Süleyman Demirel Üniversitesi Fen Edebiyat Fakültesi Fen Dergisi
Süleyman Demirel University Faculty of Arts and Sciences Journal of Science
2018, 13(2): 18-24
DOI: 10.29233/sdufeffd.425952

# The Temperature-Dependent Current-Voltage Characteristics of n-$AgInSe_2$/p-Si Heterojunction Diode

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*(Received: 22.05.2018, Accepted: 10.08.2018, Published: 30.11.2018)*

**Abstract:** *n*-$AgInSe_2$/*p*-Si heterojunction diode was fabricated by a successive layer deposition of $AgInSe_2$ thin film on *p*-type Si. The ideality factor and saturation current of the diode have exhibited temperature dependent behaviour. The activation energy was calculated by using traditional activation energy plot. The current mechanisms for diode were determined as defect-assisted tunnelling and carrier recombination. Furthermore, a modified Horvath method which was firstly presented for *n*-$AgInSe_2$/*p*-Si heterojunction here was used for calculation of activation energy.

***Key words:*** $AgInSe_2$ thin film, Temperature dependence, Modified Horvath method.

## *n*-$AgInSe_2$/*p*-Si Heteroeklem Diyodunun Sıcaklığa Bağlı Akım-Gerilim Karakteristikleri

**Özet:** *n*-$AgInSe_2$/*p*-Si heteroeklem diyodu, $AgInSe_2$ ince filminin p-tipi Si üzerine ardıl tabaka biriktirme yöntemi ile imal edilmiştir. Diyodun idealite çarpanı ve doyma akımı sıcaklığa bağlı davranış göstermiştir. Aktivasyon enerjisi, geleneksel aktivasyon enerji grafiği kullanılarak hesaplanmıştır. Diyot için akım iletim mekanizmaları kusur-destekli tünelleme ve taşıyıcı rekombinasyonu olarak belirlenmiştir. Ayrıca aktivasyon enerjisini hesaplamak için değiştirilmiş Horvath yöntemi *n*-$AgInSe_2$/*p*-Si heteroeklemi için ilk defa burada sunulmuştur.

***Anahtar kelimeler:*** $AgInSe_2$ ince film, Sıcaklık bağlılığı, Değiştirilmiş Horvath yöntemi.

## 1. Introduction

A layer of material ranging from fractions of a nanometer to several micrometers in thickness is called as a thin film. When a material is deposited as a thin film, it gains new properties that are quite different from its bulk form [1]. Owing to their less space requirements and less cost as well as the new properties, thin films have a large variety of applications in solid-state electronics industry [2, 3]. Thin films are commonly used in functional devices such as sensors, transistors, actuators, solar cells, diodes, etc.[4–6].

$AgInSe_2$ thin films can be promising candidate for solar cell and diode applications because that $AgInSe_2$ thin films have a direct band gap of 1.19 eV and high absorption coefficient [7]. They have been used in heterojunction solar cells [8–11], heterojunction diodes [12] and Schottky diodes [13]. Whereas there are a lot of studies on $AgInSe_2$ based solar cells, a little information is available in literature on $AgInSe_2$ based

***For citation:*** D. A. Aldemir and M. Kaleli, "The Temperature-Dependent Current-Voltage Characteristics of *n*-$AgInSe_2$/*p*-Si Heterojunction Diode", *Süleyman Demirel Üniversitesi Fen Edebiyat Fakültesi Fen Dergisi*, 13(2), 18-24, 2018.

heterojunction diodes. An analysis of temperature-dependent current-voltage (*I-V*) characteristic of $AgInSe_2$ based heterojunction diode is not found in literature.

The analysis of temperature dependent *I-V* characteristics of a heterojunction diode have been investigated by using traditional (Richardson plot for a Schottky diode) activation energy plot [14, 15]. The saturation current determined by extrapolation of linear part of semilogarithmic *I-V* plot are employed to draw activation energy graph. In case of a narrow linear region, it is difficult to determine the fitting region of *I-V* data and the saturation current, reliably [16]. Horvath method to eliminate this difficulty were developed by ref. [17]. The method provides to directly extract the junction parameters from *I–V* characteristics using the dependence of the forward bias on temperature.

In our study, to reveal current-transport mechanism of *n*-$AgInSe_2$/*p*-Si heterojunction diode, current-voltage (*I-V*) characteristics of the diode are investigated in the temperature range of 280 K-360 K with steps of 20 K. Temperature dependent *I-V* data is analysed by traditional activation energy plot and a new method which is developed in this study is presented by modifying of Horvath method.

