ATATÜRK ÜNİVERSİTESİ YAYINLARI
ATATURK UNIVERSITY PUBLICATIONS

Research Article *Araştırma Makalesi* DOI: 10.5281/zenodo.12174756

Statistical investigation of characteristic parameters for Au/p-TlInS$_2$/n-InP pseudo Schottky junctions produced under the same conditions

Aynı koşullar altında üretilen Au/p-TlInS$_2$/n-InP pseudo Schottky eklemlerin karakteristik parametrelerinin istatistiksel incelenmesi

Seda YAZICI[1]
Fatih AKTAŞ[1]
Ayşe Nida BEŞTAŞ[1]
Nezaket KULAKAÇ[1]
Dilek ASLANCAN[1]
Bahattin ABAY[2*]

[1]*Atatürk University, Institute of Natural and Applied Sciences, Department of Physics, Erzurum, Turkey*
[2]*Atatürk University, Faculty of Science, Department of Physics, Erzurum, Turkey*

*Sorumlu Yazar/Corresponding Author:
Bahattin Abay
E-mail: bahattinabay@yahoo.com

Geliş Tarihi/Received 10.05.2024
Kabul Tarihi/Accepted 05.06.2024
Yayın Tarihi/ Publication Date 27.06.2024

Cite this article
Yazıcı, S. et al (2024). Statistical investigation of characteristic parameters for Au/p-TlInS2/n-InP pseudo Schottky junctions produced under the same conditions. *Journal of Anatolian Physics and Astronomy, 3*(1), 7-18.

Abstract

Pseudo-Schottky junctions (PSJs) on moderately doped (MD) *n*-InP were fabricated by introducing a thin *p*-TlInS$_2$ counter layer before the assembly of gold rectifying contact. Successively annealing treatment was applied to create a stable inversion layer at the metal-semiconductor (MS) interface. PSJs were made with a significant barrier height (BH) enhancement, typically by the value of 0.260 eV for gold Schottky gate, after the second annealing process at 200 ^oC in a nitrogen atmosphere for 5 minutes. Junction parameters such as BH, ideality factor (*n*) and serial resistance (R_s) of identically fabricated (18 dots) Au/*p*-TlInS$_2$/*n*-InP PSJs have been computed by thermionic emission (TE) theory from current-voltage (*I-V*) and capacitance-voltage (*C-V*) characteristics, at room temperature and in the dark. BHs derived from *I-V* and *C-V* characteristics varied from 0.620 to 0.844 eV and 0.669 to 0.973 eV, respectively. In addition, the values of *n* varied from 1.023 to 1.706 and the serial resistances R_s varied from 28.3 to 131 Ω. Since all parameters of PSJs differ from one junction to another, even if they are prepared under the same conditions, a statistical study was made on the junction parameters using Tung's model. The mean values of the experimental BH, the ideality factor, and the series resistance data, which were fitted by the Gaussian function, were found to be $\bar{\phi}_{I-V} = (0.755 \pm 0.059)$ eV, $\bar{\phi}_{C-V} = (0.803 \pm 0.078)$ eV, *n* =(1.384 ± 0.152) and $R_s = (88.4 \pm 28.0)\Omega$, respectively. The lateral homogeneous BH ($\phi_{hom.}$) value of 0.800 eV for the Au/*p*-TlInS$_2$/*n*-InP junctions has been obtained from the $\phi_{eff.}$- n plot by using $n_{imf.} = 1.006$ and $\Delta\phi_{imf.} = 18.0\ meV$ It has been seen that the mean BH obtained from the *C-V* measurements correlates well with the value of $\phi_{hom.}$. The good agreement in these parameters indicates that the BH inhomogeneity observed in the Au/*p*-TlInS$_2$/*n*-InP PJ can be described by considering the spatial distribution hypothesis of BH put forward by Tung.

Keywords: n-InP, p-TlInS$_2$, pseudo-Schottky junction, I-V and C-V measurement, barrier inhomogeneities, Tung's model

Öz

Au/*p*-TlInS$_2$/*n*-InP Psödo-Schottky (PS) eklemleri, ön yüzüne omik kontak yapılmış *n*-InP altlığın arka yüzeyine altın (Au) doğrultucu kontak imalatından önce ince *p*-TlInS$_2$ inversiyon tabakası büyütülerek üretildi. Metal-yarı iletken arayüzeyinin kararlılığı için ardışık tavlama işlemi uygulandı. Azot gazı atmosferinde 200 ^{o}C'de 5 dakika süreli ardışık ikinci tavlama işleminden sonra engel yüksekliğinde (EY) yaklaşık 0,260 eV'luk bir artış gözlemlendi. Aynı şartlarda üretilmiş (18 nokta) Au/*p*-TlInS$_2$/*n*-InP PS eklemlerinin EY, idealite faktörü (*n*) ve seri direnc (R_s) parametreleri Termiyonik Emisyon (*TE*) teorisi kullanılarak oda sıcaklığı ve karanlıkta ölçülmüş akım-voltaj (*I-V*) ve kapasite-voltaj (*C-V*) karakteristiklerinden hesaplandı. *I-V* ve *C-V* karakteristiklerinden hesaplanan EY sırasıyla (0.620-0.844) eV ve (0.669-0.973) eV, idealite faktörü *n* (1.023-1.706) ve R_s seri direnç değerleri ise (28.3-131) Ω aralığında değişim sergilemektedir. Aynı koşullar altında hazırlanmalarına rağmen PS eklemlerin karakteristik parametreleri kendileri arasında farklılık gösterdiğinden, eklem parametreleri üzerinde Tung modeli kullanılarak istatistiksel bir çalışma yapıldı. Gauss fonksiyonu ile fit edilen EY, *n* ve R_s verilerinin ortalama değerleri sırasıyla $\bar{\phi}_{I-V} = (0.755 \pm 0.059)$ eV, $\bar{\phi}_{C-V} = (0.803 \pm 0.078)$ eV, *n* =(1.384 ± 0.152) and$R_s = (88.4 \pm 28.0)\Omega$ olarak elde edildi. Au/*p*-TlInS$_2$/*n*-InP PS eklemi için yanal homojen EY ($\phi_{hom.}$), $n_{imf.} = 1.006$ ve $\Delta\phi_{imf.} = 18.0\ meV$ değerleri kullanılarak $\phi_{eff.}$- n çiziminden $\phi_{hom.}$=0.800 eV olarak elde edilmiştir. *C-V* ölçümlerinden elde edilen ortalama EY değeri $\phi_{hom.}$ ile oldukça uyum içindedir. Parametrelerdeki bu uyum, Au/*p*-TlInS$_2$/*n*-InP PS ekleminde gözlenen EY inhomojenliğinin Tung tarafından ileri sürülen EY'nin uzaysal dağılımı hipotezi dikkate alınarak açıklanabileceğini gösterir.

