GOLDEN RESEARCH THOUGHTS

REVERSE-BIAS LEAKAGE CURRENT MECHANISMS IN METAL /GaN SCHOTTKY DIODES

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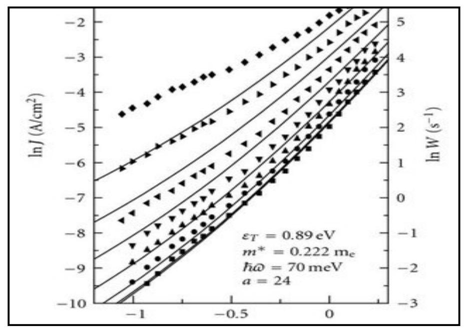
ABSTRACT

Temperature-dependent reverse-bias current-voltage characteristics obtained by other researchers for Schottky diodes fabricated on GaN are reinterpreted in terms of phonon-assisted tunnelling (PhAT) model. Temperature dependence of reverse-bias leakage current is shown could be caused by the temperature dependence of electron tunneling rate from traps in the metal-semiconductor interface to the conduction band of semiconductor. A good fit of experimental data with the theory is received in a wide temperature range (from 80 K to 500 K) using for calculation the effectivemass of 0.222 m_e and for the phonon energy the value of 70 meV. The temperature and bias voltages dependences of an apparent barrier height (activation energy) are also explicable in the framework of the PhAT model.



KEYWORDS: *leakage current, Reverse Bias, Temperature dependent, Diodes*

1. INTRODUCTION

GaN is a wide direct band gap semiconductor which has unique applications in the fabrication of blue light-emitting diodes, lasers, ultraviolet detectors, field effect transistors, and high power rectifiers [1, 2]. Metal-semiconductor contact is one of the most widely used rectifying contacts in the electronics industry. However, GaN - based Schottky contacts suffer from abnormal leakage currents under reverse bias, which is one factor presently limiting device performance.

Due to the technological importance of Schottky diodes, a full understanding of the nature of their electrical characteristics is of great interest. Recently a number of papers on reverse-bias leakage current mechanisms in M/GaNSchottky diodes appeared [3–16]. In papers [17–20], the investigation of Schottky contact on GaN nanowires were presented.

Suggestions of investigators about the reverse-bias leakage current mechanism are very different. For instance, Miller et al. [3] claimed that two dominant leakage current mechanisms in Ni/n-GaNSchottky diode (SD) fabricated onGaN grown by molecular-beam epitaxy can be identified. One associated with field-emission tunnelling and another with an exponential temperature dependence, consistent with either trap-assisted tunnelling or one-dimensionalhopping conduction. However, for the fitting of the experimentaldata with the tunnelling current model, the authors [3] have used unphysical low the effective mass (9.8 ×10−3m_e) and the value for the effective Richardson's constant $A*$(0.001 A/cm2 K2). Zhang et al. [4] analysed the leakage current mechanisms in the Schottky contacts ofboth n-GaN and AlGaN /GaN epitaxial layer structures at different temperatures and concluded that tunnelling current dominates at temperatures below 150 K whereas the Frenkel-Poole emission dominates at temperatures higher than 250 K. Huang et al. on the basis of current-voltage measurements between 27 and 350◦C in Au/Ni/GaN SDs concluded that thermionic-emission model with a Gaussian distribution of barrier heights is responsible for the electrical behaviour of the diodes at temperatures lower than 230◦C, while the generation-recombination process takes place at temperatures above 230◦C [7]. Arslan et al. [11] assumed that the reverse-bias leakage current mechanisms in SDs on Al0.83In0.17 N/AlN/GaN hetero structures, in the temperature range of 250–375 K is based on the Frenkel-Poole emission model. Moreover, Iucolano et al. [13] claimed that one dimensional variable-range hopping conduction was one of the dominant carrier transport mechanisms for the Ni /GaNSchottky sample annealed at 1150◦C for 5 minutes.

A such variety of proposed conduction mechanismsinvolved to describe the leakage current in M/GaN diodes implies that fundamental properties of the conduction mechanisms are not to date fully understood.