## 2. Material and Method

One side polished *p*-type Si <111> wafer with an acceptor concentration of $6.94 \times 10^{14}$ $cm^{-3}$ was used as a substrate material to fabricate *n*-$AgInSe_2$/*p*-Si heterojunction diode. Before the deposition of $AgInSe_2$ (AIS) thin film, the Si wafer was exposed to standard wet chemical cleaning procedure to eliminate the organic and inorganic contaminants. For purpose of a low resistive ohmic contact, aluminium (Al) was thermally evaporated on back surface (unpolished surface) of Si followed by annealing. Then, AIS thin film of 900 nm thickness was grown by a successive process in which the AIS-Ag–AIS-Ag–AIS-Ag layers were deposited by e-beam and thermal evaporation on the front surface of *p*-type Si substrate. The detailed experimental procedure, morphological properties of AIS film, current-voltage (*I-V*) and capacitance voltage (*C-V*) characteristics of *n*-$AgInSe_2$/*p*-Si heterojunction diode at room temperature were described in our early study [12]. Temperature-dependent *I-V* measurements were carried out in a Janes VPF-475 cryostat by using Keithley 2400 SourceMeter. The sample temperature was always monitored by means of a copper-constantan thermocouple and a Lakeshore 321 auto-tuning temperature controller with sensitivity better than ±0.1 K. To enable to use modified Horvath method, the voltage values was measured for the applied currents.

## 3. Results

The temperature-dependent semilogarithmic reverse and forward bias current-voltage (*I-V*) characteristics of *n*-$AgInSe_2$/*p*-Si heterojunction diode are given in Figure 1. For each temperature, the forward bias current exponentially increases with increasing voltage in medium voltage region and the diode exhibits good rectifying behaviour.

The relationship between current and voltage of a p-n heterojunction is expressed by the diode equation found in many sources [18]:

$$I = I_o \left[\exp\left(\frac{qV}{nkT}\right) - 1\right] \tag{1}$$

Here $q$ is electronic charge, $n$ is ideality factor, $k$ is Boltzmann's constant, $T$ is absolute temperature. Some values belong to energy band alignment of $n$-$AgInSe_2$/$p$-Si heterojunction diode are summarized in Table 1. In the table, $E_g$, $\chi_s$, and $\Phi_s$ represent the band gap, electron affinity, and work function, respectively.

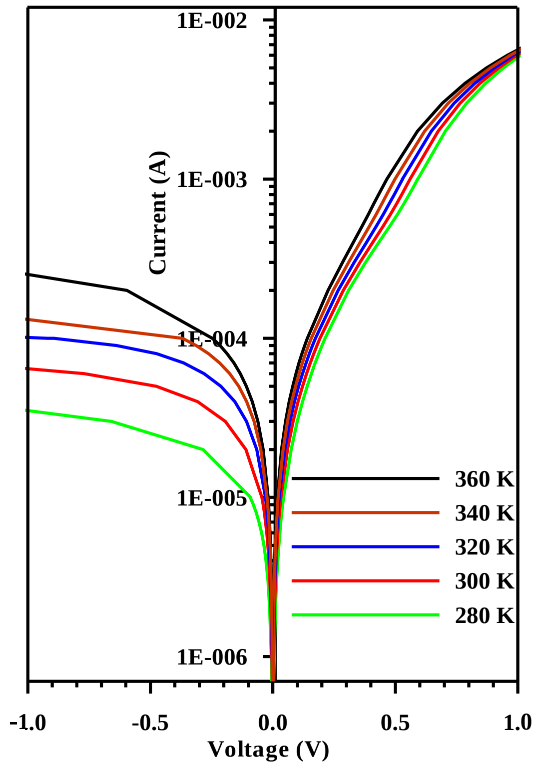


**Figure 1.** Semilogarithmic reverse and forward bias current-voltage (I-V) characteristics of n-$AgInSe_2$/p-Si heterojunction diode at five different temperature values.