Anahtar Kelimeler: n-InP, p-TlInS$_2$, pseudo Schottky eklem, I-V and C-V ölçümü, engel inhomojenliği, Tung modeli

Introduction

Indium Phosphide (InP) is one of the significant materials for high-speed and low-power device applications. Effective Schottky BH, in general, is restricted to within 0.3-0.5 eV range for *n*-InP independently from the contact metal and the performance of *n*-InP based microelectronic devices has been severely hindered (Brillson & Brucker, 1982; Hudait et al., 2001a; Hudait & Krupanidhi, 2001b; McCafferty et al., 1996). The reason for this is a high density of surface states existing at the metal/semiconductor interface. Therefore, these low barriers result a large reverse leakage current and bad electrical performance for Schottky barrier diodes (SBDs) made on *n*-InP. So, one of the essentialities for the InP-based devices is forming a high-quality junction with a high BH and a low ideality factor.

One of the methods for improving the effective BH is to fabricate a metal-insulator-semiconductor (MIS) structure (Sugino et al., 1990), while another one is to release the surface Fermi level pinning and use a gate metal with high work function for rectifying contact (Sugino et al., 1993). An enhancement of the BH up to 0.7-0.8 eV has been achieved by fabricating MIS Schottky junctions based on InP (Sugino et al., 1990). Assuming that the surface Fermi level pinning is pondered by high surface state density, passivation procedures by using various organic molecules have been applied to reduce the surface states of InP too (Çakar et al., 2002; Gupta & Singh, 2005; Kaya et al., 2007; Maeda et al., 1998; Schvartzman et al., 2001; Soylu et al., 2011). On the other hand, to enhance the effective BH of the *n*-InP based device, new energy levels in the semiconductor have been introduced to modify the band bending near the metal-semiconductor (MS) interface. This procedure is performed by creating a thin layer having opposite type doping to that of the substrate material between the substrate and the contact metal. The device, which has a hybrid structure between the p-n junction and the Schottky diode, is called pseudo-Schottky junction (PSJ) (Campbell et al., 1996; Clausen & Leistiko, 1993; Osvald & Horvath, 2004; Rhoderick & Williams, 1988; Sze, 1981). Therefore, with an increment as $\Delta\varphi_{b0}$ compared to the initial BH φ_{b0} of typical SBDs, PSJs can have new functions not realized by a conventional Schottky device.

Thermionic emission (TE) theory is used to extract the SBD parameters (Rhoderick & Williams, 1988; Sze, 1981). Generally, non-ideal current-voltage (*I-V*) characteristics of a MS interface show itself with a double diode behavior (knee effect) and a slight curvature in the semi-log *I-V* plot. Double diode property is defined by an abnormal high current at low forward bias values and modeled as considering low barrier (LB) patches embedded within a homogeneous high barrier (HB) region. The laterally nanoscale variations of the BH, *i.e*. patchy interfaces, lead to small BHs/high ideality factors, or vice versa (Tung, 1992; Sullivan et al., 1998). Recently, a plot of effective BH versus ideality factors *n* that evaluated from the *I-V* characteristic of a set of identically fabricated diodes on a substrate has been used to explain the BH inhomogeneities (Kampen & Mönch, 1995; Leroy et al., 2005).

The layered ternary crystals with chemical formula $TlBX_2$, B=Ga or In and X=S, Se or Te, have attracted increasing interest due to their 2D structural properties and great potential applications in nanoelectronics (Abay et al., 2000a; Abay et al., 2001a ; Abay et al., 2001b; Abay et al., 2001c; Abay et al., 2003; Lee, 1976; Çankaya & Abay, 2006; Güder et al 2001; Leith, 1977). 2D layers are joined to each other along the *c*-axis, *i.e*. perpendicular to layers, by weak interlayer Van der Waals-like interactions (Abay et al., 2000b). Crystals can easily be cleaved across this van der Waals gap resulting in mirror-like outer surfaces that closely resemble inner surfaces. The van der Waals planes are free of dangling bonds and very inert to chemical reactions, and hence the layered compounds can be considered as most suitable materials to investigate the basic features of surface or interface interactions (Lang et al., 1998). 2D $TlInS_2$ is a dichalcogenide *p*-type semiconductor with a direct band gap of about 2.27-2.47 eV at room temperature (Gasanly, 2010). As mentioned above, although a number of methods such as oxidation, passivation, and low-temperature deposition methods, etc., (Campbell et al., 1996; Çakar et al., 2002; Gupta & Singh, 2005; Kaya et al., 2007; Maeda et al., 1998; Osvald & Horvath, 2004; Schvartzman et al., 2001; Soylu et al., 2011; Sugino et al., 1990; Sugino et al., 1993) have been attempted for improving the characteristic parameters of devices fabricated on *n*-InP, to our knowledge, *p*-$TlInS_2$/*n*-InP system has not been tested yet. In this work, we investigated experimentally whether the *p*-$TlInS_2$ layered ternary compound behaves as an opposite counter layer on *n*-InP for producing a PSJ or not. For this purpose, *p*-$TlInS_2$/*n*-InP PSJs were fabricated by introducing a thin *p*-$TlInS_2$ counter layer on the moderately doped (MD) *n*-InP substrate before the assembly of rectifying contact. Electrical characterization of the PSJs prepared has been investigated by *I-V* and capacitance-voltage (*C-V*) measurement at room temperature and in the dark. Our main aim is to investigate statistically whether or not the effective BHs, ideality factors *n,* and serial resistance (R_s) obtained from the electrical characterization differ from one to the other even if the PSJs were identically prepared, by using Tung's model.

Material and Methods

Single crystals of $TlInS_2$ compound were grown by the directional freezing technique, from stoichiometric high-purity elements sealed in an evacuated and carbon-coated tubular quartz ampoule with a special tip at the bottom. Details of the crystal growth procedure are reported elsewhere (Abay, 1994). The PSJs have been prepared on 12x8 mm^2 substrate sliced from a 2 in. moderately S-doped (1.2x10^{16} cm^{-3}) one-side polished *n*-type InP (100) wafer. The substrate was successively cleaned with trichloroethylene/acetone/methanol and then rinsed in deionized water for 5 minutes after each step. The native oxide on the surface was then etched in sequence with acid solutions $(H_2SO_4 : H_2O_2 : H_2O = 3:1:1)$ and $(HF\ (49\%): H_2O = 1:1)$ for one minute, respectively. The substrate was blow-dried with pure nitrogen gas after a rinse in deionized water and then transferred to the vacuum chamber immediately for metalizing. High-quality ohmic contact was produced by evaporating of Au:Ge eutectic alloy (88 % Au: 12 % Ge) on the unpolished (back) side of the substrate, followed by annealing at 400 °*C* for 3 minutes in the pure nitrogen ambient. The substrate with ohmic contact was sliced into two pieces and *p*-$TlInS_2$ compound was deposited onto the front surface of one of the pieces to produce a counter layer. Ex-situ annealing has been carried out at 200 °*C* for 5 minutes in nitrogen flow to serve as an inversion layer. After all this, Au upper contacts as 600 μm diameter circular dots were deposited on the surfaces of the untreated and the opposite doping layered i.e., contoured, substrates to form Au/*n*-InP (control device) and Au/*p*-$TlInS_2$/*n*-InP PSJs through a molybdenum mask at the same stage. All of the deposition processes were performed under a pressure of less than 2x10^{-6} mbar in the Leybold-Heraeus Univex 300 vacuum-coating unit. Substrates contain 15 or more Au/*n*-InP and Au/*p*-$TlInS_2$/*n*-InP devices. Successively annealing treatment was applied for improving the Au/*p*-$TlInS_2$/*n*-InP device characteristics. PSJs were achieved with a significant BH, typically by the value of 0.260 eV for Au Schottky gate, after second annealing process at 200 °*C* in nitrogen ambient for 5 minutes. *I-V* and *C-V* measurements were performed by a computer-controlled Keithley 487 picoammeter-voltage source and an HP 4192A LF impedance analyzer at room temperature and in the dark.