Another problem which emerges in examining thepractical diodes characteristics is observed dependence of the barrier height derived from *I-V/T* measurements on applied bias voltage and temperatures. In terms of a classical thermionic emission theory [21] the forward current density is given by

$$j = j_0\left[\exp\left(\frac{qV}{nkT}\right) - 1\right], \qquad (1)$$

Where

$$j_0 = A^* T^2 \exp\left(-\frac{q\Phi_{BO}}{kT}\right) \qquad (2)$$

$j_o$is the saturation current density, $A*$is the effective Richardsonconstant, Φ_{BO} is the Schottkybarrier height (**SBH**), k is the Boltzmann constant, q is the electronic charge unit,
and$n$ is the ideality factor which describes the deviation of practical diodes from the pure thermionic-emission model characterized by $n = 1$.

A so-called Richardson plot of ln($j0/A*T2$) versus inversetemperature $1/T$ is often used to determine the SBH from the slope of the thermally activated behaviour. According to (2)

$$\ln\left(\frac{j_0}{A^* T^2}\right) = -\frac{q\Phi_{BO}}{kT} \qquad (3)$$

and the plot ln($j0/A*T2$) versus $1/T$ (Richardson plot)should yield a straight line with an activation energy ET $=-q\Phi_{BO}$ if the SBH Φ_{BO} is temperature dependent. But in most cases these plots do not yield straight lines (see e.g., [15, 16]). The curving in these plots results in (determines) dependence of $E_T$on temperature.

In the case of reverse bias voltage when (qV/kT) _ 1 for the current density jr from (2) one obtains

$$j_r = A^* T^2 \exp\left(-\frac{q\Phi_{br}}{kT}\right). \qquad (4)$$

The apparent SBH Φ_{br} calculated from the gradient ofthe Richardson plot lines will be lower than ΦBO due to the lowering of the barrier height caused by image-force, but temperature dependence of both Φ_{BO} and Φ_{br}has the same shape [14].

Analysis of the *I-V/T* characteristics of Schottky diodeson the basis of thermionic emission theory reveals a decrease in the apparent barrier height ΦBO and an increase in the
ideality factor n with a decrease in temperature [5, 6, 12, 15, 16, 19]. The temperature dependence of the apparent barrier height is frequently explained by invoking a Gaussian
distribution of the SBH values at the interface between the Schottky metal and the semiconductor [15, 16, 19].

In previous work [22], we have shown that in Ni/n-GaNSD the leakage current dependence on temperature in a wide range of temperatures can be described in the framework of phonon-assisted tunnelling (PhAT) model. The purpose of this work is on the basis of thismodel to explain the peculiarities of the reverse-bias current dependence on bias voltage and their temperature behaviour in the M/GaNSchottky diodes presented by various authors in recent publications. Dependence of the apparent SBH on temperature discussed by many investigators is also explained in the framework of the PhAT model.

2. THEORY AND COMPARISON WITH EXPERIMENTAL DATA

2.1 The Phonon Assisted Tunnelling Model: In accordancewith phonon-assisted tunnelling model, the current transport through the barrier is governed by a process of tunnelling from states nearbymetal-semiconductor interface to the conduction band of the semiconductor. The electron population in the states is assumed to be independent of bias voltage due to the continuous filling of interface states from the metallic electrode (see Figure 1). If the electrons released from these centers dominate the current through the diode, the current density, neglecting scattering of electrons by phonons and recombination process, will be equal to

$$I_r = qN_S WS, \qquad (5)$$

where*NS* is the charged states density at the interface,*S* is the area of barrier electrode, and *W* is the electron tunnelling rate from these states into the conduction band which is a function of field strength *E* and temperature *T*. Therefore, *Ir*≈ *W*(*E*,*T*), and we can fit the current dependences obtained by measurements with the theoretical tunnel transition through the barrier rate dependences on temperature.

The electrons tunnelling rate *W*(*E*,*T*) from centers of $\varepsilon_T$depth at the metal /semiconductor interface is [22, 23]

$$W(E,T) = \frac{qE}{(8m^*\varepsilon_T)^{1/2}}\left[\left(1+\gamma^2\right)^{1/2}-\gamma\right]^{1/2}\left[1+\gamma^2\right]^{-1/4}$$
$$\times \exp\left\{-\frac{4}{3}\frac{(2m^*)^{1/2}}{qE\hbar}\varepsilon_T^{3/2}\times\left[\left(1+\gamma^2\right)^{1/2}-\gamma\right]^2 \times\left[\left(1+\gamma^2\right)^{1/2}+\frac{1}{2}\gamma\right]\right\},$$
$$\gamma = \frac{(2m*)^{1/2}\Gamma^2}{8q\hbar E\varepsilon_T^{1/2}}. \qquad (6)$$

