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# Analysis of Hopping Conduction and Space Charge Limited Currents in Nearly Ideal Metal/Semiconductor Contacts

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**ABSTRACT**

We have formed a nearly ideal Au/n-Si Schottky contact and deposited gold (Au) metal on n-Si (100) using thermally evaporation method for an explanation of space charge limited current (SCLC) from current-voltage (*I-V*) characteristic, interface trap density from capacitance-conductance-voltage (*C-G-V*) characteristics and hopping conduction from conductance-frequency (*G-f*) characteristic in nearly ideal metal/semiconductor contacts. The device showed good intimate rectifying behavior. To observe the SCLC mechanism and determine interface trap density of the sample, the log (*I*)−log (*V*) and *C-G-V* characteristics are plotted. The interface trap density values for low frequency (5 kHz) and high frequency (1 MHz) are determined as 4.98 x $10^{14}$ $eV^{-1}$ $cm^{-3}$ and 7.81 x $10^{12}$ $eV^{-1}$ $cm^{-3}$, respectively. At the same time the main diode parameters such as ideality factor and barrier height are determined as 1.048 and 0.807 eV, respectively. These diode parameters refer a nearly ideal metal-semiconductor contact.

*Keywords:* Metal-semiconductor contact, I-V, C-V, space charge limited current, hopping conduction, interface trap density, ideality factor, Schottky barrier height.

## 1. INTRODUCTION

Up to now metal-semiconductor (MS) (or Schottky) contacts have attracted a great deal of attention in the field of electronic and optoelectronic engineering [1-8]. The most important electronic properties of a Schottky contact are characterized by its ideality factor and barrier height parameters. The basic methods consist of four main categories, namely photoelectric, activation energy, capacitance–voltage (*C–V*) and current–voltage (*I–V*) measurements. The C–V method, for example, is carried out using a high frequency excitation signal and mostly in reverse-bias, where it is expected that the diode will not show a low-voltage resonance peak. It is believed that the peak is caused by interfacial charges. It is also believed that the peak is caused by interfacial charges that track the alternating current signal and generally contribute to measured capacitance at frequencies lower than 1 MHz [9-16].

Many investigators have attempted to determine the these parameters of MS contacts according to *I-V* mesurement. Uğurel et al. [6] reported Au/n-Si contact and they determined the values of $\phi_{B0}$ and *n* as 0.73eV and 1.44 for the sample at room temperature (300 K). Keffous et al. [17] have reported the characteristics of Au/n-Si and Ag/n-Si Schottky contact. They determined that the ideality factor (*n*) and barrier height ($\phi_{B0}$) values are 1.094 and 0.858 eV for Au/n-Si, respectively. The current-voltage (*I-V*) characteristics of the Au/n-Si Schottky diodes have also been studied by Evans-Freeman et al. [18] and Lin et al. [19]. They found that

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the values of $n$ and $\phi_{B0}$ are about 2.50-0.70 eV and 1.22-0.78 eV, respectively. Aydemir et al. [20] have deposited gold (Au) metal on n-type (phosphor doped) float zone (FZ) (100) single crystal Si wafer. The current–voltage (*I–V*) characteristics of Au/n-Si contact have been investigated at room temperature (300 K) and they found the values of $n$ and $\phi_{B0}$ as 1.65 and 0.62 eV, respectively.

Since Schottky contacts have the technological significance, a full determining of the nature of conduction mechanism of the contacts is of great importance. There are different methods such as space charge limited current (SCLC) and hopping effect to explain the charge transport mechanism in MS contacts [3,18-21-23].

Our aim in this work is to investigate the mechanism of the charge transport and localized states in intimate metal/semiconductor contact. For this purpose we have fabricated a intimate Au/n-Si Schottky contact. The current-voltage (*I-V*) and capacitance-conductance-voltage (C-G-V) and conductance-frequency characteristics (*G-f*) of the contact is measured and the properties of conduction mechanism are determined.

## 2. EXPERIMENTAL PROCEDURES

In this study, it is used a n-Si (100) substrate grown by CZ technique with P-doped, resistivity of 1–20 Ωcm and thickness of 380 µm. Before ohmic and rectifying contacts, the substrate is cleaned by the RCA method [24]. The ohmic and rectifying contacts are formed by evaporating aluminium (Al) and gold (Au) metals through a Edwards E306A vacuum thermal evaporation system at 1x $10^{-6}$ Torr respectively. The thickness of Al and Au metal are determined as 150 nm and 200 nm using a Edwards FTM6 quartz-crystal thickness monitor, respectively. The contact area of the Schottky diode was selected to be 21.38 x $10^{-3}$ $cm^2$. The variation with voltage of current and voltage and frequency of capacitance-conductance in Au/n-Si(100)/Al Schottky contact is determined by a Keithley 2410 SourceMeter and HP 4192A LF Impedance Analyzer at 300 K, respectively.