Results and Discussion

The characteristic parameters of the devices were investigated using the *I-V* and *C-V* characteristics. The current (*I*) through a device a forward bias (*V*), according to thermionic emission (TE) theory, is given by (Rhoderick & Williams, 1998; Sze, 1981)

$$I = I_0 \exp\left(\frac{qV}{nkT}\right)\left[1-\exp\left(-\frac{qV}{kT}\right)\right] \tag{1}$$

where *q*, *V*, *n*, *k,* and *T*, are the electronic charge, the applied bias voltage, the ideality factor, the Boltzmann constant, and the absolute temperature in Kelvin, respectively, and I_0 is the saturation current derived from the straight-line intercept of $\mathrm{In}(I)$-*V* plot at zero-bias defined by:

$$I_0 = AA^* T^2 \exp\left(-\frac{q\varphi_{b0}}{kT}\right). \tag{2}$$

where A (= 2.83x10^{-7} m^2) is the effective diode area, A^* (= 9.40 $AK^{-2}cm^{-2}$ for *n*-type InP) is the effective Richardson constant, φ_{b0} is the zero-bias current-BH (apparent or measured BH) which can be obtained using the following equation by using the determined value of I_0:

$$\varphi_{b0} = kT \ln\left(\frac{AA^*T^2}{I_0}\right). \tag{3}$$

The ideality factor (*n*) of a Schottky barrier diode is described the deviation of experimental *I-V* data from the TE theory. Considering the deviation of the experimental *I-V* data from the ideal TE theory a slop parameter (ideality factor *n*) is introduced to Eq. (1). Using the definition, ideality factor can be expressed as:

$$n = \frac{q}{\mathrm{kT}}\left(\frac{\mathrm{dV}}{\mathrm{d}\,In\,(I)}\right) \tag{4}$$

On the other hand, by neglecting the image-force barrier lowering ($\Delta\varphi_{\mathrm{if.}}$), capacitance-voltage BH (φ_{CV}) for a MS device fabricated on an *n*-type semiconductor can be expressed as (Rhoderick & Williams, 1998; Sze, 1981):

$$\phi_{\text{C-V}} = V_{bi} + \frac{\mathrm{kT}}{q}\left[1 + ln\frac{N_c}{N_i}\right] \tag{5}$$

where, V_{bi} is the built-in voltage determined from the extrapolation of the C^{-2}-V plot to the voltage axis, N_c (=5.47x10^{17} cm^{-3}) is the effective density of states in the conduction band for *n*-InP at 300 K (Donald, 1982; Singh, 2001) and N_{i} is the concentration of the non-compensated ionized donors, respectively.

Fig. 1 shows typically experimental semilog forward and reverse bias *I-V* characteristics for Au/*n*-InP SBD and Au/*p*-$TlInS_2$/*n*-InP PSJ at room temperature and in the dark. As can be seen from Fig. 1, the forward *I-V* characteristic of the Au/*p*-$TlInS_2$/*n*-InP PSJ also shows the rectifying behavior and the reverse curve exhibits slightly soft behavior in which the current does not saturate to a constant value. The apparent BHs of the devices were calculated from the *y*-axis intercepts of the semilog forward bias *I-V* characteristics according to Eq. (3). The values of *n* were calculated from the slope of the linear regions of the forward *I-V* characteristics according to Eq. (4).

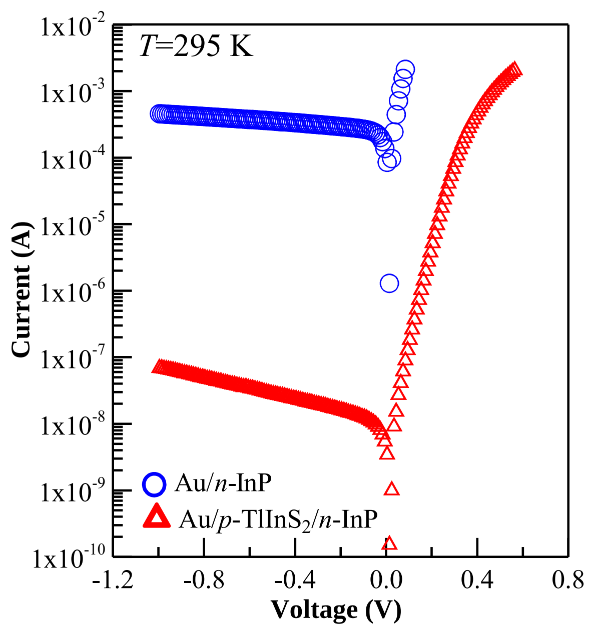

Figure 1. *I-V* characteristics for typical Au/*n*-InP SBD and Au/*p*-$TlInS_2$/*n*-InP PSJ at room temperature

The extrapolation of the *I-V* curves to zero-bias yields the value of saturation current as 1.09x10^{-4} and 4.26x10^{-9} A for the reference Au/*n*-InP SBD and Au/*p*-$TlInS_2$/*n*-InP PSJ, respectively. As can be seen from these data, the presence of an intentionally grown opposite-type counter layer on the *n*-InP reduces the value of saturation current by about four orders of magnitude, indicating an increase in the BH. The values of current BH for the reference and Au/*p*-$TlInS_2$/*n*-InP PSJ were calculated as 0.429 and 0.687 eV, respectively. The values of φ_{b0} are the effective values and do not consider the image-force lowering. The apparent BH of 0.429 eV for the reference diode is in close agreement with the previously published data (Brillson & Brucker, 1982; Campbell et al., 1996; Shi et al., 1991; Chou et al., 1998; Çakar et al., 2002; Gupta & Singh, 2005; Hökelek & Robinson, 1981; Hudait et al., 2001a; Hudait & Krupanidhi, 2001b; İsmail et al., 1987; Kaya et al., 2007; Maeda et al., 1998; McCafferty et al., 1996; Schvartzman et al., 2001; Soylu et al., 2011; Soylu & Abay, 2009; Sugino et al., 1990; Sugino et al., 1993).