Here, $\Gamma^2 = \Gamma_0^2(2n + 1) = 8a(\omega)2(2n + 1)$ is the width of the centre absorption band caused mainly by interaction with optical phonons of energy _*ω*, $n = [\exp(h\omega/kT) - 1]^{-1}$is the temperature distribution of phonons, *m*∗is the effective density mass of the electron in the semiconductor, and *a*is the electron-phonon coupling constant. The parameter *γ*provides the temperature dependence for tunnelling process. If *γ* is very small due to a very large electrical field or low temperature, the tunnelling process is temperature independent, and in this case PhAT is similar to classical tunnelling.

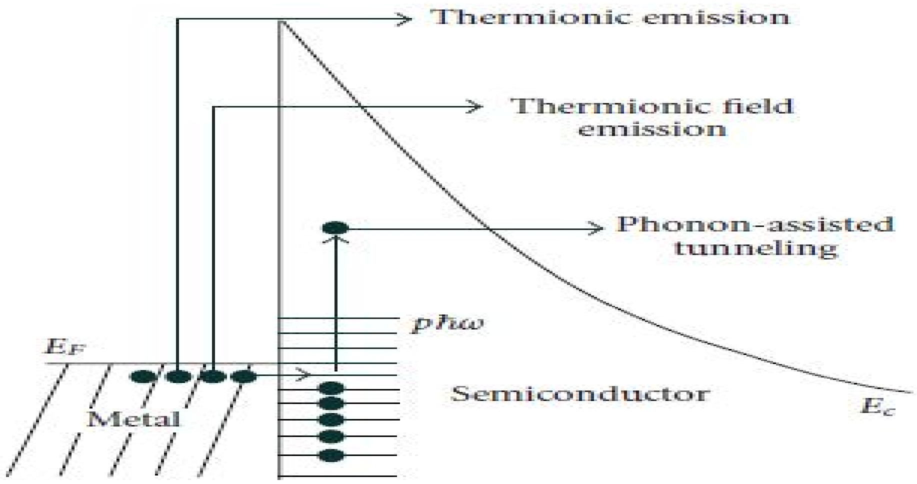
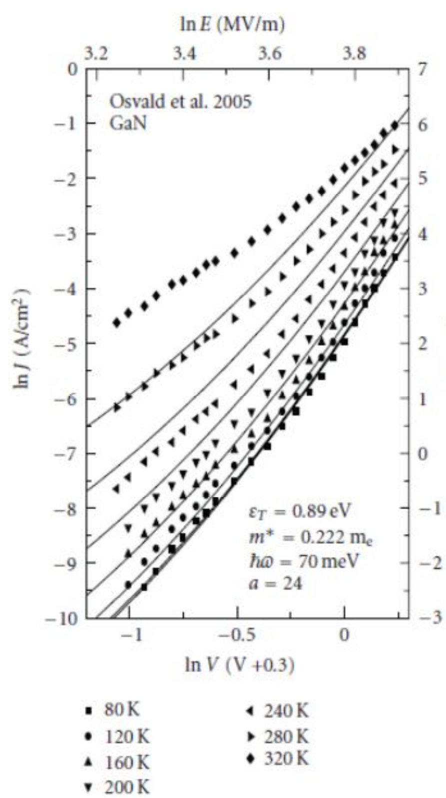