## 3. RESULTS and DISCUSSION

Fig.1(a) illustrates typical room-temperature forward and reverse-bias current–voltage *(I–V)* characteristic of Au/n-Si (100) Schottky contact. As demonstrated in the Fig. 1(a), this contact clearly display the perfect rectification behavior. Fig. 1(b) is plotted log $I$ vs. the voltage axis of the sample to better examine the rectifier contact. A rectification ratio (RR) of the contact is calculated according to $RR = \left(I_{forward} / I_{reverse}\right)_{V=\cos\tan t}$ [25] at a certain applied voltage and plotted against to the applied voltage at 300 K as illustrated in Fig. 2. As seen in Fig. 2, it sharply increases with increase in bias voltage up to 0.5 V and slightly reaches the saturation up to 2 V. The rectification ratio of the sample is calculated as 1.56 x$10^5$ at 2V. Figs. 3(a) and (b) illustrate the forward-reverse bias semi-logarithmic $I–V$ characteristics and the logarithmic plot of $I/[1-\exp(-qV/kT)]$ vs. $V$ of the Au/n-Si (100) Schottky structure at 300 K, respectively. As can be illustrated from the figures, the Schottky contact has perfect rectifying contact behavior.

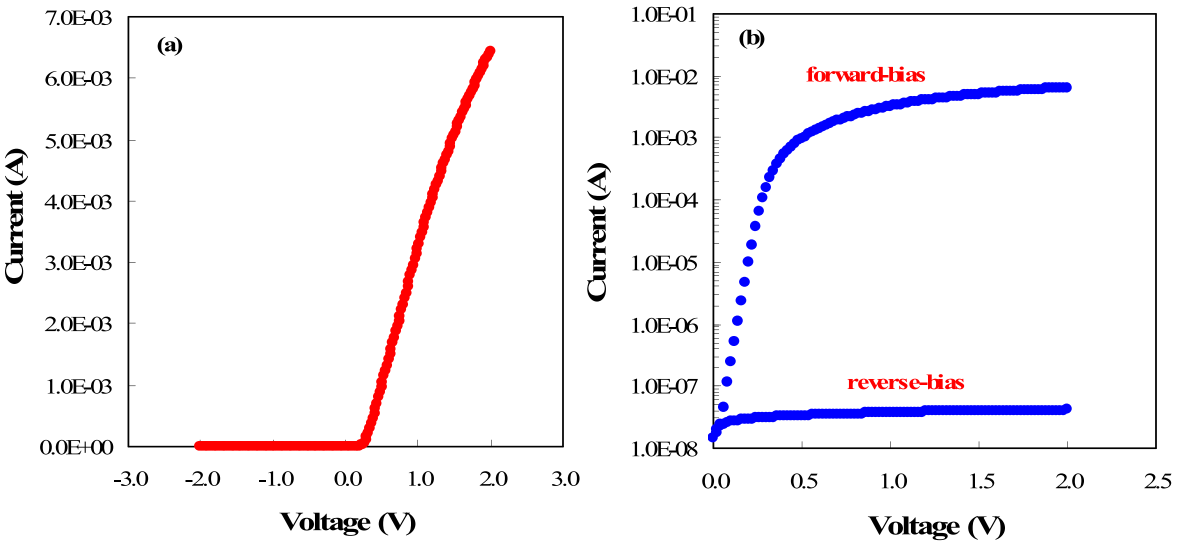


Figure 1. The forward and reverse bias (a) current–voltage (*I-V*) characteristics and (b) $\ln I - V$ characteristics at positive voltage for the Au/n-Si (100) Schottky contact.