From the slope of the *I-V* curves, the ideality factors were obtained as 1.002 and 1.066 for the reference and Au/*p*-$TlInS_2$/*n*-InP PSJ, respectively. The low ideality factors ($n \leq 1.10$) indicate that TE is the dominant transport mechanism for all devices. As can be seen, the leakage current has been reduced after the surface modification of *n*-InP by $TlInS_2$ deposition, effectively giving an increased BH, accompanied by a little departure of the ideality factor (1.066) from unity. The increase in the BH was about 260 meV.

The effective BH and *n* values were obtained as many as 18 Au/*p*-$TlInS_2$/*n*-InP PSJ, from individual *I-V* characteristics via Eq. (3) and (4), respectively (Fig. 2). The BHs for the diodes varied from 0.620 to 0.844 eV while, the values of ideality factor *n* varied from 1.023 to 1.706. It is seen clearly that our PSJs have significantly larger ideality factors.

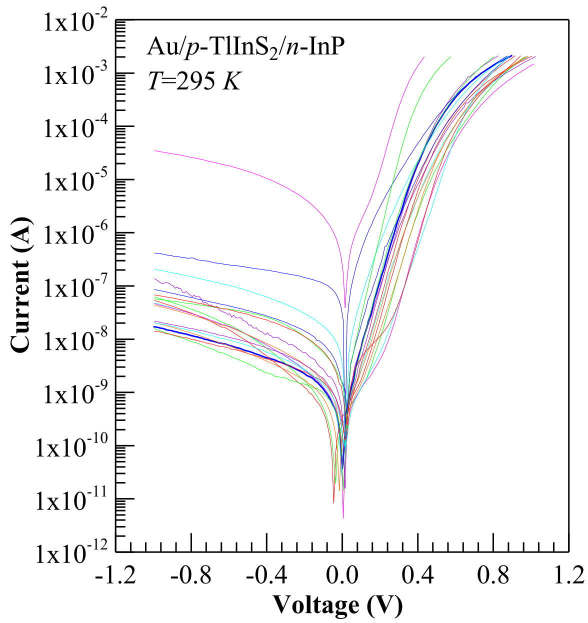

Figure 2. Experimental forward and reverse bias *I-V* characteristic for eighteen Au/*p*-$TlInS_2$/*n*-InP PSJs at room temperature

The results showed that both parameters of SBDs differ from one device to another even if they are identically prepared. Therefore, the first and common practice comes to mind to average these values. However, it is highly important to understand both the physical origin of such differences in the conventional parameters of SBDs and of non-ideal behavior in *I-V* characteristics for improving future device applications. Tung's inhomogeneity model proposes that this non-ideal behavior could be explained quantitatively by considering the specific distribution of nanometer-scale interfacial patches of reduced BH (Tung, 1992). The inhomogeneity model is based on small local regions or patches on the lateral contact area. Non-uniformity of the interfacial charges, interfacial oxide layer thickness, grain boundaries, multiple phases, facets, defects mixing phases, etc. causes this inhomogeneity offered by a vast of researchers (Im et al., 2001; Kampen & Mönch, 1995; Leroy et al., 2005; Mönch, 1999; Mönch, 2001; Schmitsdorf et al., 1998; Sze, 1981; Sullivan et al., 1998; Tung, 1992).

The ideality factor (*n*) of a MS device represents a direct measure of the interface uniformity. In general, the values of *n* greater than unity sign to the presence of a lateral inhomogeneous distribution of BHs at the MS interface. To date, the existence of a linear correlation between the effective BH and the ideality factor *n* in different diode sets prepared on various semiconductor substrates has been reported in many studies (Im et al., 2001; Mönch, 1999; Mönch, 2001; Schmitsdorf et al., 1998).

In Fig. 3, effective BHs versus ideality factory values ($\varphi_{eff.}$ vs n plot) are given. As can be seen from this figure, the BHs become smaller mutually as the ideality factors increase and there is a linear relationship between the experimental effective BHs and the experimental ideality factors for the Au/*p*-$TlInS_2$/*n*-InP PSJs that have been explained by lateral inhomogeneities of the BHs (Im et al., 2001; Kampen & Mönch, 1995; Leroy et al., 2005; Mönch, 1999; Mönch, 2001; Schmitsdorf et al., 1998; Sullivan et al., 1998; Sze, 1981; Tung, 1992).

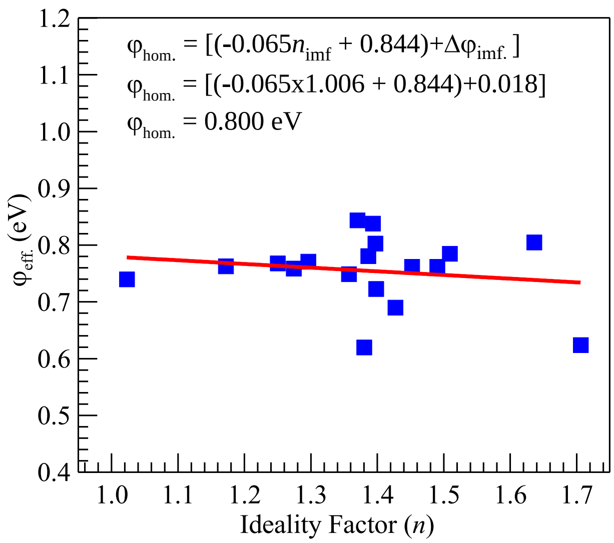

Figure 3. Effective BHs versus ideality factors ($\varphi_{\text{eff.}}$ vs n) of the identically prepared eighteen Au/*p*-$TlInS_2$/*n*-InP PSJs

It has been mentioned in the related studies that (Im et al., 2001; Kampen & Mönch, 1995; Leroy et al., 2005; Mönch, 1999; Mönch, 2001; Schmitsdorf et al., 1998; Sullivan et al., 1998; Sze, 1981; Tung, 1992) the higher values of *n* among identically prepared diodes were often found to accompany lower BHs. The straight line in Fig. 3 is least square fitting curve to the experimental data. Therefore, it can be concluded that our Au/*p*-$TlInS_2$/*n*-InP PSJ are patchy (Im et al., 2001; Mönch, 1999; Mönch, 2001; Schmitsdorf et al., 1998). The lateral homogeneous BH ($\varphi_{\text{hom.}}$) value of 0.800 eV for the Au/*p*-$TlInS_2$/*n*-InP junctions has been obtained from the $\varphi_{\text{eff.}} - n$ plot by using $n_{\text{imf.}} = 1.006$ and $\Delta\varphi_{imf.} = 18.0$ meV.

