_n B \frac{\partial n}{\partial y} \tag{3}$$

$$J_{px} = pe\mu_p E_x + pe\mu_p E_y \mu_p B - eD_p \frac{\partial p}{\partial x} - eD_p \mu_p B \frac{\partial p}{\partial y} \tag{4}$$

The steady-state current flow through a p-n junction is described by adding the following equation:

$$q(G_{n,p} - R_{n,p}) = -(\vec{\nabla}\cdot\vec{J}_p) = (\vec{\nabla}\cdot\vec{J}_n) \tag{5}$$

where $\boldsymbol{G_{n,p}}$ is the electron/hole generation rate (in the dark $G_{n,p} = 0$), $\boldsymbol{R_{n,p}}$ is the electron/hole recombination rate.
By writing equations of J_n and J_p in Equation 5 and by assuming the junction is very sharp and outside of this region electrical neutrality is expected ($E_x = E_y = 0$), we obtain the following differential equations for n-type region:

$$\frac{\partial^2 \delta_p}{\partial x^2} + \mu_p B \frac{\partial^2 \delta_p}{\partial x \partial y} - \frac{\delta_p}{{L_p}^2} = 0 \tag{6}$$

here $\boldsymbol{\delta_p}$ is the excess minority carriers and $\boldsymbol{L_p} = \sqrt{\boldsymbol{D_p}\boldsymbol{\tau_p}}$, L_p is the holes diffusion lenght and $\boldsymbol{\tau_p}$ is the holes lifetime. This equation is second order partial differential equation with constant coefficients and factored inseparable. For this reason, it is referred to as irreducible equation. The solution of this equation is obtained using the method of the operator as follows:

$$\delta_p(x,y) = K_p\, e^{-\left\{\left(\frac{-\mu_p Bc + \sqrt{(\mu_p B)^2 c^2 + \frac{4}{{L_p}^2}}}{2}\right)x + cy\right\}} \tag{7}$$

here **c** is a constant size $1/m$ and $\boldsymbol{K_p}$ is a constant which can be found using the boundary conditions.
Boundary conditions are given in Equation 8, 9 and 10:

$$x = x_n \qquad \boldsymbol{\delta_p(x,y) = p_{n0}(e^{qV/kT} - 1)} \tag{8}$$

$$x = \infty \qquad \boldsymbol{\delta_p(x,y) = 0} \tag{9}$$

$$B = 0 \qquad \boldsymbol{\delta_p(x,y) = p_{n0}(e^{qV/kT} - 1)e^{(x_n - x)/L_p}} \tag{10}$$

where $\boldsymbol{p_{n0}}$ is holes which is minority carriers in the n-type region, in the thermal equilibrium and **V** is the voltage drop on the space charge depletion layer.
In these conditions the current density of the hole injected into the n-type region is given by Equation 11:

$$J_p(B)\big|_{x=x_n} = \frac{eD_p p_{n0}\left(e^{qV/kT} - 1\right)\left(-\mu_p B + \sqrt{\frac{(\mu_p B)^2 + 4}{{L_p}^2}}\right)}{2L_p} \tag{11}$$

Similarly, electron current density injected into the p-type region is given by Equation 12:

$$J_n(B)|_{x=-x_p} = \frac{eD_n n_{p0}\left(e^{qV/kT} - 1\right)\left(\mu_n B + \sqrt{\frac{(\mu_n B)^2 + 4}{{L_n}^2}}\right)}{2L_n} \tag{12}$$

The total current density under the presence of magnetic field (the current of the carrier generation – recombination in the space-charge layer was neglected) is given by Equation 13 and 14:

$$J_{total} = J_n(x = -x_p) + J_p(x = x_n) \tag{13}$$

$$J_{Total}(B) = \frac{\left(e^{qV/kT} - 1\right)eD_p}{2L_pL_n}\left\{b^2 L_p n_{p0}\mu_p B + p_{n0}\left(-\mu_p B + L_pL_n\sqrt{\frac{{\mu_p}^2B^2 + 4}{{L_p}^2}} + bL_pL_n n_{p0}\sqrt{\frac{b^2{\mu_p}^2B^2 + 4}{{L_n}^2}}\right)\right\}$$

where **b** is the ratio of electron to hole mobility, $b = \frac{\mu_n}{\mu_p}$.