Fig 1.Engery level diagram of the metal/ Semiconductor contact



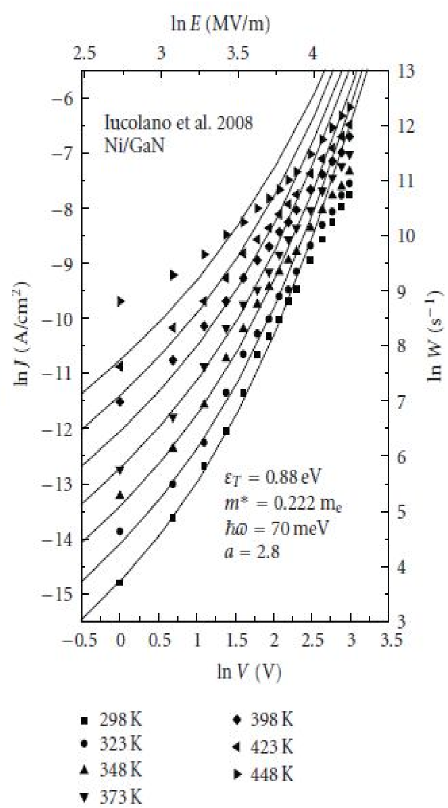


Fig.2: Comparison of I-V dependences for metal/n-GaNSchottky diode from Figure 2 [5] (symbols) with theoretical W(E,T) against E dependences (solid curves), computed using parameters: εT= 0.89 eV, m∗= 0.222me, h ω= 70 meV, a = 2.4.	***Fig(3); The I-V characteristics of Ni/Ga N diode extracted from Figure -6 in {[13] (symbols) fitted to the theory (solid curves).Parameters for computation :εT=*** **0.88 eV,*m*∗= 0.222meV, *h ω* = 70 m eV, *a* = 2.8. Estimated states density *Ns* = 6.2 × 10^{10} cm–^{2}.**

2.2.The Comparison of the Leakage Current Dependences on Bias for Different Temperatures with Theoretical W(E,T) Dependences.

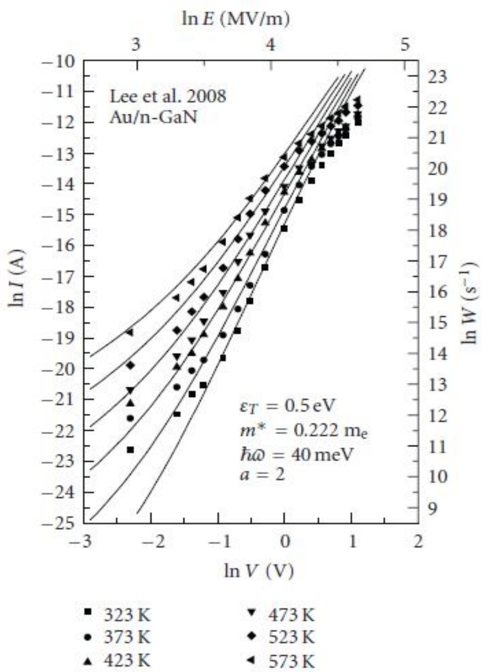
Now let us represent the comparison of some*I-V/T* characteristics measured on diodes fabricated both onepitaxial GaN and on GaN nanowires with the PhAT ratedependence on field strength computed using (6). The fit ofthe leakage *I-V/T* curves obtained by Osvald et al. [5] in the temperature range from 80 to 320 K for metal/n-GaN diode fabricated on N-polarity GaN grown by molecular-beam epitaxy to the tunnelling rate dependences on field strength $W(E,T)$ is shown in Figure 2. The fit is performed under the assumption that the field strength is proportional to the square root of applied voltage, that is, the tunnelling occurs in the high field region. The theoretical $W(E,T)$ versus E dependences were computed using for the barrier height $\varepsilon T$the value of 0.89 eV estimated from the *C-V* data [5], andfor the electron effective mass the value of 0.222me [24] was used. For the phonon energy the value of 70meV (i.e.,somewhat lower than the energy of LO phonon, which inGaN is equal to 91 meV [25]) was selected. The couplingconstant *a*was chosen in order to get the best fit of theexperimental data with the calculated dependences. As isseen in Figure 2, the theoretical $W(E,T)$ dependences fitreasonably well with the experimental data for entire rangeof the measured temperatures. It is possible to notice thatthe higher the reverse bias is, the weaker is the temperaturedependence. The estimated density of charged states in theinterface was found to be equal to 1.5 × 1015 cm−2.

Figure 3 shows the *I-V/T* data measured by Iucolanoet al. [13] for Ni/GaNSchottky diode made on epitaxial n-GaN layer fitted to the theoretical $W(E,T)$ curves. As is seen from Figure 3, the theoretical curves describe well theexperimental data in the temperature range from 298 K to448 K. Only the *I-V* curvemeasured at 448 K signally deviates from theoretical ones. Other discrepancy between the theory and experiment emerges at higher voltages/fields when the current approaches to saturation. The observed trend to saturation of the current at higher electric field could be due to limitation of the filled centers in the interface when theirexhaustion rate is very high (approximately 1010 s−1). The assessed traps density for this diode was found to be equal to 6×10^{10} cm−2.