The capacitance-voltage (*C-V*) characteristics of the Au/*p*-$TlInS_2$/*n*-InP PSJ under 1.00 MHz operation frequency were also performed to get detailed information about the junction parameters. Capacitance BH φ_{CV} for a Schottky-type junction with the interfacial layer can be defined as the following relation (Donald, 1982; Rhoderick & Williams, 1988; Singh, 2001; Sze, 1981; Van der Ziel, 1968):

$$\varphi_{\text{CV}} = \gamma V_{\text{bi}} + V_{\text{n}} + kT/q\,. \quad (6)$$

where, γ is the reciprocal of the ideality factor *n* which gives rise to voltage drop across an interfacial layer (Abay, 2015; Chand & Bala, 2007; Chattopadhyay & Daw, 1986). If γ is equal to unity, in that case, the device shows an ideal behavior. V_{n} is the energy difference between the Fermi level and the bottom of the conduction band. The φ_{CV} values have been obtained using the intercept voltage values (V_{bi}) determined from the reverse bias C^{-2}-*V* curves (not shown in here) and the values of γ (=1/*n*) for each Au/*p*-$TlInS_2$/*n*-InP PSJ via Eq. (6). Details for calculating procedure for the φ_{CV} values have been given by Abay (2015).

Figs. 4 and 5 show the statistical distribution of BHs evaluated from forward bias *I-V* and reverse bias *C-V* characteristics of the Au/*p*-$TlInS_2$/*n*-InP PSJs (18 dots), respectively. The experimental values of the effective BHs were fitted by a Gaussian function. Mean BH values were obtained as $\bar{\varphi}_{\text{I-V}} = (0.755 \pm 0.059)$ eV and $\bar{\varphi}_{\text{C-V}} = (0.803 \pm 0.078)$ eV, respectively from the statistical analysis.

In Figs. 6 and 7, the statistical distribution of ideality factors and serial resistance values evaluated from the forward bias *I-V* characteristics of the Au/*p*-$TlInS_2$/*n*-InP PSJ were given, respectively. The experimental values of the *n* and R_s were fitted by a Gaussian function too. From the statistical analysis of this fit the values of the mean ideality factor and serial resistance were obtained as *n* = (1.384 ± 0.152) and $R_{\text{s}} = (88.4 \pm 28.0)\ \Omega$, respectively.

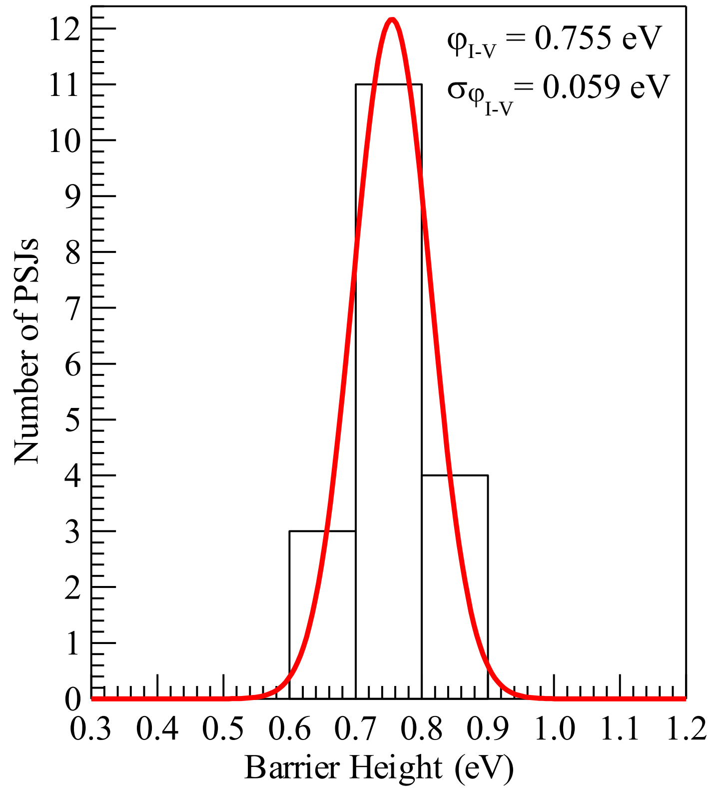

Figure 4. Gaussian distribution of effective BHs for the Au/*p*-$TlInS_2$/*n*-InP PSJs evaluated from forward bias *I-V* characteristics

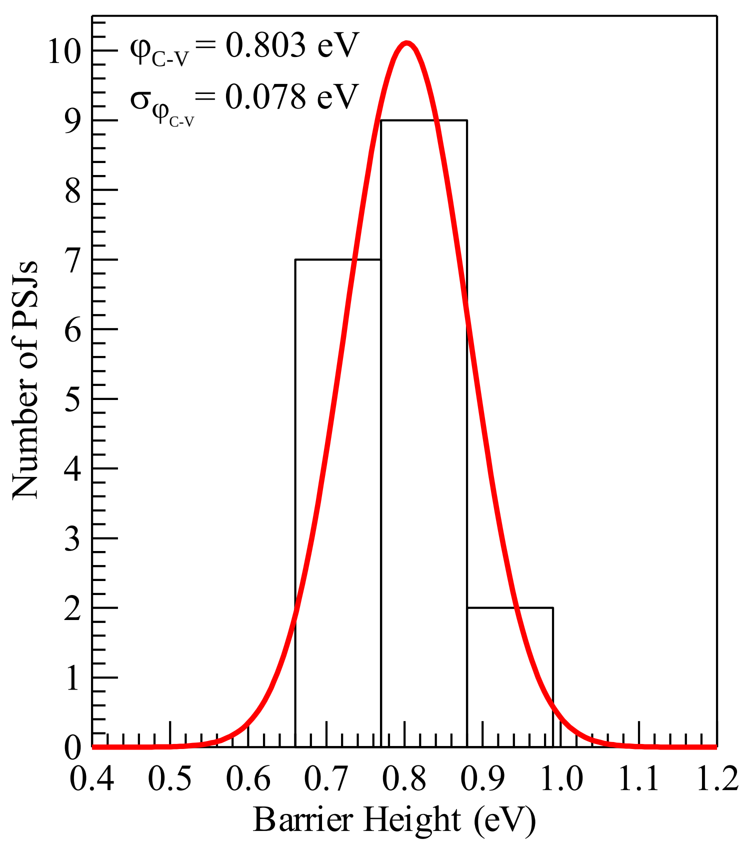

Figure 5. Gaussian distribution of BH for the Au/*p*-$TlInS_2$/*n*-InP PSJs evaluated from reverse bias *C-V* characteristics.

It has been seen that the mean BH obtained from the *C-V* measurements is correlated well with the value of φ_{hom}. . The good agreement of these parameters indicates that the BH inhomogeneity of the Au/*p*-$TlInS_2$/*n*-InP pseudo junction can be well described by spatial distributions of BH, that is, electron transport at the MS interface is significantly affected by nanoscale spatial variations.