Using total current density, we can find magnetic field dependent total current equation, in other words we can write magnetic field dependent diode equation as follows,

$$I(B,V) = A\left[\frac{\left(e^{qV/kT}-1\right)eD_p}{2L_pL_n}\left\{b^2L_pn_{p0}\mu_pB + p_{n0}\left(-\mu_pB + L_pL_n\sqrt{\frac{{\mu_p}^2B^2+4}{{L_p}^2}} + bL_pL_nn_{p0}\sqrt{\frac{b^2{\mu_p}^2B^2+4}{{L_n}^2}}\right)\right\}\right] \quad (14)$$

and here, if we take B=0, this equation will be reduced to the following diode equation (Equation 15):

$$I(V) = I_0\left[e^{\frac{qV}{kT}} - 1\right] \quad (15)$$

where I_0 is saturation current and A is the diode area.

3. Results and Discussion

To observe the magnetic field effect on germanium homojunction diode, using our theoretical model, we focused on current-voltage, static magnetoresistance and dynamic magnetoresistance characteristics. The effect of magnetic field on Current voltage shifting can be seen in Figure 1 and Figure 2 clearly. For the evaluation, we employed the magnetic field dependent diode equation (equation 14) where T=300 K , A=$7.5\text{x}10^{-6}$ m^{-2} , D_p=$1,24\text{x}10^{-3}$ m^2s^{-1}, μ_p=$0,048m^2V^{-1}s^{-1}$, L_p= $2,236\text{x}10^{-3}$ m, L_n=$3,535\text{x}10^{-3}$ m, b=2,81. To obtain the numerical simulation for the current-voltage characteristics of the germanium diode, theoretical data are created by changing the magnetic field in the range of 0-1 T. Since the magnetic field dependency is dominant in low applied voltage area and room temperature, we prefer to study the I-V characteristics under these circumstances.

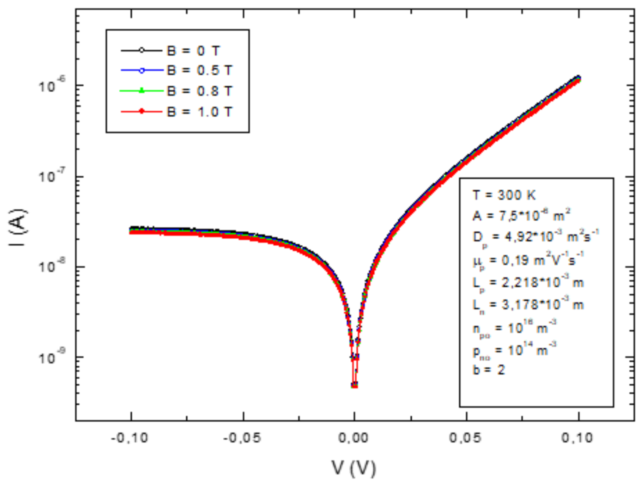

Figure 1. Current voltage (*I-V*) characteristics of Germanium p-n homojunction diode under different magnetic fields.

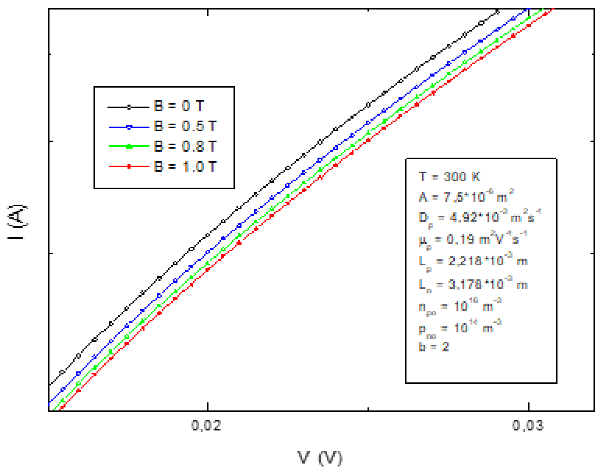

Figure 2. I-V curves under forward bias (zoom-in)

As can be seen from Figure 2, as the magnetic field increases, the forward bias I-V characteristics of the germanium diode is shifting to the right. And junction current decreases systematical with increasing magnetic field. Figure 3 shows the reverse bias I-V characteristics of the germanium diode under magnetic field which varies from 0.0 T to 1.0 T. It is found that as magnetic field increases, the reverse bias current decreases.

