# Temperature Effect on Al/p-$CuInS_2$/$SnO_2$(F) Schottky Diodes

Tarek Ben Nasrallah
Physics Department, University of Hail,
Hail, Saudi Arabia and
FST, UPDS, University of Tunis El-Manar, Tunis, Tunisia
tarek.bennasrallah@fst.utm.tn

Djelloul Mahboub
Physics Department,
University of Hail,
Hail, Saudi Arabia
djmahboub@gmail.com

Mohcen Jemai
Physics Department, FST, LMAPQ,
University of Tunis El-Manar,
Tunis, Tunisia
mohcen.jemai@gmail.com

Said Belgacem
Physics Department, FST, UPDS,
University of Tunis El-Manar,
Tunis, Tunisia
saidbelgacem55@gmail.com

*Abstract*—**In this paper, Schottky diodes (SDs) obtained by evaporated thin films of aluminum on pulverized p-$CuInS_2$/$SnO_2$:F have been studied using J-V-T characteristics in a temperature range of 200-340K. These characteristics show that aluminum acts as a rectifier metal-semiconductor contact. Characteristic variables of the Al/p-$CuInS_2$/$SnO_2$:F junctions, such as the current density, the serial resistance, the parallel conductance, the Schottky barrier height (SBH), and the ideality factor of the SD were obtained by fitting the J-V-T data using the Lambert function. Data analysis was conducted with the use of MATLAB. Results showed that n is greater than 1, which could be explained by the existence of inhomogeneities due to the grain boundaries in $CuInS_2$. Through this analysis, one can see a good agreement between experimental and modeled data. The study has shown that the main contribution in the current conduction in such heterostructures is the thermionic emission (TE) supported by the recombination of the carriers. The last phenomenon appears mainly in the grain boundaries, which contain both intrinsic and extrinsic defects (secondary phases, segregated oxygen). An investigation of the J-V-T characteristics according to TE theory has demonstrated that the current density and the SBH increase while serial resistance, parallel conductance decrease with an increase in temperature. After an SBH inhomogeneity correction, the modified Richardson constant and the mean barrier height were found to be $120AK^{-2}cm^{-2}$ and 1.29eV respectively. This kind of behavior has been observed in many metal-semiconductor contacts.**

***Keywords-$CuInS_2$; thin films; spray pyrolysis; Schottky diodes; Lambert function***

## I. INTRODUCTION

The ternary semiconductors with the chemical formula of $AB_nC_m$ (A=Cu, Ag, Zn, Cd, B=Ga, In, C=S, Se, Te, n, m: integers) have aroused considerable interest [1-3]. Their physicochemical properties allow them to be used in many applications in fields such as solar cells [3-5], photocatalysis [6], non-linear optics [7], lasers [8], solar cells, optronic devices [9], etc. A particular type of the ternary chalcogenides has emerged, which has proven the ability of these semiconductors to be used as an absorber in terrestrial photovoltaic applications. One of the main I-III-$VI_2$ types of semiconductors, namely $CuInS_2$ (CIS) crystallize in the chalcopyrite structure, has a high absorbance in the visible and near-infrared region [4], a direct bandgap of 1.5eV, and non-toxic environmental constituents. All these properties allow the CIS to be an excellent candidate for several applications in the field of optoelectronics in general [10-14]. On the other hand, the metal-semiconductor contacts (MS) are at the base of all electronic devices, whether ohmic type or rectifiers (Schottky diode (SD)). Nevertheless, it should be emphasized that the efficiency and reliability of an SD are highly influenced by the quality of the interface between the two (metal and semiconductor) surfaces [15-17]. Therefore, special attention should be given to the state of the MS interface when analyzing the *J-V-T* characteristics of the SD with respect to the ideal thermionic emission (TE) actual model [18-23]. Recent studies have demonstrated a temperature dependence of the Schottky barrier parameters [24-34]. Throughout these studies and according to the TE theory, the SBH decreases when the temperature increases whereas the ideality factor n increases with a decrease in temperature. The standard TE theory seems to be unsuccessful in explaining these experimental results [35], since the barrier height (BH) does not depend on temperature, as the bandgap of the semiconductor [24].

The most used devices with Schottky contacts and operating at cryogenic temperatures, as the infrared detectors in thermal imaging [34, 36-38], use low BH Schottky diodes. This factor makes the analysis of *J-V-T* characteristics of the Schottky barrier diodes at ambient temperature unable to provide us the transport phenomena of charge carriers as well as the nature of barrier formation. Moreover, an in-depth study

Corresponding author: Tarek Ben Nasrallah

of the *J-V-T* characteristics of Schottky contacts allows determining the aspects of their conduction mechanisms. The conduction mechanisms and therefore the BH of MS contacts, whether they are ohmic or rectifiers, depends on intrinsic or extrinsic defects such as the atomic structure, the doping, and thickness inhomogeneities at the metal-semiconductor interface, the grain boundaries secondary phases as shown in [39-47]. These defects should introduce and develop substantial inhomogeneities in the Schottky barrier height (SBH) [34, 48]. To the best of our knowledge, the electrical transport characteristics of $A\ell$/p-CIS/$SnO_2$:F Schottky contacts at low temperatures have not been reported yet. However, we have to cite [49] concerning the elaboration of $A\ell$/ZnO/CdS/$CuInS_2$/Mo/Glass solar cells, were the J-V characteristic of $A\ell/CuInS_2$ was carried out at room temperature. Therefore, the primary goal of the present paper is the study of the current-voltage characteristics of $A\ell$/p-CIS/$SnO_2$:F Schottky diodes in the temperature range of 200-340K and therefore extract the five parameters ($J_S$, n, $R_S$, $G_P$ and $\Phi_B$) of the elaborated Schottky diodes. The influence of the temperature on the ideality factor n and the barrier height $\Phi_B$ will also be presented.