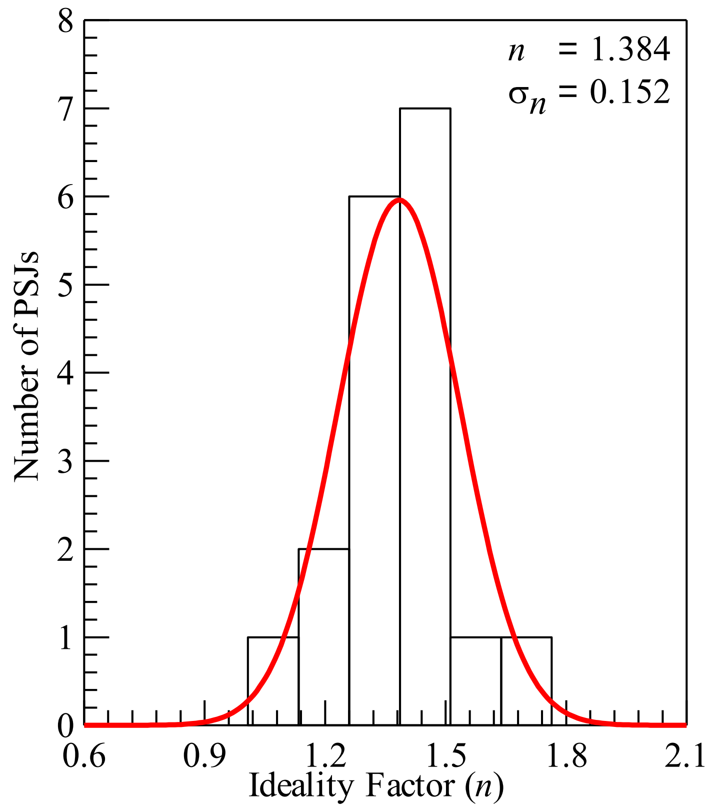

Figure 6. Gaussian distribution of the ideality factors for the Au/p-$TlInS_2$/n-InP PSJs evaluated from forward bias *I-V* characteristics

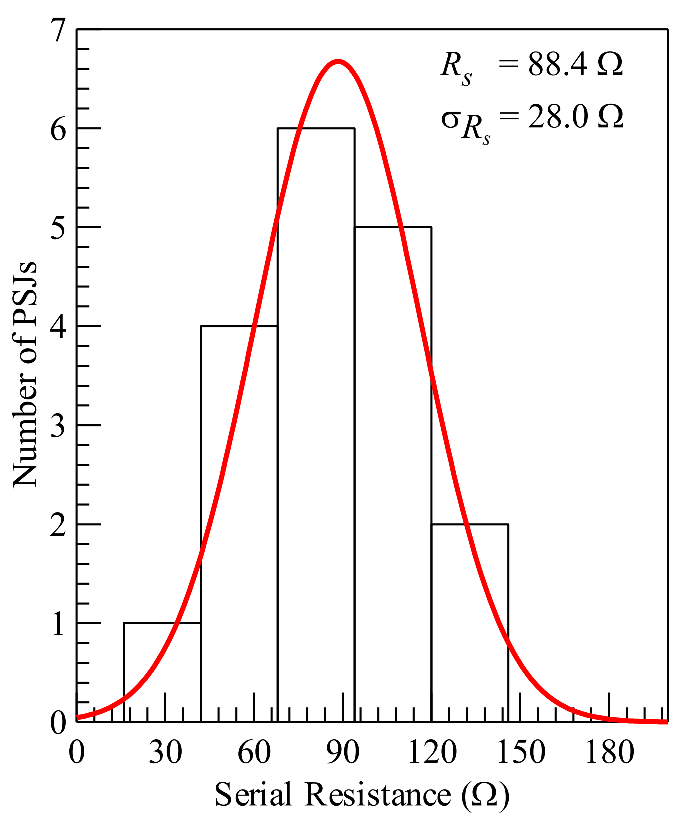

Figure 7. Gaussian distribution of the serial resistance for the Au/p-$TlInS_2$/n-InP PSJs evaluated from Cheung's functions

Conclusion

- Au/*p*-$TlInS_2$/*n*-InP PSJs have been fabricated by introducing a thin chalcogenide ternary compound counter layer of *p*-$TlInS_2$ on the MD *n*-InP substrate, for the first time.
- Room temperature electrical characterizations of the Au/*p*-$TlInS_2$/*n*-InP PSJs have been investigated by *I-V* and *C-V* measurements at and in the dark.
- Fabricated Au/*p*-$TlInS_2$/*n*-InP PSJs have good rectifying properties. The leakage current value of Au/*p*-$TlInS_2$/*n*-InP PSJ was reduced by four orders compared to the unmodified Au/*n*-InP structure, effectively giving an increased BH, accompanied by a little departure of the ideality factor (*n*=1.066) from unity. The increase in the BH was about 260 meV.
- Statistical investigations, by using Tung's model, showed that all parameters of PSJs differ from one junction to another even if they are identically prepared. The experimental values of BH, ideality factor, and serial resistance are fitted by a Gaussian function, and their mean values were found to be $\bar{\varphi}_{I-V} = (0.755 \pm 0.059)$ eV, $\bar{\varphi}_{C-V} = (0.803 \pm 0.078)$ eV, $n = (1.384 \pm 0.152)$ and $R_s = (88.4 \pm 28.0)\ \Omega$, respectively. A lateral homogeneous BH ($\varphi_{hom.}$) value of 0.800 eV for the Au/*p*-$TlInS_2$/*n*-InP junctions has been obtained from the $\varphi_{eff.}$ vs. n plot by using $n_{imf.} = 1.006$ and $\Delta\varphi_{imf.} = 18.0$ meV.

From the good agreement with the values of $\varphi_{hom.}$ and $\bar{\varphi}_{C-V}$ it has been concluded that BH inhomogeneity of Au/*p*-$TlInS_2$/*n*-InP junction can be well described by spatial distributions of BH considering based on the TE mechanisms.