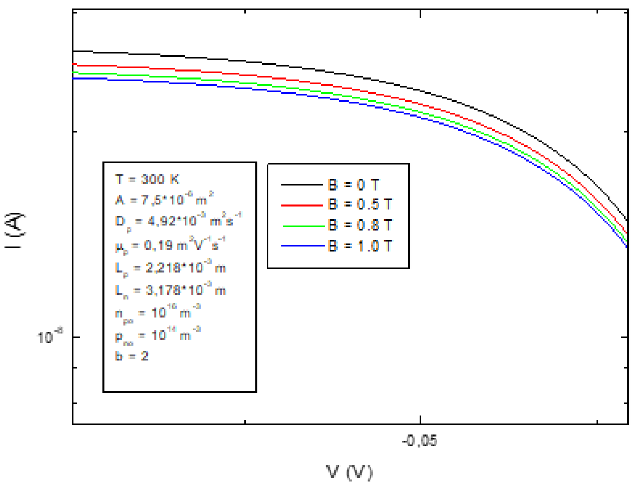

Figure 3. I-V curves under reverse (zoom in)

Reverse biased current and potential barrier which were calculated from the ln I versus V curves for Germanium based devices under varied magnetic field are given in the Table 1.

Table 1. Potential barrier V_{bi} and saturation current I_0 of Germanium p-n junction diode under different magnetic fields.

Magnetic Field	I_0 (x10^{-8} A)	V_{bi} (V)
B = 0,0 T	1.7406	0.3488
B = 0,5 T	1.7024	0.3429
B = 0,8 T	1.4914	0.3362
B = 1,0 T	1.4803	0.3407

Static magnetoresistance is calculated from the data of current voltage for Germanium. The Static magneto resistance- (versus) voltage graphic is drawn obtained from data of theoretical current voltage under different magnetic fields. As can be seen in the Figure 4, as the magnetic field increases, static magnetoresistance of the Germanium p-n junction increases.

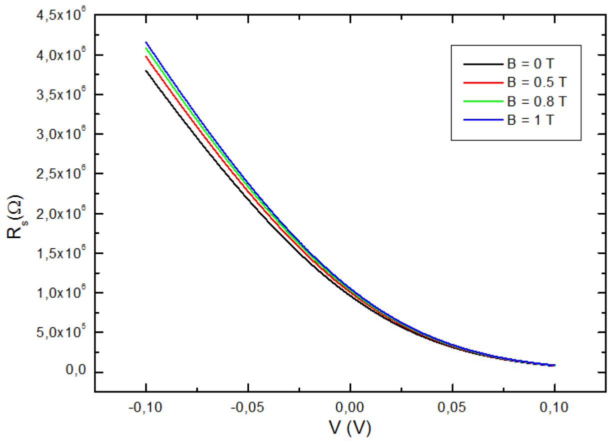

Figure 4. Static Magnetoresistance – Voltage graph of Germanium p-n Junction.

The other study has been focused on investigating effects of magnetic fields for germanium p-n junction by calculating the dynamic magnetoresistance from the current voltage data of p-n junction. Calculated dynamic magnetoresistance versus voltage graphics is given in the Figure 5. In the R_d-V graphics, as the magnetic field increases, dynamic magnetoresistance of germanium p-n junction increases. The closer vision of R_d-V curve can be seen in Figure 6 which shows the magnetic field dependent magnetoresistance shifting clearly.