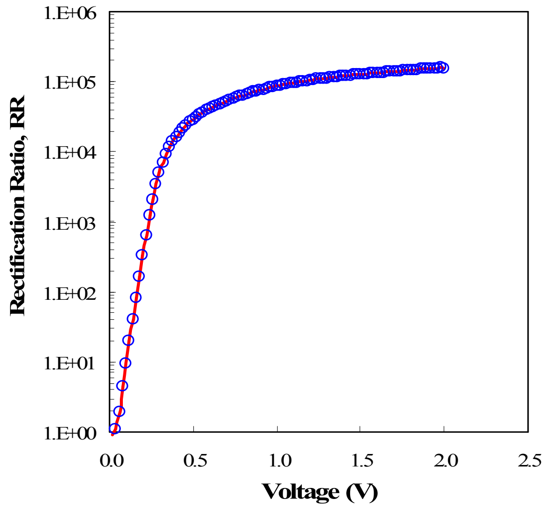


Figure 2. Curve of rectification ratio (RR) vs. voltage ($V$) of the intimate Au/n-Si (100) Schottky contact.

According to thermionic emission theory, the *I-V* characteristics of the Schottky contact can be analyzed by the following relations [1-7]

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

$$I_0 = AA^* T^2 \exp\left(-\frac{q\phi_{B0}}{kT}\right) \quad (1)$$

where $A$ is the Schottky contact area, $\phi_{B0}$ is the Schottky effective barrier height, $n$ is the diode quality factor, $I_0$ is the saturation current, $q$ is the electronic charge, $A^*$ is the effective Richardson constant and $T$ is the absolute temperature in Kelvin. Fig. 3(b) gives a linear plot and $I_0$ is determined from the y-axis intercept at zero voltage. According to this $I_0$ value, the barrier height of the contact is calculated using the following equation (Eq. 2). At the same time, the ideality factor ($n$) and the barrier height at zero bias ($\phi_{B0}$) values can be determined from slope and intercept of the forward-bias curve of the Figs. 3(a) and (b), respectively, as [1,3,6-8]

$$n = \frac{q}{kT}\left(\frac{dV}{d\ln I}\right)$$

$$\text{and} \quad \phi_{B0} = \frac{kT}{q}\ln\left(\frac{AA^*T^2}{I_0}\right) \quad (2)$$

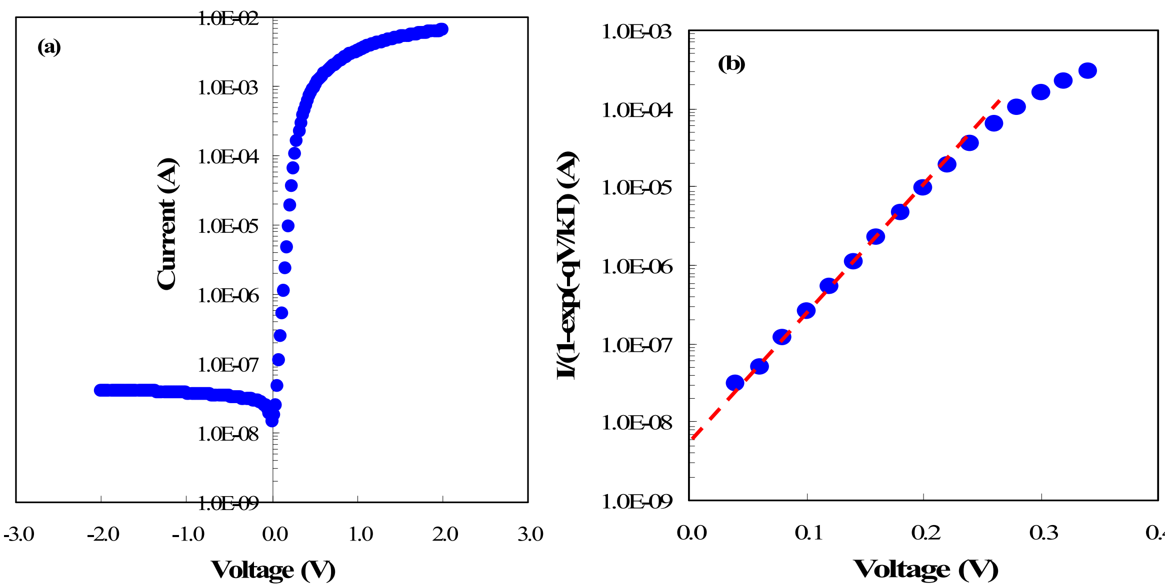


Figure 3 (a) The forward-reverse bias semi-logarithmic $I$–$V$ characteristics and (b) the logarithmic plot of $I/[1-\exp(-qV/kt)]$ vs. $V$ of the Au/n-Si (100) Schottky contact.