**Table 1.** Some values belong to energy band alignment of $n$-$AgInSe_2$/$p$-Si heterojunction diode.

| **Semiconductor** | $E_g$ **(eV)** | $\chi_s$ **(eV)** | $\Phi_s$ **(eV)** |
|---|---|---|---|
| Si | 1.12 | 4.01 | 4.79[b] |
| $AgInSe_2$ | 1.19 | 4.15[a] | 4.56[b] |

[a)] Because the experimental value of the electron affinity of $AgInSe_2$ is not available in literature, the electron affinity value of its binary analog (CdSe) are used [13].
[b)] Calculated values for acceptor concentration of $N_A=6.94\times10^{14}$ $cm^{-3}$ for $p$-Si and for donor concentration of $N_D=6.06\times10^{14}$ $cm^{-3}$ for $n$-$AgInSe_2$ at room temperature [12].

By using the values in Table 1, the discontinuities in conduction ($\Delta E_c$ ) and valance band ($\Delta E_v$ ) were calculated as 0.14 eV and 0.21 eV, respectively. Since the conditions of $\chi_s$ ($p$-Si) < $\chi_s$ ($n$-$AgInSe_2$) < $\chi_s$ ($p$-Si) + $E_g$ ($p$-Si) and $\Phi_s$ ($p$-Si) >$\Phi_s$ ($n$-$AgInSe_2$) are provided , the saturation current ($I_o$) is given by [19],

$$I_o = C \exp\left[-\frac{q(\Delta E_c + V_{bi})}{kT}\right] \quad (2)$$

where $C$ is a constant and $V_{bi}$ is built-in voltage of the heterojunction. Table 2 contains $I_o$ and $n$ values obtained by fitting of Eq. 1 to the temperature-dependent $I$-$V$ data of $n$-$AgInSe_2$/$p$-Si heterojunction diode in the low bias region.

As refer to Table 2, $I_o$ increases with increasing temperature while $n$ decreases. Similar results for $p$-$n$ junctions have been reported for several studies [8, 20–23]. The values of *n* are quite large according to an ideal *p*-*n* junction. Decreasing trend in *n* values with increasing temperature can be due to the thermionic emission over the barrier of $\Delta E_c + V_{bi}$ but this case cannot explain the large values for each temperature [24, 25]. The large values of *n* can be attributed to defect-assisted tunnelling and carrier recombination in the depletion region by virtue of interface states which are stem from lattice defects during the deposition of $AgInSe_2$ film and intrinsic states of Si [8, 24, 26].

**Table 2.** Some parameters of *n*-$AgInSe_2$/*p*-Si heterojunction diode obtained from temperature-dependent *I*-*V* data.

| Temperature (K) | $I_o$ ($10^{-5}$ A) | *n* |
|---|---|---|
| 280 | 1.26 | 4.23 |
| 300 | 1.48 | 3.86 |
| 320 | 1.78 | 3.62 |
| 340 | 2.04 | 3.36 |
| 360 | 2.28 | 3.06 |

An activation energy plot is widely used tools for further analysis for transport mechanism of a heterojunction. If Eq. 2 is re-arranged,

$$\ln I_o = \ln C - \frac{q(\Delta E_c + V_{bi})}{kT} \tag{3}$$

is obtained. According to Eq. 3, $\ln I_o$ vs $(kT)^{-1}$ plot gives a straight line and $\Delta E_c + V_{bi}$ can be determined by its slope. Figure 2 shows $\ln I_o$ vs $(kT)^{-1}$ plot of *n*-$AgInSe_2$/*p*-Si heterojunction diode.