## II. EXPERIMENTAL PROCEDURE

$CuInS_2$ (p) thin films have been deposited using spray pyrolysis technique on $SnO_2$:F/Pyrex substrates. The sprayed thin films were carried out at the optimized substrate temperature of 600K, and the concentration elements ratios in the spray solution were: $[Cu^+]/[In^{3+}]$=1.1 and $[S^{2-}]/[In^{3+}]$=4 with constant indium concentration $[In^{3+}]$=3.3 $10^{-2}$mol.l$^{-1}$ [50, 51]. Finally, a thin film of high purity (99.999%) aluminum ($A\ell$) with a thickness of 700Å has been evaporated, under vacuum ($10^{-6}$Torr) onto $CuInS_2$ sprayed film to complete the SD development process (Figure 1).

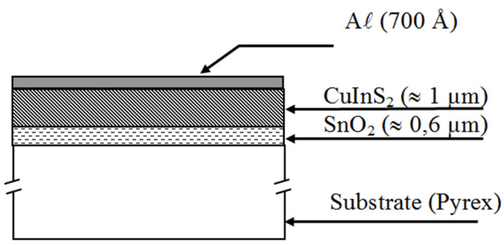


Fig. 1. Structure of $A\ell/CuInS_2$ Schottky diodes

The $SnO_2$ doped with fluorine (F), prepared with the same spray technique [52] is used as a back ohmic contact. Figure 2 shows that the *J–V* characteristic of the Au/$CuInS_2$/$SnO_2$ contact is symmetric and rectilinear. The specific contact resistance $R_c$=6.25Ωcm$^2$ is independent of the applied voltage's value or polarity, proving that the structure Au/$CuInS_2$/$SnO_2$ is an excellent ohmic contact. The current density-voltage (*J-V*) characteristics at low temperatures (200K≤*T*≤340K) using liquid nitrogen have been carried out using a programmable voltage source (Keithley 230) and a lock-in amplifier (SR 830). Data acquisition was done using LabView.

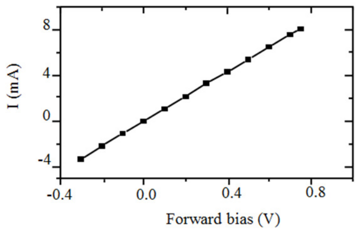


Fig. 2. I-V characteristic of Au/$CuInS_2$/$SnO_2$ contact

## III. RESULTS AND DISCUSSION

### A. Forward-bias J-V-T Characteristics of $A\ell$/p-CIS/$SnO_2$:F

The determination with reasonable accuracy of the Schottky diode parameters ideality factor $n$, barrier height $\Phi_{B0}$, series resistance $R_s$, shunt conductance $G_p$, and saturation current $J_s$ is fundamental to determine the charge carrier's transport mechanisms and to optimize the electrical performance of these devices. Several numerical analysis methods have been developed to extract these parameters [16, 53-59]. The method used in this work is based on the analytical solution of (1), while taking into account (2). A similar problem was shown in [58], but only with three parameters and straightforward relation between voltage and current, as shown in [59]. The Lambert W-function method has been used to determine $R_s$, $G_p$, $n$, $\Phi_{B0}$ and $J_s$. The Lambert W-function is the solution to the implicit equation W($x$)exp[W($x$)]=$x$. The problem is to be solved with the evaluation of a set of five parameters to fit a given experimental *J–V-T* characteristic. To understand if an SD has an ideal diode behavior, an analysis of its *J-V-T* characteristics must be analyzed using the TE model [15, 16]:

$$J(V) = J_S\left[\exp\left(\frac{V-R_SJ}{nV_{th}}\right)-1\right] + G_P\,(V-R_SJ) \qquad (1)$$

with:

$$J_S = A^*T^2\exp\left(-\frac{\Phi_{B0}}{V_{th}}\right) \qquad (2)$$

where $J_S$ is the saturation current, $V$ is the forward bias voltage, $V_{th}=\frac{kT}{q}$ is the thermal voltage, $R_S$ the serial resistance, $G_P$ the parallel conductance. $A^*$ is the effective Richardson constant, $T$ the absolute temperature, $\Phi_{B0}$ the zero bias effective barrier height, $k$ is the Boltzmann constant and $q$ is the elementary charge.

For an ideal diode where the conduction mechanism is governed only by the TE process, the ideality factor has a value of $n$=1. This ideality factor $n$ can be greater than 1 in the case of recombination of charge carrier in the depletion zone and/or if a tunneling effect through the barrier has been occurred for such diodes. Typical forward bias *J-V* characteristics of $A\ell$/p-$CuInS_2$/$SnO_2$:F Schottky contacts as a function of temperature in the range 200-340K are shown in Figures 3-4. As expected, these characteristics deviate from ideality at low temperatures (200–265K), $n \gtrsim 3$, in this case, the conduction is due to the recombination of charge carriers in the depletion region [15, 16] also to the carriers tunneling through the barrier. At temperatures above 265K, the TE process becomes dominant.

Matlab was used to fit the data using (1) and (2) to extract the experimental values of $R_s$, $G_p$, $n$, $\Phi_{B0}$ and $J_s$ as described above. Experimental and fitted data are given in Figures 3-4 for the temperature range of 200K≤$T$≤340K. It can be seen that the fitted data correspond to the experimental data. The electrical parameters obtained by this approach are summarized in Table I.