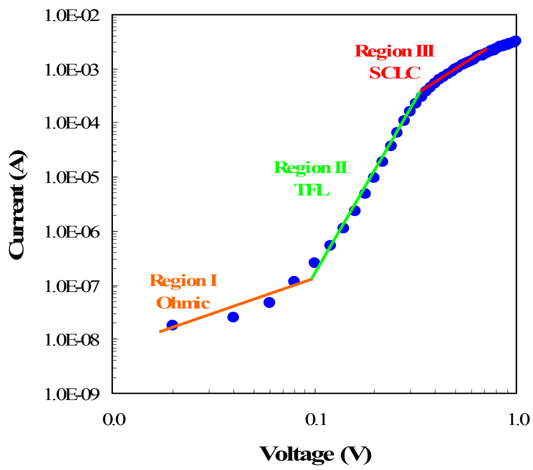


Figure 4. log $I$ –log $V$ curve of a intimate Au/n-Si (100) Schottky contact.

The ideality factor ( $n$ )and barrier height ( $\phi_{B0}$ ) values have been obtained as 1.048 and 0.807 eV using the Eq. 2 according to the data of Fig. 3, respectively. Low value of $n$ can be attributed to the intimate metal/semiconductor contact. The interfacial layer thickness ( $\delta$ ) value corresponding to the ideality factor of our Au/n-Si diode is 6.5 Å for $n = 1.04$ according to references 4 and 5. This result shows that the Au/n-Si contact is a intimate contact [1,2,5]. It has been seen that the value of the Schottky barrier height calculated for our diode is very close to the barrier height value of 0.8 eV for the conventional Au/n-Si diode [1]. Many attempts to obtain the $\phi_{B0}$ and $n$ of metal/semiconductor contact have been reported [1-8]. Kılıçoğlu and Asubay [5] determined a barrier height ( $\phi_{B0}$ ) value of 0.742 eV and a ideality factor ( $n$ ) value of 1.04 for gold/n-Si Schottky contact. Nuhoğlu ve Gülen [7] have reported 1.04 and 0.64 eV as the values of ideality factor and barrier height at 300 K for the Au/n-Si contact, respectively. Tataroğlu [8] found that the ideality factor and barrier height values of 4.43 and 0.51 eV for Au/n-Si Shottky contact. Kumar and Kanjilal [26] determined that the $n$ and $\phi_{B0}$ values are 1.1 and 0.82 eV, respectively. When metal makes contact with a semiconductor, a barrier is formed at the metal/semiconductor interface. This barrier is responsible for controlling the current conduction as well as its capacitance behavior. The formation of barrier height depends on the existence of interfacial layer (deposited or native), doping concentration of semiconductor, process of surface preparation, , the atomic inhomogenities at M/Si nterface caused by grain boundaries, multiple phases, facets, defects, mixture of different phases and the distribution of interface trap states [20,27]. The nature and origin of the decrease in the barrier height ( $\phi_{B0}$ ) and increase in ideality factor ($n$) of metal-semiconductor contacts reported in literature is due to the mentioned above causes. Furthermore, Schottky diodes with low barrier height ( $\phi_{B0}$ ) have found applications in devices operating at cryogenic temperatures as infrared detectors and sensors in thermal imaging [28]. In addition for many devices such as metal-semiconductor field effect transistors (MESFETs) and metal-semiconductor-metal (MSM) photodedectors, it is necessary to achieve a high Schottky barrier height [29].

We have illustrated log $I$ –log $V$ curve at 300 K in Fig. 4 to observe space charge limited currents for Au/n-Si (100) Schottky diode. It is seen that the plot shows three different regions: (Region I) in the voltage range of 0.0 – 0.08 V the slope is equal about to unity $\left(I \approx V^{1.26}\right)$ corresponding to the ohmic region, (Region II) in the voltage range of 0.1 – 0.32 V the slope is equal about to 6.11 $\left(I \approx V^{6.11}\right)$ corresponding to the trap-filled limit (TFL) law because the slope is greather than two [30], (Region III) in the voltage range of 0.34 – 1.02 V the slope is equal about to two $\left(I \approx V^{2.03}\right)$, representing the trap free space charge-limited current (SCLC) region. Lampert [31,32] reported that the $I$-$V$ dependence in the SCLC region, follows a relationship $I - V^m$, where $m$ is a power index. The $m$ values are calculated as 1.26, 6.11 and 2.03 for each region, respectively.