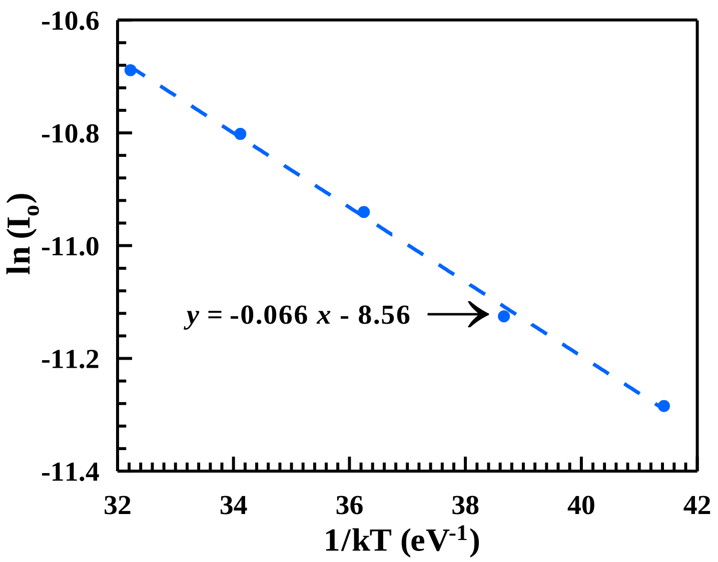


**Figure 2.** Activation energy plot of *n*-$AgInSe_2$/*p*-Si heterojunction diode.

The plot is quite linear and this behaviour implies that the temperature dependence of $I_o$ value is in close agreement with estimation of Eq. 2. The value of $\Delta E_c+V_{bi}$ is determined 0.066 eV. This value is too low than expected. The low value implies that the concentration of the trap states is high and defects or traps assisted tunnelling process is the dominant current transport mechanism across the *n*-$AgInSe_2$/*p*-Si interface [21, 25, 27, 28]. The value of $\ln C$ is determined as -8.56.

In this study, a new tool to determine the activation energy was obtained by inspiring of Horvath method [17]. In Horvath's method, the Schottky diode parameters such as barrier height and Richardson constant are directly calculated from the measured experimental data instead of saturation current which is determined extrapolation of ln*I*-*V* plot to *V*=0. Horvath method assumes a unity ideality factor (i.e. $n$=1) whereas non-ideal behaviour is taken into account in here. For $V > 3kT/q$, substituting an actual current level $I_i$ and expression of $I_o$ in Eq. 1, and taking the natural logarithm of both sides, after a re-arrangement one obtains: If the forward bias is greater than $3kT/q$, "1" on the right side of the Eq.1 can be neglected. After a rearrangement of Eq. 1 by substituting an actual current level $I_i$ and taking the natural logarithm of both sides, one obtains:

$$Z_i = lnI_i - \frac{qV}{nkT} = \ln C - \frac{q(\Delta E_c + V_{bi})}{kT} \quad (4)$$

The second term in Eq. 4 are directly calculated by determining the temperature dependent $V$ values for a constant applied current ($I_i$). The $n$ values in Table 2 are used in Eq. 4. A plot of $Z_i$ vs $1/kT$ is linear and its slope gives the activation energy of $\Delta E_c+V_{bi}$. Note that a current source should be employed to achieve reliable results because the measured values of $V$ for the applied currents for each temperature are used to calculate $Z_i$ values. Figure 2 shows $Z_i$ vs $1/kT$ plots as a function of applied currents in the range of $1\times10^{-5}$ A and $9\times10^{-5}$ A with steps of $1\times10^{-5}$ A for $n$-$AgInSe_2$/$p$-Si heterojunction diode.

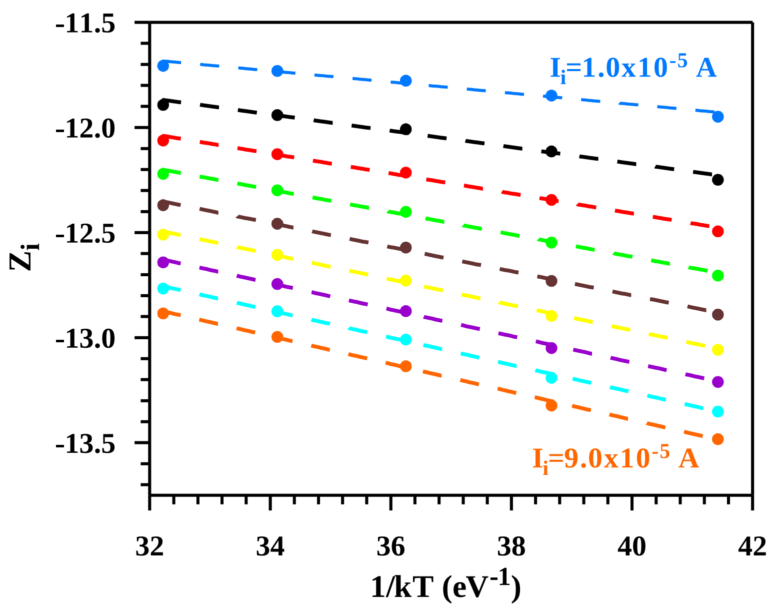


**Figure 3.** The plots belongs to modified Horvath method in the applied current range between $1\times10^{-5}$ A and $9\times10^{-5}$ A with steps of $1\times10^{-5}$ A.