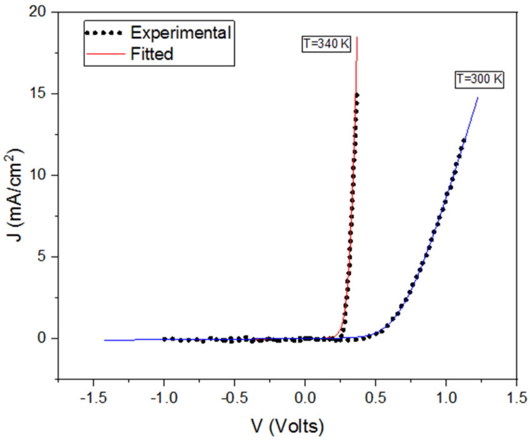


Fig. 3. *J-V* curve of Aℓ/CIS/$SnO_2$ Schottky diode for $T$=340K and $T$=300K. The fit using the Lambert function is also shown.

TABLE I. TEMPERATURE DEPENDENCE OF ELECTRICAL PARAMETERS

| $T$ (K) | $Js$ (nA.cm$^{-2}$) | $n$ | $Rs$ (Ω) | $G_p$ (μΩ$^{-1}$) | $\Phi_{B0}$ (eV) |
|---|---|---|---|---|---|
| 340 | 60 | 1.5 | 1.36 | 1.13 | 1.122 |
| 300 | 2.96 | 2 | 30.55 | 6.71 | 1.098 |
| 280 | 0.99 | 2.49 | 43.68 | 7.56 | 1.032 |
| 265 | 0.4 | 2.85 | 179.5 | 7.56×10$^2$ | 0.950 |
| 250 | 7×10$^{-2}$ | 3.5 | 207.3 | 7.85×10$^3$ | 0.888 |
| 230 | 1.43×10$^{-2}$ | 4.25 | 294.71 | 4.97×10$^4$ | 0.830 |
| 200 | 1.25×10$^{-3}$ | 7.51 | 473.22 | 13.74×10$^5$ | 0.750 |

Figure 5 shows the plots of $\Phi_{B0}$ and $n$ respectively vs. temperature for Aℓ/p-CIS/$SnO_2$:F. Decrease in the ideality factors and increase in the barrier heights with an increase in temperature are observed. During the elaboration of the different thin films, especially the sprayed one, inhomogeneities in the structure of the interface of the MS contacts are induced which could explain the strong dependence of these parameters ($\Phi_{B0}$ and $n$) on temperature [60]. One can deduce that the transport of charge carriers through the metal-semiconductor interface is temperature-activated, the SBH could contain inhomogeneities, and the current transport will be dominated by current flow through small interfacial regions with a weaker SBH that the electrons can overcome at low temperatures [17, 42]. Due to these inhomogeneities, charge transport over the interface is never again commanded by TE. Moreover, numerous models have been put forward to clarify the inhomogeneity in the barrier [17, 42, 46]. Authors in [17, 42] proposed a potential fluctuation model to describe BHs, which shows a more significant deviation from the classical thermionic theory at low temperature. According to the potential fluctuation model, at adequately low temperatures, a nonnegligible current is flowing through discontinuities at the MS interface, which probably presents a lower barrier height, when the temperature increases, electrons gain more thermal energy to cross the threshold of the higher barrier [60,61]. As a result, both parameters ($\Phi_{B0}$ and $n$) exhibited temperature-dependent *J-V-T* characteristics (Figure 5) consistent with SBH inhomogeneity.

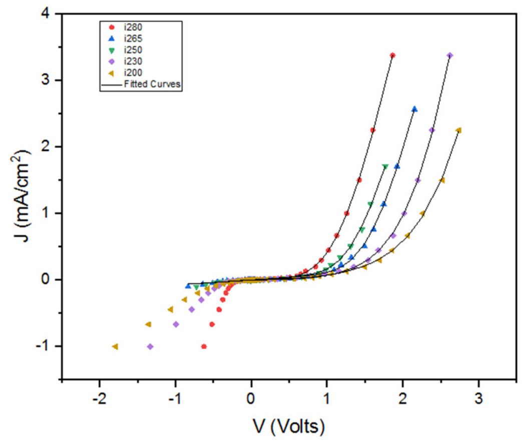


Fig. 4. Temperature dependence of Aℓ/CIS/$SnO_2$ *J-V* curves and their fitting curves

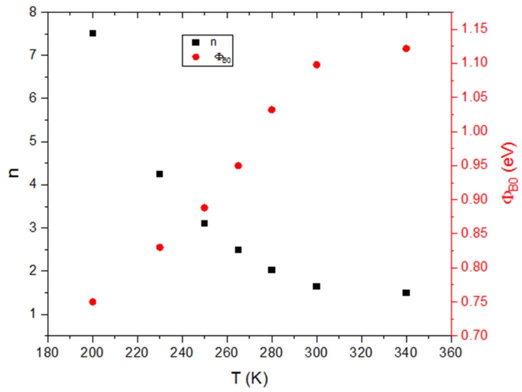


Fig. 5. Temperature dependence of ideality factor and BH for Aℓ/p-$CuInS_2$/$SnO_2$:F Schottky contact in the temperature range 200-340K