Hakem Değerlendirmesi: *Dış bağımsız.*
Yazar Katkıları: *Fikir-BA; Tasarım-BA; Denetleme-BA; Kaynaklar-SY,FA,ANB,NK,DA; Veri Toplanması ve/veya İşlemesi-SY,FA,ANB,NK,DA; Analiz ve/veya Yorum-BA,SY,FA,,ANB,NK,DA; Literatür Taraması-BA,SY,FA,ANB,NK,DA; Yazıyı Yazan-BA,SY; Eleştirel İnceleme-BA,SY,FA,ANB,NK,DA; Diğer-BA*
Çıkar Çatışması: *Yazarlar, çıkar çatışması olmadığını beyan etmiştir.*
Finansal Destek: *Yazarlar, bu çalışma için finansal destek almadığını beyan etmiştir.*

Peer-review*: Externally peer-reviewed.*
Author Contributions: *Concept -BA; Design-BA; Supervision-BA; Resources--SY,FA,ANB,NK,DA; Data Collection and/or Processing- SY,FA,ANB,NK,DA; Analysis and/or Interpretation- BA,SY,FA,ANB,NK,DA; Literature Search-BA,SY,FA,ANB,NK,DA; Writing Manuscript-BA,SY; Critical Review-BA,SY,FA,ANB,NK,DA; Other-BA*
Conflict of Interest: *The authors have no conflicts of interest to declare.*
Financial Disclosure: *The authors declared that this study has received no financial support.*

References

Abay, B. (2015). Barrier characteristics of biopolymer-based organic/inorganic Au/CTS/n-InP hybrid junctions. *The Philosophical Magazine a Journal of Theoretical Experimental and Applied Physics*, *95*(31), 3413–3428. https://doi.org/10.1080/14786435.2015.1076583

Abay, B., Ankaya, G., Der, H. S. G., Efeoglu, H., & U, Y. K. Y. (2002). Barrier characteristics of Cd/p-GaTe Schottky diodes based onI V Tmeasurements. *Semiconductor Science and Technology*, *18*(2), 75–81. https://doi.org/10.1088/0268-1242/18/2/302

Abay, B., Efeoglu, H., Yogurtçu, Y. K., & Alieva, M. (2001b). Low-temperature visible photoluminescence spectra of Tl2GaInSe4layered crystals. *Semiconductor Science and Technology*, *16*(9), 745–749. https://doi.org/10.1088/0268-1242/16/9/302

Abay, B., Güder, H., Efeoğlu, H., & Yoğurtçu, Y. (2001a). Temperature dependence of the optical energy gap and Urbach–Martienssen's tail in the absorption spectra of the layered semiconductor Tl2GaInSe4. *Journal of Physics and Chemistry of Solids*, *62*(4), 747–752. https://doi.org/10.1016/s0022-3697(00)00236-5

Abay, B., Güder, H. S., Efeoglu, H., & Yogurtçu, Y. K. (2000b). Excitonic absorption and Urbach-Martienssen tails in Gd-doped and undoped p-type GaSe. *Semiconductor Science and Technology*, *15*(6), 535–541. https://doi.org/10.1088/0268-1242/15/6/308

Abay, B., Güder, H., Efeoğlu, H., & Yoğurtçu, Y. (2001c). Urbach-Martienssen Tails in the Absorption Spectra of Layered Ternary Semiconductor TlGaS2. *Physica Status Solidi. B, Basic Research*, *227*(2), 469–476. https://doi.org/10.1002/1521-3951(200110)227:2

Abay, B., Onganer, Y., Sağlam, M., Efeoğlu, H., Türüt, A., & Yoğurtçu, Y. (2000a). Current–voltage and capacitance–voltage characteristics of metallic polymer/InSe(:Er) Schottky contacts. *Microelectronic Engineering*, *51–52*, 689–693. https://doi.org/10.1016/s0167-9317(99)00532-8

Abay, A. (1994), Growth and investigation for some optical and electrical properties of $TlInSe_2$ and $TlGaSe_2$ ternary layered semiconductor crystals as a function of temperature, PhD Thesis (in Turkish), Atatürk University Graduate School of Natural & Applied Science Erzurum, Turkey (unpublished).

Brillson, L. J., Brucker, C. F., Katnani, A. D., Stoffel, N. G., Daniels, R., & Margaritondo, G. (1982). Fermi-level pinning and chemical structure of InP–metal interfaces. *Journal of Vacuum Science & Technology/Journal of Vacuum Science and Technology*, *21*(2), 564–569. https://doi.org/10.1116/1.571764

Campbell, I. H., Rubin, S., Zawodzinski, T. A., Kress, J. D., Martin, R. L., Smith, D. L., Barashkov, N. N., & Ferraris, J. P. (1996). Controlling Schottky energy barriers in organic electronic devices using self-assembled monolayers. *Physical Review. B, Condensed Matter*, *54*(20), R14321–R14324. https://doi.org/10.1103/physrevb.54.r14321

Chand, S., & Bala, S. (2007). Simulation studies of current transport in metal–insulator–semiconductor Schottky barrier diodes. *Physica. B, Condensed Matter*, *390*(1–2), 179–184. https://doi.org/10.1016/j.physb.2006.08.011

Chattopadhyay, P., & Daw, A. (1986). On the current transport mechanism in a metal—insulator—semiconductor (MIS) diode. *Solid-state Electronics*, *29*(5), 555–560. https://doi.org/10.1016/0038-1101(86)90078-x

Chou, L. J., Hsieh, K. C., Wohlert, D. E., Cheng, K. Y., & Finnegan, N. (1998). Formation of amorphous aluminum oxide and gallium oxide on InP substrates by water vapor oxidation. *Journal of Applied Physics*, *84*(12), 6932–6934. https://doi.org/10.1063/1.368993

Clausen, T., & Leistiko, O. (1993). High effective Schottky barriers on n-type InP using Zn-based metallizations and rapid thermal annealing. *Semiconductor Science and Technology*, *8*(9), 1731–1740. https://doi.org/10.1088/0268-1242/8/9/011

Çakar, M., Türüt, A., & Onganer, Y. (2002). The Conductance- and Capacitance-Frequency Characteristics of the Rectifying Junctions Formed by Sublimation of Organic Pyronine-B on p-Type Silicon. *Journal of Solid State Chemistry*, *168*(1), 169–174. https://doi.org/10.1006/jssc.2002.9706

Çankaya, G., & Abay, B. (2005). Current- and capacitance-voltage characteristics of Cd/p-GaTe Schottky barrier diodes under hydrostatic pressure. *Semiconductor Science and Technology*, *21*(2), 124–130. https://doi.org/10.1088/0268-1242/21/2/004

Donald, A.N. (1982). Semiconductor Physics and Devices, (Boston, Irwin).