As can been seen from the Figure 3, $Z_i$ vs $1/kT$ is linear for each applied current value and this shows the presented method is useful for calculation of activation energy value of $n$-$AgInSe_2$/$p$-Si heterojunction diode. The activation energy and ln*C* values obtained for each applied current are summarized in Table 3. Activation energies obtained from $Z_i$ vs $1/kT$ plots are different for each applied current. The energies get closer to traditional activation energy plot results as the applied current increases. For modified Horvath method, a constant $n$ value is assumed for each temperature but the value of $n$ is not constant for whole current region. For example, the series resistance of the diode causes the higher value of $n$ at high current levels. Therefore the applied current dependence of activation energy may be attributed to changing of *n* with applied current. ln*C* values obtained from modified Horvath method are approximately same and are in close agreement with ln*C* value that determined from traditional activation energy plot, reasonably.

**Table 3.** The activation energies obtained from $Z_i$ vs 1/kT plots.

| $I_i$ ($10^{-5}$A) | $\Delta E_c+V_{bi}$ (eV) | ln*C* |
|---|---|---|
| 1.0 | 0.027 | -10.83 |
| 2.0 | 0.039 | -10.61 |
| 3.0 | 0.047 | -10.51 |
| 4.0 | 0.053 | -10.48 |
| 5.0 | 0.057 | -10.50 |
| 6.0 | 0.061 | -10.54 |
| 7.0 | 0.063 | -10.60 |
| 8.0 | 0.065 | -10.67 |
| 9.0 | 0.066 | -10.74 |

## 4. Conclusion and Comment

The temperature-dependent *I-V* characteristics of *n*-$AgInSe_2$/*p*-Si heterojunction diode is investigated in the temperature range of 280-360 K to reveal the dominant transport mechanism of the diode. The saturation current obtained from semilogarithmic forward bias *I-V* plot exhibits weak temperature dependence while ideality factor value is strong temperature dependence. The large values of *n* and relatively small value of activation energy that is obtained traditional activation energy plot imply that the dominant current transport mechanism in *n*-$AgInSe_2$/*p*-Si heterojunction diode is defects or traps assisted tunnelling process. Furthermore, a modified Horvath model for determination of the activation energy is presented for *n*-$AgInSe_2$/*p*-Si heterojunction diode in this study. The results obtained from the model and traditional activation energy plot is in close agreement, reasonably.

## References

[1] K. N. Chopra and A. K. Maini, *Thin Films and Their Applications in Military and Civil Sectors*. New Delhi: Defence Research and Development Organisation, 2010.

[2] J. Tringe, “Trends in thin film photovoltaic technology development [for space application],” *IEEE Aerospace Conference Proceedings*, vol. 4. pp. 61–68 vol.4, 2000.

[3] G. Strasser, “Thin Film Technology for Data Storage Disks,” *Vak. Forsch. und Prax.*, vol. 9, no. 1, pp. 42–46, 1997.

[4] A. G. Aberle, “Thin-film solar cells,” *Thin Solid Films*, vol. 517, no. 17, pp. 4706–4710, 2009.

[5] G. Sberveglieri, “Recent developments in semiconducting thin-film gas sensors,” *Sensors Actuators B. Chem.*, vol. 23, no. 2–3, pp. 103–109, 1995.

[6] R. A. Street, “Thin-film transistors,” *Advanced Materials*, vol. 21, no. 20. pp. 2007–2022, 2009.

[7] M. Ait Aouaj, “AgInSe2 Thin Films Prepared by Electrodeposition Process,” *Int. J. Mater. Sci. Appl.*, vol. 4, no. 1, p. 35, 2015.

[8] P. Paul Ramesh, O. M. Hussain, S. Uthanna, B. Srinivasulu Naidu, and P. Jayarama Reddy, “Photovoltaic performance of p-AgInSe2/n-CdS thin film heterojunctions,” *Mater. Lett.*, vol. 34, no. 3–6, pp. 217–221, Mar. 1998.

[9] H. Mustafa, D. Hunter, A. K. Pradhan, U. N. Roy, Y. Cui, and A. Burger, “Synthesis and characterization of AgInSe2 for application in thin film solar cells,” *Thin Solid Films*, vol. 515, no. 17, pp. 7001–7004, 2007.

[10] M. A. Abdullaev, A. B. Alhasov, and D. K. Magomedova, “Fabrication and properties of

CuInSe2/AgInSe2/CdS double heterojunction cascade solar cells," *Inorg. Mater.*, vol. 50, no. 3, pp. 228–232, Mar. 2014.