The ideality factor is merely a manifestation of barrier uniformity. BH inhomogeneities, potentially begin from structural defects in semiconductors, inhomogeneous doping, contamination on semiconductor surfaces during the deposition process (chemical solution), thickness nonuniformity, roughness of thin films, and the presence of an insulating layer ($A\ell_2O_3$) at the MS interface [50, 51]. Authors in [48, 62] claim that the BH obtained under the flat band condition must be considered as a reference value of $\Phi_{B0}$ for which one can assume that the electric potential is zero. In this case, the effect of image force lowering the BH should be compensated, and accordingly, the influence of inhomogeneity would be removed [62]. To describe the disparity with respect to TE theory, authors in [60] proposed a Gaussian distribution $P(\Phi_B)$ for the spatial dispersion of the barrier height at the MS interface with a standard deviation ($\sigma_s$) around an average value $\overline{\Phi}_B$. The barrier height can be determined by using (2) as follows:

$$\ln\left(\frac{J_S}{T^2}\right) = \ln(A^*) - \frac{\Phi_{B0}}{V_{th}} \qquad (3)$$

The plot of $\ln\left(\frac{J_S}{T^2}\right)$ versus ($q/kT$) should yield a straight-line if the SBH ($\Phi_{B0}$) is independent of temperature $T$. However, the Richardson plot of the experimental data (Figure 6) described by (3) deviates from linearity for low temperatures $T \leq 265$K. This nonlinearity can be justified by the fact that the ideality factor $n$ and the SBH $\Phi_{B0}$ depend on temperature as described for many types of materials [27, 48, 61-67]. The Richardson constant ($A^*$) extrapolated from the y-axis intercept has a value of $22.68\ Acm^{-2}K^{-2}$. This value of ($A^*$) is much lower than the theoretical value which is $A^*_{th} = 120\, m^*/m_0 = 156\text{Acm}^{-2}\text{K}^{-2}$, where $m^*=1.3m_0$ is the hole effective mass in CIS [62, 65, 68] and $m_0$ is the electron mass. Likewise, an SBH value of 0.83eV deduced from the slope of the linear part of this Richardson plot was found for $T \geq 265$K.

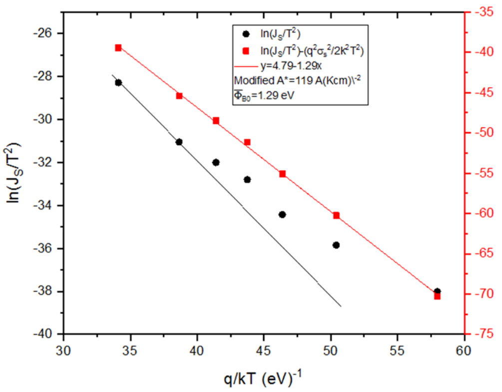


Fig. 6. Classical and Modified Richardson plot for Aℓ/p-$CuInS_2$/$SnO_2$:F Schottky contact

The discrepancy in the Richardson plot is most likely due to the inhomogeneities of the BH and applied potential fluctuation at the MS interface. These morphological and structural inhomogeneities incorporate a low and high barrier along with the MS interface. At low temperature the current through the lower barriers lies in the applied potential distribution [60, 69, 70]. Authors in [64] showed that the Richardson constant calculated from the *J-V-T* characteristics depends strictly on the barrier inhomogeneities.

### B. *Analysis of the Schottky BH Inhomogeneities (SBHI)*

Authors in [60, 61] introduced a Gaussian distribution to describe the potential fluctuation of the SBH to explain its abnormal behaviors. In this approach, the BH $\Phi_{B0}$ and the ideality factor $n$ are replaced in (1) and (2) by the apparent BH $\Phi_{ap}$ at zero bias and apparent ideality factor $n_{ap}$ as follows:

$$\Phi_{ap} = \overline{\Phi}_{B0}(T=0) - \frac{q\sigma_s^2}{2kT} \qquad (4)$$

$$\frac{1}{n_{ap}} - 1 = \rho_2 + \frac{q\rho_3}{2kT} \qquad (5)$$

where $\overline{\Phi}_{B0}$ and $\sigma_s$ are the mean value and standard deviation of $\Phi_{B0}$ respectively. The temperature-dependent coefficients $\rho_2$ and $\rho_3$ quantify the voltage deformation of the BH distribution. Furthermore, one can consider that $\sigma_s$ is independent on temperature [33, 61, 65]. The barrier inhomogeneities affect the current flow of electrons through the Schottky barrier. At low temperatures ($T$<265K), tunneling of electrons is the dominant process, given the electrons do not have enough energy to overcome the BH, but the existence of low barrier areas facilitate to the charge carries further tunneling through the BH. A linear fit for $n_{ap}$, which obeys to (5) has been obtained as shown in Figure 7. The voltage coefficients values of $\rho_2$=–0.68 and $\rho_3$=–7.59×$10^{-4}$V from the intercept and slope respectively have been deduced. Otherwise, the linear fit of the experimental data using (3) gives the value of the apparent BH, which should obey to (4). The values of $\overline{\Phi}_{B0}$=0.953eV and $\sigma_s$=0.139V from the intercept and slope respectively have been obtained. The lower the value of $\sigma_s$, the better is the quality of the barrier height and the diode rectifying performance.

### C. *The Modified Richardson Plots*

The Richardson plots can be adjusted using (3) and (4) simultaneously:

$$\ln\left(\frac{J_S}{T^2}\right) - \frac{q^2\sigma_S^2}{2(kT)^2} = \ln(A^{**}) - \frac{\Phi_{ap}}{V_{th}} \qquad (6)$$

where $A^{**}$ is the modified Richardson constant.