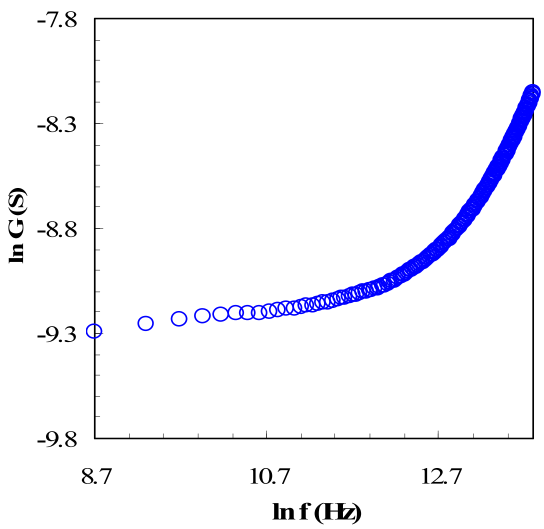


Figure 5. ln $G$–ln $f$ curve of the Au/n-Si (100) Schottky contact.

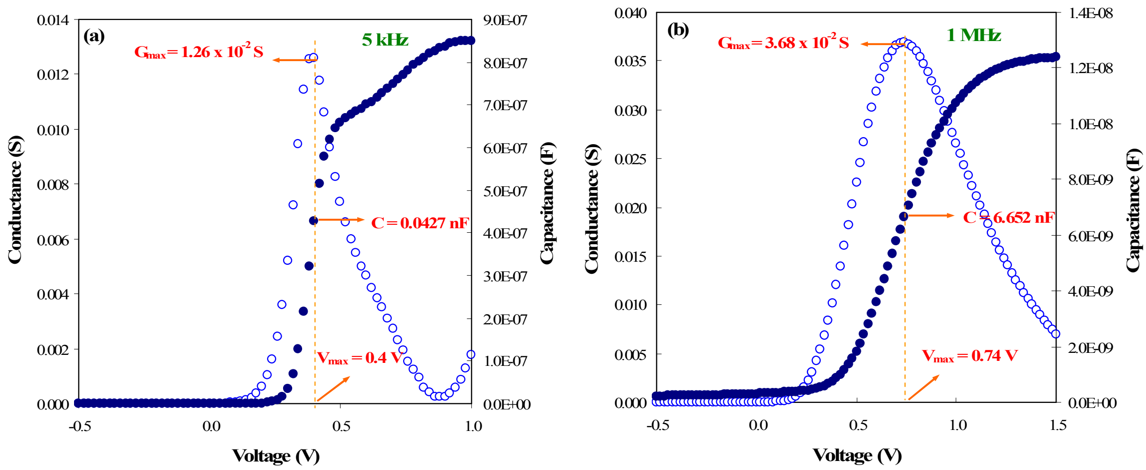


Figure 6. Plot of capacitance-conductance-voltage (*C-G-V*) for (a) 5 kHz and (b) 1 MHz of the Au/n-Si (100) Schottky contact.

The *G–f* curve in the idealized case is frequency independent [1,2,21,33-35]. However, this idealized case is frequently deviated due to the presence of interface states at the interfacial layer and semiconductor interface [33-35]. In Fig. 5, the ln*G* - ln*f* characteristic of Au/n-Si Schottky contact is plotted for zero voltage and at room temperature (300 K). Fig. 5 displays two regions, which are high- and low - frequency regions. the conductance is constant at lower frequencies between 1 x $10^3$ Hz and 1 x $10^5$ Hz, and is similar to direct current (DC), conductance whereas at higher frequencies between 1 x $10^5$ Hz and 1 x $10^6$ Hz, the conductance corresponds to alternating current (AC) conductance, in which the conductance rapidly increases with increasing frequency. It is known that the higher frequency region is characteristic of trapped carriers hopping between filled and empty states at the Fermi level [21]. The incorporated atoms in the thin interlayer at metal–semiconductor interface act as additional impurities in the disordered layer. Thus, hopping conductance mechanism through this layer takes place and can be expressed as [21]

$$G(f) \propto f^{s} \qquad (3)$$

where $s$ is a constant, which is a measure of number carriers that are free [21]. $s$ value is calculated from the slope of plot shown in Fig. 5. In order to obtain $s$ value, ln *G*–ln *f* data is fitted by a polynomial form,