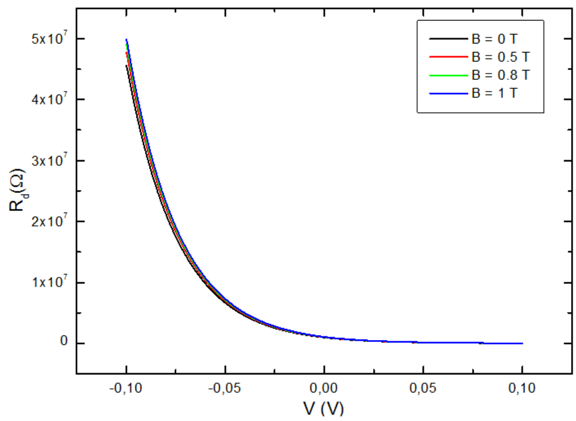

Figure 5. Dynamic Magnetoresistance – Voltage graph of Germanium p-n Junction.

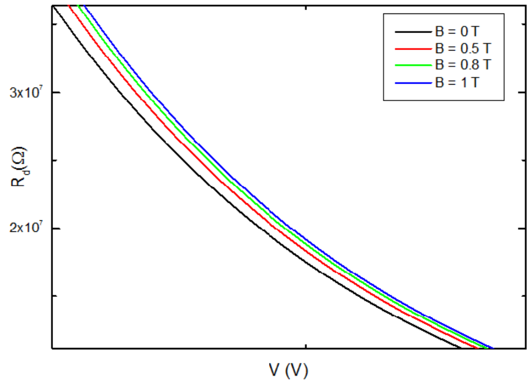

Figure 6. Dynamic Magnetoresistance – Voltage (zoom in)

4. Conclusion

In this study, the behavior of a Germanium p-n homojunction diode under different magnetic fields was investigated. According to Lorentz Force Law, magnetic force is maximum when the external applied magnetic field is perpendicular to current of p-n junction. That is why, the total current across the junction has been calculated theoretically taking into account that the magnetic field is perpendicular to p-n junction. In the presence of magnetic field, we focused on the diffusion current derivation since it is assumed that the diffusion is the dominant mechanism in simulated devices. In this step, for the Germanium p-n homojunction diodes, continuity equations for excess minority carriers in the n and p region are written. After solving the continuity equations analytically in the dark and steady state conditions, we obtained the second order partial differential equations with magnetic field dependent constant coefficients for the n and p regions. The 2-dimensional solution of these differential equations under boundary conditions have been written (inserted) in the diffusion current equation for the n and p regions separately and diffusion current density was obtained as a function of magnetic field. When there is no magnetic field in Equation 14, the equation reduced the standard diode equation of p-n homojunction. This result shows that the diffusion current solution is consistent with the equality of p-n homojunction diodes including magnetic field. Numerical values of mobility, diffusion coefficient, diffusion length and lifetime at room temperature for Germanium p-n homojunctions was taken from the literature. We can see the dependence of magnetic field on current potential characteristics of p-n homojunction from the graphics drawn by using the theoretically calculated data for different (magnitude) magnetic fields. According to our calculations, increased magnetic field lead to a systematically reduction in the forward and reverse bias currents. This result has been confirmed by the experimental studies in the literature [9-12]. We can say that this decrease in the device current under magnetic field might come from the decreased charge carrier concentration in the out of equilibrium state. Also, the increase of the potential barrier could explain the decrease of current by using calculation of the potential barrier [13-15]. Otherwise, When the electric and magnetic fields have been applied to the junction, mean free paths of charge carriers would decrease since the charge carriers would be scattered by magnetic field. Hence resistance of p-n homojunction would increase and changing of the resistance brings us the definition of the magnetoresistance [16-18]. To understand the resistance variation across the junction under different magnetic field, R_d-V and R_s-V characteristics have been investigated for germanium diodes at room temperature using the theoretical current voltage data. The graphics show that if the magnetic field increases, the dynamic and static magnetoresistance increases as well. These results match with studies in literature and it confirms that magnetoresistance effect in decreasing current [19-21]. In addition, reverse saturation current (I_0) was calculated, it was observed that high magnetic field gave rise to reduced reverse saturation current which is compatible with literature.