The fitting of the new Richardson plot using (6) generates a straight line. $\overline{\Phi}_{B0}$ and $A^{**}$ are deduced from the slope and intercept respectively as shown in Figure 6. The graph has been plotted for the 200K–340K temperature range. The modified Richardson constant was $A^{**} = 120\ \text{AK}^{-2}\ \text{cm}^{-2}$ and mean BH of 1.29eV. Authors in [70] used the same method for Al/p-$CuInAlSe_2$ SD and obtained a modified Richardson constant of $A^{**} = 26\ \text{AK}^{-2}\ \text{cm}^{-2}$ and a mean barrier height of 1.02eV.

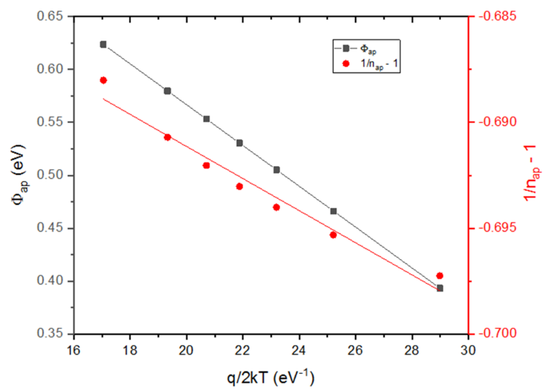


Fig. 7. Zero-bias apparent barrier and apparent ideality factor versus $q/(2kT)$ curves of Aℓ/p-$CuInS_2$/$SnO_2$:F Schottky contact

## IV. CONCLUSION

The *J-V-T* characteristics of Aℓ/p-$CuInS_2$/$SnO_2$:F Schottky contacts elaborated with the use of the physical vapor deposition system and spray pyrolysis were measured in the 200K-340K temperature range. It was noted that the ideality factors increase whereas barrier heights decrease when temperature decreases. These results have been attributed to the fluctuations in the barrier height due to the metal-semiconductor interface morphological and structural inhomogeneities. Barrier height inhomogeneities can be related to the composition of the interface such as secondary phase, surface roughness, defects, presence of insulating layer ($A\ell_2O_3$) and non-stoichiometry, etc. The ideality factors and the barrier heights were obtained from the *J-V-T* characteristics of the Schottky diodes. It has been shown that the ideality factors and therefore, the barrier heights varied from diode to diode even though they were identically made-up. The homogeneous barrier height values were obtained for the metals CIS Schottky contacts from the linear relationship between the *J-V-T* apparent barrier heights and ideality factors, which can be explained by the presence of many kinds of inhomogeneities as described above. The experimental data and the theoretical predictions for $A\ell$/p-$CuInS_2$/$SnO_2$:F Schottky diodes are in good agreement for the temperature range of 200K-340K. The p-CIS Schottky contacts exhibited a significant dependence on temperature. The current transport mechanism is predominately thermionic emission at high temperatures (280-340K) whereas, the Schottky contacts exhibited the dominance of the recombination and/or tunneling current at low temperatures. From the *J-V-T* measurements, the ideality factors were seen to increase and barrier heights to decrease with decrease in temperature. This has been related to the presence of low SBH areas at the metal-CIS interface, overriding to the flow of excess current at low voltages and temperatures. From the modified Richardson plot, the modified Richardson constant for CIS is $A^{**} = 120\ \mathrm{AK}^{-2}\ \mathrm{cm}^{-2}$ with a mean barrier height of 1.29eV. $A^{**}$ has shown a strong dependence on the metal–semiconductor contact quality, saturation current, and probably temperature as shown in [62, 68, 70]. In determining $A^{**}$, barrier inhomogeneities should be considered to get an accurate value. The procedure used in this study was proven to be the best for CIS as good diodes with very low reverse leakage currents and high rectification properties were obtained. Furthermore, the results obtained through the study based on *J-V-T* characteristics, should be corroborated by capacitance voltage temperature (*C-V-T*) measurements.

## ACKNOWLEDGMENT

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## REFERENCES


[1] J. S. Gardner, E. Shurdha, C. Wang, L. D. Lau, R. G. Rodriguez, J. J. Pak, "Rapid synthesis and size control of CuInS2 semi-conductor nanoparticles using microwave irradiation", Journal of Nanoparticle Research, Vol. 10, No. 4, pp. 633-641, 2008

[2] M. O. Lopez, O. V. Galan, F. C. Gandarilla, O. S. Feria, "Preparation of $AgInS_2$ chalcopyrite thin films by chemical spray pyrolysis", Materials Research Bulletin, Vol. 38, No. 1, pp. 55-61, 2003

[3] Y. Akaki, S. Kurihara, M. Shirahama, K. Tsurugida, S. Seto, T. Kakeno, K. Yoshino, "Structural, electrical and optical properties of $AgInS_2$ thin films grown by thermal evaporation method", Journal of Physics and Chemistry of Solids, Vol. 66, No. 11, pp. 1858-1861, 2005

[4] C. C. Landry, J. Lockwood, A. R. Barron, "Synthesis of chalcopyrite semiconductors and their solid solutions by microwave irradiation", Chemistry of Materials, Vol. 7, No. 4, pp. 699-706, 1995

[5] R. Klenk, J. Klaer, R. Scheer, M. C. L. Steiner, I. Luck, N. Meyer, U. Ruhle, "Solar cells based on $CuInS_2$-An overview", Thin Solid Film, Vol. 480-481, pp. 509-514, 2005