Gasanly, N. M. (2010). Coexistence of Indirect and Direct Optical Transitions, Refractive, Index and Oscillator Parameters in TlGaS2 , TlGaSe2 , and TlInS2 Layered Single Crystals. *Journal of the Korean Physical Society*, *57*(1), 164–168. https://doi.org/10.3938/jkps.57.164

Güder, H., Abay, B., Efeoğlu, H., & Yoğurtçu, Y. (2001). Photoluminescence characterization of GaTe single crystals. *Journal of Luminescence*, *93*(3), 243–248. https://doi.org/10.1016/s0022-2313(01)00192-2

Gupta, R. K., & Singh, R. A. (2005). Junction properties of Schottky diode based on composite organic semiconductors: Polyaniline-polystyrene system. *Journal of Polymer Research*, *11*(4), 269–273. https://doi.org/10.1007/s10965-005-2412-2

Hökelek, E., & Robinson, G. (1981). A comparison of Pd Schottky contacts on InP, GaAs and Si. *Solid-state Electronics*, *24*(2), 99–103. https://doi.org/10.1016/0038-1101(81)90001-0

Hudait, M., & Krupanidhi, S. (2001b). Doping dependence of the barrier height and ideality factor of Au/n-GaAs Schottky diodes at low temperatures. *Physica. B, Condensed Matter*, *307*(1-4), 125–137. https://doi.org/10.1016/s0921- 4526(01)00631-7

Hudait, M., Venkateswarlu, P., & Krupanidhi, S. (2001a). Electrical transport characteristics of Au/n-GaAs Schottky diodes on n-Ge at low temperatures. *Solid-state Electronics*, *45*(1), 133–141. https://doi.org/10.1016/s0038-1101(00)00230-6

Im, H. J., Ding, Y., Pelz, J. P., & Choyke, W. J. (2001). Nanometer-scale test of the Tung model of Schottky-barrier height inhomogeneity. *Physical Review. B, Condensed Matter*, *64*(7). https://doi.org/10.1103/physrevb.64.075310

Ismail, A., Brahim, A. B., Dumas, M., & Lassabatere, L. (1987). The interaction of Ag and Al overlayers with InP (110): Surface and diode studies of the effect of Sb interlayers. *Journal of Vacuum Science & Technology. B, Microelectronics*

Processing and Phenomena, *5*(3), 621–623. https://doi.org/10.1116/1.583793

Kampen, T., & Mönch, W. (1995). Lead contacts on Si(111):H-1 × 1 surfaces. *Surface Science*, *331–333*, 490–495. https://doi.org/10.1016/0039-6028(95)00079-8

Kaya, M., Çetin, H., Boyarbay, B., Gök, A., & Ayyildiz, E. (2007). Temperature dependence of the current–voltage characteristics of Sn/PANI/p-Si/Al heterojunctions. *Journal of Physics. Condensed Matter*, *19*(40), 406205. https://doi.org/10.1088/0953-8984/19/40/406205

Lang, O., Schlaf, R., Tomm, Y., Pettenkofer, C., & Jaegermann, W. (1994). Single crystalline GaSe/WSe2 heterointerfaces grown by van der Waals epitaxy. I. Growth conditions. *Journal of Applied Physics*, *75*(12), 7805–7813. https://doi.org/10.1063/1.356562

Lee, P. A. (1976). *Optical and Electrical Properties*.

Leroy, W., Opsomer, K., Forment, S., & Van Meirhaeghe, R. (2005). The barrier height inhomogeneity in identically prepared Au/n-GaAs Schottky barrier diodes. *Solid-state Electronics*, *49*(6), 878–883. https://doi.org/10.1016/j.sse.2005.03.005

Lieth, R. M. A. (2014). *Preparation and Crystal Growth of Materials with Layered Structures*.

Maeda, F., Watanabe, Y., & Oshima, M. (1993). Surface chemical bonding of (NH4)2Sx-treated InP(001). *Applied Physics Letters*, *62*(3), 297–299. https://doi.org/10.1063/1.108996

McCafferty, P., Sellai, A., Dawson, P., & Elabd, H. (1996). Barrier characteristics of Schottky diodes as determined from I-V-T measurements. *Solid-state Electronics*, *39*(4), 583–592. https://doi.org/10.1016/0038-1101(95)00162-x

Mönch, W. (1999). Barrier heights of real Schottky contacts explained by metal-induced gap states and lateral inhomogeneities. *Journal of Vacuum Science & Technology. B, Microelectronics and Nanometer Structures*, *17*(4), 1867–1876. https://doi.org/10.1116/1.590839

Mönch, W. (2001). Semiconductor Surfaces and Interfaces. In *Springer series in surface sciences*. https://doi.org/10.1007/978-3-662-04459-9

Osvald, J., & Horváth, Z. (2004). Theoretical study of the temperature dependence of electrical characteristics of Schottky diodes with an inverse near-surface layer. *Applied Surface Science*, *234*(1–4), 349–354. https://doi.org/10.1016/j.apsusc.2004.05.046

Rhoderick, E. H., & Williams, R. H. (1988). *Metal-semiconductor Contacts*. Oxford University Press, USA.

Schmitsdorf, R. F., Kampen, T. U., & Mönch, W. (1997). 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*, *15*(4), 1221–1226. https://doi.org/10.1116/1.589442

Schvartzman, M., Sidorov, V., Ritter, D., & Paz, Y. (2001). Surface passivation of (100) InP by organic thiols and polyimide as characterized by steady-state photoluminescence. *Semiconductor Science and Technology*, *16*(10), L68–L71. https://doi.org/10.1088/0268-1242/16/10/103

Shi, Z. Q., Wallace, R. L., & Anderson, W. A. (1991). High-barrier height Schottky diodes on N-InP by deposition on cooled substrates. *Applied Physics Letters*, *59*(4), 446–448. https://doi.org/10.1063/1.105458

Singh, J. (2000). *Semiconductor Devices*. John Wiley & Sons.

Soylu, M., & Abay, B. (2009). Barrier characteristics of gold Schottky contacts on moderately doped n-InP based on temperature dependent I–V and C–V measurements. *Microelectronic Engineering*, *86*(1), 88–95. https://doi.org/10.1016/j.mee.2008.09.045

Soylu, M., Abay, B., & Onganer, Y. (2011). Electrical characteristics of Au/Pyronine-B/moderately doped n-type InP Schottky structures in a wide temperature range. *Journal of Alloys and Compounds*, *509*(16), 5105–5111. https://doi.org/10.1016/j.jallcom.2011.01.183

Sugino, T., Ito, H., & Shirafuji, J. (1990). Barrier height enhancement of InP Schottky junctions by treatment with photo-decomposed PH3. *Electronics Letters*, *26*(21), 1750. https://doi.org/10.1049/el:19901124

Sugino, T., Sakamoto, Y., Sumiguchi, T., Nomoto, K. N. K., & Shirafuji, J. S. J. (1993). Barrier Heights of Schottky Junctions on n-InP Treated with Phosphine Plasma. *Japanese Journal of Applied Physics*, *32*(9A), L1196. https://doi.org/10.1143/jjap.32.l1196

Sullivan, J. P., Tung, R. T., Pinto, M. R., & Graham, W. R. (1991). Electron transport of inhomogeneous Schottky barriers: A numerical study. *Journal of Applied Physics*, *70*(12), 7403–7424. https://doi.org/10.1063/1.349737

Sze, S. M. (1981). *Physics of Semiconductor Devices*. Wiley-Interscience.

Tung, R. T. (1992). Electron transport at metal-semiconductor interfaces: General theory. *Physical Review. B, Condensed*

Matter, *45*(23), 13509–13523. https://doi.org/10.1103/physrevb.45.13509
Van Der Ziel, A. (1968). *Solid State Physical Electronics*. Prentice Hall.