[11] L. C. Chen, Y. C. Ho, R. Y. Yang, J. H. Chen, and C. M. Huang, "Electrodeposited AgInSe 2 onto TiO 2 films for semiconductor-sensitized solar cell application: The influence of electrodeposited time," *Appl. Surf. Sci.*, vol. 258, no. 17, pp. 6558–6563, 2012.

[12] M. Kaleli, D. A. Aldemir, and M. Parlak, "Electric and photoelectric properties of n-AgInSe2/p-Si heterojunction diode fabricated by successive layer deposition," *Appl. Phys. A*, vol. 123, no. 9, p. 593, Sep. 2017.

[13] P. P. Ramesh, S. Uthanna, B. S. Naidu, and P. J. Reddy, "Characteristics of Ni/nAgInSe2 polycrystalline thin film Schottky barrier diodes," *Thin Solid Films*, vol. 292, no. 1–2, pp. 290–292, Jan. 1997.

[14] S. Dias, B. Murali, and S. B. Krupanidhi, "Transport properties of solution processed Cu2SnS3/AZnO heterostructure for low cost photovoltaics," *Sol. Energy Mater. Sol. Cells*, vol. 143, pp. 152–158, 2015.

[15] S. Duman, B. Gurbulak, and A. Turut, "Temperature-dependent optical absorption measurements and Schottky contact behavior in layered semiconductor n-type InSe(:Sn)," *Appl. Surf. Sci.*, vol. 253, no. 8, pp. 3899–3905, 2007.

[16] V. Aubry and F. Meyer, "Schottky diodes with high series resistance: Limitations of forward I - V methods," *J. Appl. Phys.*, vol. 76, no. 12, pp. 7973–7984, Dec. 1994.

[17] Z. J. Horváth, "Evaluation of Schottky junction parameters from current-voltage characteristics exhibiting large excess currents," *Appl. Surf. Sci.*, vol. 255, no. 3, pp. 743–745, 2008.

[18] S. M. Sze and K. N. Kwok, *Physics of Semiconductor Devices*, 3nd ed. New Jersey: John Wiley & Sons, 2006.

[19] B. L. Sharma and R. K. Purohit, *Semiconductor Heterojunctions*. Oxford: Pergamon Press, 1974.

[20] F. Chen *et al.*, "Current transport characteristics of SiGeC/Si heterojunction diode," *IEEE Electron Device Lett.*, vol. 17, no. 12, pp. 589–591, Dec. 1996.

[21] S. S. Ou, O. M. Stafsudd, and B. M. Basol, "Current transport mechanisms of electrochemically deposited CdS/CdTe heterojunction," *Solid. State. Electron.*, vol. 27, no. 1, pp. 21–25, Jan. 1984.

[22] M. Kaleli, M. Parlak, and C. Ercelebi, "Studies on device properties of an n-AgIn5Se8/p-Si heterojunction diode," *Semicond. Sci. Technol.*, vol. 26, no. 10, 2011.

[23] F. Ö. Kuş, T. Serin, and N. Serin, "Current transport mechanisms of n-ZnO/p-CuO heterojunctions.pdf," *J. Optoelectron. Adv. Mater.*, vol. 11, no. 11, pp. 1855–1859, 2009.

[24] S. Mridha and D. Basak, "Investigation of a p-CuO/n-ZnO thin film heterojunction for H2 gas-sensor applications," *Semicond. Sci. Technol.*, vol. 21, no. 7, pp. 928–932, 2006.

[25] S. Majumdar and P. Banerji, "Temperature dependent electrical transport in p-ZnO/n-Si heterojunction formed by pulsed laser deposition," *J. Appl. Phys.*, vol. 105, no. 4, pp. 1–5, 2009.

[26] E. H. Rhoderick and R. H. Williams, *Metal-semiconductor contacts*. Clarendon Press Oxford, 1988.

[27] J. Liang, M. Morimoto, S. Nishida, and N. Shigekawa, "Band structures of Si/InGaP heterojunctions by using surface-activated bonding," *Phys. Status Solidi Curr. Top. Solid State Phys.*, vol. 10, no. 11, pp. 1644–1647, 2013.

[28] J. Fischer *et al.*, "Composition dependent characterization of copper indium diselenide thin film solar cells synthesized from electrodeposited binary selenide precursor stacks," *Sol. Energy Mater. Sol. Cells*, vol. 126, pp. 88–95, 2014.

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