[6] W. Vallejo, C. A. Arredondo, G. Gordillo, "Synthesis and characterization of Zn(O,OH)S and $AgInS_2$ layers to be used in thin film solar cells", Applied Surface Science, Vol. 257, No. 2, pp. 503-507, 2010

[7] W. Zhang, D. Li, Z. Chen, M. Sun, W. Li, Q. Lin, X. Fu, "Microwave hydrothermal synthesis of $AgInS_2$ with visible light photocatalytic activity", Materials Research Bulletin, Vol. 46, No. 7, pp. 975–982, 2011

[8] J. Hu, Q. Lu, K. Tang, Y. Qian, G. Zhou, X. Liu, "Solvothermal reaction route to nanocrystalline semiconductors $AgMS_2$ (M=Ga, In)", Chemical Communications, Vol. 12, pp. 1093-1094, 1999

[9] Z. Aissa, A. Bouzidi, M. Amlouk, "Study of the I–V characteristics of $SnO_2$:F/$AgInS_2$ (p)/Al Schottky diodes", Journal of Alloys and Compounds, Vol. 506, No. 2, pp. 492-495, 2010

[10] T. Wada, H. Kinoshita, S. Kawata, "Preparation of chalcopyrite-type $CuInSe_2$ by non-heating process", Thin Solid Film, Vol. 431-432, pp. 11-15, 2003

[11] B. Mao, C. H. Chuang, J. Wang, C. Burda, "Synthesis and photophysical properties of ternary I–III–VI $AgInS_2$ nanocrystals: Intrinsic versus surface states", Journal of Physical Chemistry C, Vol. 115, No. 18, pp. 8945-8954, 2011

[12] L. Tian, J. J. Vittal, "Synthesis and characterization of ternary $AgInS_2$ nanocrystals by dual- and multiple-source methods", New Journal of Chemistry, Vol. 31, pp. 2083-2087, 2007

[13] K. Yoshino, H. Komaki, T. Kakeno, Y. Akaki, T. Ikari, "Growth and characterization of p-type $AgInS_2$ crystals", Journal of Physics and Chemistry of Solids, Vol. 64, No. 9-10, pp. 1839-1842, 2003

[14] L. L. Kazmerski, S. Wagner, Current Topics in Photovoltaics, Academic Press, New York, 1985

[15] E. H. Rhoderick, R. H. Williams, Metal-Semiconductor Contacts, Clarendon Press, 1988

[16] S. M. Sze, K. K. Ng, Physics of Semiconductor Devices, Wiley, New York, 1981

[17] R. T. Tung, "Recent advances in Schottky barrier concepts", Materials Science and Engineering: R: Reports, Vol. 35, No. 1-3, pp. 1-138, 2001

[18] E. Gur, S. Tuzemen, B. Kilic, C. Coskun, "High-Temperature Schottky Diode Characteristics of Bulk ZnO", Journal of Physics: Condensed Matter, Vol. 19, No. 19, Article ID 196206, 2007

[19] N. Rouag, L. Boussouar, S. Toumi, Z. Ounnoughi, M. A. Djouadi, "On the difference in the apparent barrier height of inhomogeneous Schottky diodes with a Gaussian distribution", Semiconductor Science and Technology, Vol. 22, No. 4, pp. 369-373, 2007

[20] D. M. Kim, D. H. Kim, S. Y. Lee, "Characterization and modeling of temperature-dependent barrier heights and ideality factors in GaAs Schottky diodes", Solid-State Electron., Vol. 51, No. 6, pp. 865-869, 2007

[21] J. Dhananjay, S. Nagaraju, B. Krupanidhi, "Investigations on magnetron sputtered ZnO thin films and Au/ZnO Schottky diodes", Physica B: Condensed Matter, Vol. 391, No. 2, pp. 344-349, 2007

[22] A. R. Arehart, B. Moran, J. S. Speck, U. K. Mishra, S. P. Den Baars, S. A. Ringel, "Effect of Threading Dislocation Density on Ni / n-GaN Schottky Diode I-V Characteristics", Journal of Applied Physics, Vol. 100, No. 2, Article ID 023709, 2006

[23] A. F. Qasrawi, "Fabrication and characterization of TO/GaSe/(Ag, Au) Schottky diodes", Semiconductor Science and Technology, Vol. 21, No. 6, pp. 794-798, 2006

[24] J. H. Werner, H. H. Guttler, "Temperature dependence of Schottky barrier heights on silicon", Journal of Applied Physics, Vol. 73, No. 3, pp. 1315-1319, 1993

[25] S. Chattopadhyay, L. K. Bera, S. K. Ray, C. K. Maiti, "Pt/p -strained-Si Schottky diode characteristics at low temperature", Applied Physics Letters, Vol. 71, No. 7, pp. 942-944, 1997

[26] T. P. Chen, T. C. Lee, C. C. Ling, C. D. Beling, S. Fung, "Current transport and its effect on the determination of the Schottky-barrier height in a typical system: Gold on silicon", Solid-State Electronics, Vol. 36, No. 7, pp. 949-954, 1993

[27] M. K. Hudait, P. Venkatesvarlu, S. B. Krupanidhi, "Electrical transport characteristics of Au/n-GaAs Schottky diodes on n-Ge at low temperatures", Solid-State Electronics, Vol. 45, No. 1, pp. 133-141, 2001

[28] S. Karata, S. Altindal, A. Turut, A. Ozmen, "Temperature dependence of characteristic parameters of the H-terminated Sn/p-Si(1 0 0) Schottky contacts", Applied Surface Science, Vol. 217, No. 1-4, pp. 250-260, 2003