$$\ln G(f) = a + b\ln f + c(\ln f)^{2} \qquad (4)$$

The slope at any *f* can be written as

$$s = \frac{d\ln G}{d\ln f} \qquad (5)$$

$s$ is found with the help of Eqs. (4) and (5) by the relation

$$s = b + 2c\ln f \qquad (6)$$

The $s$ value was calculated from plot of conductance–frequency shown in Fig. 5, and the conductance for the high frequency region after 1 x $10^5$ Hz can be given as

$$G(f) \propto f^{0.86} \qquad (7)$$

Such a value of the $s$ indicates that 86 % of traps are empty and a same behavior is also found Tuğluoğlu et al. [21] for In/p-Si Schottky contact.

For more information on the interface trap density ($N_{ss}$) of the nearly ideal Au/n-Si Schottky contact, Hill–Coleman method [36] was applied on the conductance-voltage (*G-V*) plot at low (5 kHz) and high frequency (1 MHz). To calculate the density of interface trap, this method is confirmed by some researchers [10-12,14,15]. In this purpose, in Figs. 6(a) and (b), we have plotted capacitance-conductance characteristics versus voltage at 5 kHz and 1 MHz, respectively. The $N_{ss}$ values of the sample at low (5 kHz) and high frequency (1 MHz) are determined by the relation [36]

$$N_{ss} = \frac{2(G_{max}/\omega)}{qS}\left[\left(1 - C/C_{il}\right)^{2} + \left(G_{max}/\omega C_{il}\right)^{2}\right]^{-1} \qquad (8)$$

where $S$ is the area of the diode, $q$ is the elementary electrical charge, $\omega\,(=2\pi f)$ is the angular frequency, $C_{il}$ is the interface layer capacitance, $G_{max}$ conforms to maximum *G–V* curve and $C$ is the capacitance of the diodes according to $G_{max}$.

As seen in Figs. 6(a) and (b), the conductance plots show a peak. The existence of conductance peak refers the presence of interface states. In the same time, the peak position changes to the lower positive voltages from 0.74 V (1 MHz) to 0.4 V (5 kHz) with decreasing frequency. The values of $C_{il}$, $G_{\max}$, and $C$ were found as 8.491 x $10^{-7}$ F, 0.0126 S, and 4.271 x $10^{-7}$ F for 5 kHz and 1.238 x $10^{-8}$ F, 0.0368 S, and 6.653 x $10^{-9}$ F for 1 MHz, respectively. According to these values, the calculated interface trap density ($N_{ss}$) values for the sample are 4.98 x $10^{14}$ and 7.81 x $10^{12}$ $eV^{-1}$ $cm^{-2}$ for 5 kHz and 1 MHz from Eq. (8), respectively. As seen, the $N_{ss}$ values of the sample decrease with increasing frequency. The charges at the interface traps cannot follow an ac signal at higher frequencies ( 1 MHz $\leq f$), In contrary to, the charges can readily contribute an ac signal at low frequencies and they are capable of these charges increase with decreasing frequency [9-16].

## 4. CONCLUSIONS

*I-V* characteristic of the nearly ideal Au/n-Si (100) Schottky contact has been studied at 300 K. The experimental values of ideality factor and barrier height of Au/n-Si Schottky diode have been determined as 1.048 and 0.807 eV, respectively. At low voltage region ohmic behavior and at high voltage region space charge limited current (SCLC) conduction have been observed. The presence of SCLC may be related to the quality of Au/n-Si (100) Schottky contact. The interface state density and current transport properties of the nearly ideal contact in capacitance-conductance-voltage (*C-G-V*) and conductance-frequency (*G-f*) characteristics are investigated. .The behavior of the nearly ideal Au/n-Si (100) Schottky contact demonstrated that it has a hopping model, namely, the conductance is constant at lower frequencies as the conductance increases obviously with increasing frequency. Furthermore, the density of interface traps for the contact was found to be 7.81 x $10^{12}$ $eV^{-1}$ $cm^{-2}$ at 1 MHz and 4.98 x $10^{14}$ $eV^{-1}$ $cm^{-2}$ at 5 kHz at room temperature (300 K). The value of the *s* of 0.86 determined from the ln $G$–ln$f$ plot (Fig. 11) suggests that 86 % of traps are empty and the conduction may be explained by the model of charge carriers hopping.

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## CONFLICT OF INTEREST

No conflict of interest was declared by the authors.

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