5. References

[1] Holt D. B., Yacobi B.G., "Extended Defects In Semiconductors", *Cambridge University Pres*, 2007.
[2] Sze S.M., "Semiconductor Devices", *John Wiley&Sons, New York*, 18, 2002, pp.112-235.
[3] J. R. Hook, H. E. Hall, "solid state physics", *John Wiley&Sons*, second edition, 1992.
[4] He, J., Fang, M., Li, B. ve Cao, Y., "A new analytic approximation to general diode equation", *Solid State Electronics*, 50, 2006, pp.1371-1374.
[5] Achuthan, M. K. ve Bhat, K. N., "Fundamentals of Semiconductor Devices", *The McGraw-Hill Companies*, 2008, pp.1330-1344.
[6] Aldridge, R. V., Davis, K. Ve Holloway, M., "An investigation of the effect of a magnetic field on the forward characteristics of some silicon diodes at low tempereatures", *J Phys D Appl Phys*, 8, 1974, pp.64-68.
[7] Aldridge, R. V., "On the behaviour of forward biased silicon diodes at low temperatures", *Solid - State Electronics*, 17, 1973, pp.617-619.
[8] Constantinescu, C. and Dolocan, V., "On the p-n junctions in the electric and magnetic field", *Int J Electronics*, 28, 1970, pp.433-440.
[9] Desai, P., Shakya, P., Kreouzis, T. ve Gillin, P.W., "Magnetoresistance in organic light-emitting diode structures under illumination", *Physical Review B*, 76, 2007, pp.235202-235210.
[10] Gadjialiev, M. M. ve Pirmagomedov, Z. Sh., "Effect of Magnetic Field on the Current-Voltage Characteristic of the n-GaAs-p-Ge Heterojunction", ISSN 1063-7826, *Semiconductors*, 42, 2008, pp.1034-1036.
[11] Luo, Z. ve Gao, J., "Anomalous temperature and magnetic field dependences of current voltaj characteristics in $Pr_{0.6}$ $Ca_{0.4}$ MnO_3/Nb doped $SrTiO_3$ heterojunctions", *J Phys D Appl Phys*, 43, 2010, pp.175003-175015.
[12] Abdelaoui, M. ve Benzohra, M., "Effect of a magnetic field on the conduction mechanism in silicon P+N junctions", *Microelectronics Journal*, 37, 2006, pp.127-132.
[13] Misra, M. ve Srivastava, G. P., "Diffusion of Minority Carriers in the Base Region of an Alloy Junction Transistor in the Presence of a Magnetic Field", *J Appl. Phys*, 39, 1968, pp.2127-2131.
[14] Moll, J. L., "The Evolution of the Theory of the Current-Voltage Characteristics of p-n Junctions", *Proc IRE*, 46, 1958, pp.10761089.
[15] Pietonpol, W. J., "pn junction rectifier and photocell", *Phys Rev*, 82, 1951, pp.120-131.
[16] Sah, C. T., Noyce, R. N. ve Shockley, W., "Carrier Generation and Recombination in p-n Junction and p-n Junction Characteristics", *Proc. IRE*, 45, 1957, pp.1228-1235.
[17] Shockley, W., "The Theory of p-n Junctions in Semiconductors and p-n Junction Transistors", *Bell Sys Tech J*, 28, 1949, pp.435-489.
[18] Streetman, B. G., Banerjee, S., "Solid State Electronic Devices", *Prentice Hall International, Inc.*, United States of America, 2000.
[19] Swami, R. ve Tantry, B., "Effect of an intense magnetic field on the difussion of minority carriers in semiconductors", *J Phys D Appl Phys*, 5, 1971, pp.639-645.
[20] Dunstan, W., "Variation of photovoltaic response with magnetic field for a germanium p-n junction", *Proc Phys Soc*, 77, 1961, pp.459457.
[21] Zhang, Y., Liu, R., Lei, Y. L. ve Xiong, Z.H., "Low temperature magnetic field effects in Alq3- based organic light emitting diodes", *Appl Phys Letter*, 94, 2009, pp.83307-83319.