[29] T. Sawada, Y. Ito, N. Kimura, K. Imai, K. Suzuki, S. Sakai, "Characterization of metal/GaN Schottky interfaces based on I–V–T characteristics", Applied Surface Science, Vol. 190, No. 1-4, pp. 326-329, 2002

[30] J. Osvald, Zs. J. Horvath, "Theoretical study of the temperature dependence of electrical characteristics of Schottky diodes with an inverse near-surface layer", Applied Surface Science, Vol. 234, No. 1-4, pp. 349-354, 2004

[31] N. Tugluoglu, S. Karadeniz, M. Sahin, H. Safak, "Temperature dependence of current–voltage characteristics of Ag/p-SnSe Schottky diodes", Applied Surface Science, Vol. 233, No. 1-4, pp. 320-327, 2004

[32] M. Soylu, B. Abay, "Barrier characteristics of gold Schottky contacts on moderately doped n-InP based on temperature dependent I–V and C–V measurements", Microelectronic Engineering, Vol. 86, No. 1, pp. 88-95, 2009

[33] W. Mtangi, F. D. Auret, C. Nyamhere, P. J. J. V. Rensburg, M. Diale, A. Chawanda, "Analysis of temperature dependent I-V measurements on Pd/ZnO Schottky barrier diodes and the determination of the Richardson constant", Physica B: Condensed Matter, Vol. 404, No. 8-11, pp. 1092-1096, 2009

[34] F. E. Cimilli, M. Saglam, H. Efeoglu, A. Turut, "Temperature-dependent current–voltage characteristics of the Au/n-InP diodes with inhomogeneous Schottky barrier height", Physica B: Condensed Matter, Vol. 404, No. 8-11, pp. 1558-1562, 2009

[35] O. F. Yuksel, "Temperature dependence of current–voltage characteristics of Al/p-Si (100) Schottky barrier diodes", Physica B: Condensed Matter, Vol. 404, No. 14-15, pp. 1993-1997, 2009

[36] M. Pattabi, S. Krishnan, Ganesh, X. Mathew, "Effect of temperature and electron irradiation on the I–V characteristics of Au/CdTe Schottky diodes", Solar Energy, Vol. 81, No. 1, pp. 111-116, 2007

[37] F. Brovelli, B. L. Rivas, J. C. Bernede, "Synthesis of polymeric thin films by electrochemical polymerization of 1-furfuryl pyrrole. characterization and charge injection mechanism", Journal of the Chilean Chemical Society, Vol. 52, No. 1, pp. 1065-1068, 2007

[38] F. Yakuphanoglu, "The current–voltage characteristics and inhomogeneous-barrier analysis of ddq/p-type Si/Al diode with interfacial layer", Physica B: Condensed Matter, Vol. 389, No. 2, pp. 306-310, 2007

[39] H. J. Im, Y. Ding, J. P. Pelz, W. J. Choyke, "Nanometer-Scale Test of the Tung Model of Schottky-Barrier Height Inhomogeneity", Physical Review B, Vol. 64, Article ID 075310, 2001

[40] R. F. Schmitsdorf, T. U. Kampen, W. Monch, "Explanation of the linear correlation between barrier heights and ideality factors of real metal-semiconductor contacts by laterally nonuniform Schottky barriers", Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures Processing, Measurement, and Phenomena, Vol. 15, No. 4, pp. 1221-1226, 1997

[41] J. P. Sullivan, R. T. Tung, M. R. Pinto, W. R. Graham, "Electron transport of inhomogeneous Schottky barriers: A numerical study", Journal of Applied Physics, Vol. 70, No. 12, pp. 7403-7424, 1991

[42] R. T. Tung, "Electron transport at metal-semiconductor interfaces: General theory", Physical Review B, Vol. 45, pp. 13509-13523, 1992

[43] W. P. Leroy, K. Opsomer, S. Forment, R. L. V. Meirhaeghe, "The barrier height inhomogeneity in identically prepared Au/n-GaAs Schottky barrier diodes", Solid-State Electronics, Vol. 49, No. 6, pp. 878-883, 2005

[44] F. E. Cimilli, M. Saglam, A. Turut, "Determination of the lateral barrier height of inhomogeneous Au/n-type InP/In Schottky barrier diodes", Semiconductor Science and Technology, Vol. 22, No. 8, pp. 851-854, 2007

[45] M. B. Reddy, A. A. Kumar, V. Janardhanam, V. R. Reddy, P. N. Reddy, "Current–voltage–temperature (I–V–T) characteristics of Pd/Au Schottky contacts on n-InP (1 1 1)", Current Applied Physics, Vol. 9, No. 5, pp. 972-977, 2009

[46] F. A. Padovani, R. Stratton, "Field and thermionic-field emission in Schottky barriers", Solid-State Electronics, Vol. 9, No. 7, pp. 695-707, 1996

[47] I. Dokme, S. Altindal, M. M. Bulbul, "The barrier height inhomogeneity in Al/p-Si Schottky barrier diodes with native insulator layer", Applied Surface Science, Vol. 252, No. 22, pp. 7749-7754, 2006

[48] S. Karadeniz, M. Sahim, N. Tougluoglu, H. Safak, "Temperature-dependent barrier characteristics of Ag/p-SnS Schottky barrier diodes", Semiconductor Science and Technology, Vol. 19, No. 9, pp. 1098-1103, 2004

[49] J. D. Harris, K. K. Banger, D. A. Scheiman, M. A. Smith, M. H. C. Jin, A. F. Hepp, "Characterization of CuInS2 films prepared by atmospheric pressure spray chemical vapor deposition", Materials Science and Engineering B, Vol. 98, No. 2, pp. 150-155, 2003

[50] M. C. Zouaghi, T. B. Nasrallah, S. Marsillac, J. C. Bernede, S. Belgacem, "Physico-chemical characterization of spray-deposited $CuInS_2$ thin films", Thin Solid Films, Vol. 382, No. 1-2, pp. 39-46, 2001

[51] S. Marsillac, M. C. Zouaghi, J. C. Bernede, T. Ben Nasrallah, S. Belgacem, "Evolution of the properties of spray-deposited CuInS2 thin films with post-annealing treatment", Solar Energy Materials and Solar Cells, Vol. 76, No. 2, pp. 125-134, 2001

[52] S. Belgacem, M. Amlouk, R. Bennaceur, "Effet du rapport Cu/In sur la structure des couches minces de $CuInS_2$ airless spray. Application : Conversion photovoltaique", Revue de Physique Appliquee, Vol. 25, No. 12, pp. 1213-1223, 1990 (in French)

[53] H. J. Norde, "A modified forward I‐V plot for Schottky diodes with high series resistance", Journal of Applied Physics, Vol. 50, pp. 5052-5053, 1979

[54] S. K. Cheung, N. W. Cheung, "Extraction of Schottky diode parameters from forward current‐voltage characteristics", Applied Physics Letters, Vol. 49, pp. 85-87, 1986

[55] V. Mikhelashvili, G. Eisenstein, V. Garber, S. Fainleib, G. Bahir, D. Ritter, M. Orenstein, A. Peer, "On the extraction of linear and nonlinear physical parameters in nonideal diodes", Journal of Applied Physics, Vol. 85, pp. 6873-6883, 1999

[56] A. O. Conde, F. J. G. Sanchez, J. J. Liou, J. Andrian, R. J. Laurence, P. E. Schmidt, "A generalized model for a two-terminal device and its applications to parameter extraction", Solid-State Electronics, Vol. 38, No. 1, pp. 265-266, 1995

[57] A. F. Hamida, Z. Ouennoughi, A. Hoffmann, R. Weiss, "Extraction of Schottky diode parameters including parallel conductance using a vertical optimization method", Solid-State Electronics, Vol. 46, No. 5, pp. 615-619, 2002

[58] T. C. Banwell, A. Jayakumar, "Exact analytical solution for current flow through diode with series resistance", Electronics Letters, Vol. 36, No. 4, pp. 291-292, 2000

[59] W. Jung, M. Guziewicz, "Schottky diode parameters extraction using lambert w function", Materials Science and Engineering: B, Vol. 165, No. 1-2, pp. 57-59, 2009

[60] J. H. Werner, H. H. Guttler, "Barrier inhomogeneities at Schottky contacts", Journal of Applied Physics, Vol. 69, No. 3, pp. 1522-1533, 1991

[61] Y. P. Song, R. L. Van Meirhaeghe, W. H. Laflere, F. Cardon, "On the Difference in Apparent Barrier Height as Obtained from Capacitance-voltage and Current-voltage- temperature Measurements on Al/p-InP

Schottky Barriers", Solid-State Electronics, Vol. 29, No. 6, pp. 633-638, 1986

[62] I. Dokme, "The analysis of I–V characteristics of Schottky diodes by thermionic emission with a Gaussian distribution of barrier height", Microelectronics Reliability, Vol. 51, No. 2, pp. 360-364, 2011

[63] M. Oda, T. Miyaoka, S. Yamada, T. Tani, "Synthesis, Characterization and its Photoluminescence Properties of Group I-III-$VI_2CuInS_2$ nanocrystals", Physics Procedia, Vol. 29, pp. 18-24, 2012

[64] K. Sarpatwari, O. O. Awadelkarim, M. W. Allen, S. M. Durbin, S. E. Mohney, "Extracting the Richardson constant: IrOx/n-ZnOIrOx/n-ZnO Schottky diodes", Applied Physics Letters, Vol. 94, Article ID 242110, 2009

[65] S. Hamrouni, M. F. Boujmil, K. B. Saad, "Electrical properties of the Al/$CuInSe_2$ thin film Schottky junction", Advances in Materials Physics and Chemistry, Vol. 4, pp. 224-235, 2014

[66] C. Rincon, J. Gonzalez, "Acoustic deformation potentials in $A^{IBIIICVI2}$ chalcopyrite semiconductors", Physical Review B, Vol. 40, No. 12, pp. 8552-8554, 1989

[67] S. Acar, S. Karadeniz, N. Tugluoglu, A. B. Selcuk, M. Kasap, "Gaussian distribution of inhomogeneous barrier height in Ag/p-Si (1 0 0) Schottky barrier diodes", Applied Surface Science, Vol. 233, No. 1-4, pp. 373-381, 2004

[68] B. Abay, G. Cankaya, H. S. Guder, H. Efeoglu, Y. K. Yogurtcu, "Barrier characteristics of Cd/p-GaTe Schottky diodes based on I–V–T measurements", Semiconductor Science and Technology, Vol. 18, No. 2, pp. 75-81, 2003

[69] J. Racko, D. Donoval, M. Barus, V. Nagl, A. Grmanova, "Revised theory of current transport through the Schottky structure", Solid-State Electronics, Vol. 35, No. 7, pp. 913-919, 1992

[70] U. Parihar, J. Ray, C. J. Panchal, N. Padha, "Influence of temperature on Al/p-$CuInAlSe_2$ thin-film Schottky diodes", Applied Physisc A, Vol. 122, No. 6, Article ID 568, 2016