I-V/T characteristics for Au/n-GaNnano-Schottkydiode measured by Lee et al. [19] in the temperature range from 323 to 573 K are shown in Figure 4. The temperature behaviour of the *I-V* curves are very similar to the curves in Figure 3 and are also well described by the PhAT model. The electrical characteristics of a single GaN nanowire Schottkydiode by authors of [19] were explained by a thermionic-fieldemission and an enhancement of the tunnelling effects.

I-V/T characteristics for Au/n-GaNnano-Schottkydiode measured by Lee et al. [19] in the temperature range from 323 to 573 K are shown in **Figure 4.** The temperature behaviour of the *I-V* curves are very similar to the curves in Figure 3 and are also well described by the PhAT model. The electrical characteristics of a single GaN nanowire Schottkdiode by authors of [19] were explained by a thermionic-field emission and an enhancement of the tunnelling effects.

In a very recent paper, the temperature-dependent *IV*characteristics of PtSchottky contacts to a-plane ntypeGaN were presented [26]. A notable deviation fromthe theoretical Richardson constant value was observedin the conventional Richardson plot. The authors of [26]. have concluded that the thermionic emission model is inapplicable for these diodes. To explain the observed electricalbehaviours, defect-assisted tunnelling was necessary toinvoke.



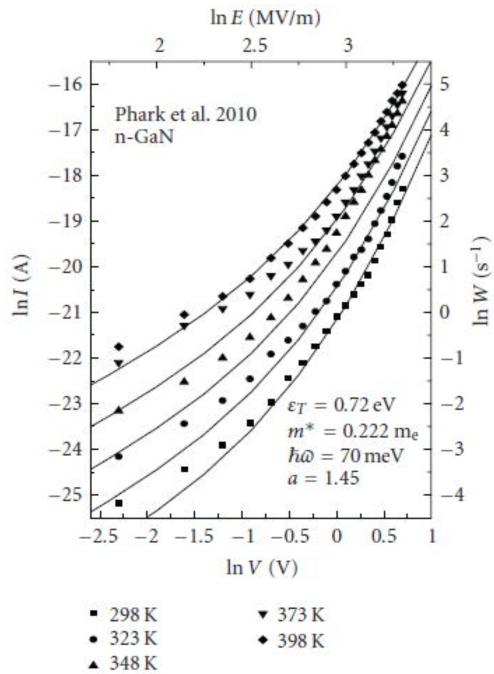


Figure 4: The I-V characteristics of Au/n-GaNnano-Schottky diode represented from Figure 2 [19] (symbols) fitted to theoretical W(E,T) against E dependences (solid curves). Parameters for computation: εT= 0.5 eV, m⍰= 0.222me, h ω= 40 m eV, a = 2.0.

Figure 5: Reverse bias I-V characteristics of the PtSchottky contacts to a-plane n-GaN extracted from Figure 2 [26] (symbols) fitted to theory (solid curves) Parameters: εT= 0.72 eV, m⍰= 0.222me, h ω= 70 meV, a = 1.45. Assessed state density NS = 1.4x10^{13} cm^{-2}.

In **Figure 5**, the fit of the reverse bias branch of *Ir-V/T* characteristics from Figure 2 [26] with PhAT model isexposed. As can be seen the theoretical curves describe wellthe experimental data for all measured temperatures usingthe same value of *εT*= 0.72 eV assessed in [26]. From the fitof the experimental data with the theory and using (5) (S =4.2 × 10−4 cm2) estimated states density at the interface was found to be equal to 1.4 × 10^{13}cm^{-2}.

2.3. Apparent Barrier Height Dependence on Temperature.

Inthis section, I present a comparison of the apparent barrier height dependence on temperature with envisaged for such dependence by PhAT model.

The reason for SBH derived from *I-V/T* characteristics depends on temperature lies in the fact that Φbris calculated from the gradient of Richardsons' plots which, in general, are not straight lines. The steepness of ln(*IR/T*2) versus *1/T*curves at higher voltages was found to decline at lower temperatures, and the bowing of these curves is observed [15, 16]. The phonon-assisted theory predicts, namely, the same value of decrease in Φbr as obtained from *I-V/T*characteristics. The correctness of this assertion will be confirmed by the comparison of the theoretical activation energy *ET* dependences upon temperature with the apparent barrier height dependence on the same parameter. *ET* was calculated as the gradient of theoretical "Richardon plot" using

$$E_T = \frac{k}{q}\frac{d\ln(W/T^2)}{d(1/T)}. \qquad (7)$$

In **Figure 6** the apparent SBH dependence on temperatureassessed by Do˘ganet al. for Au/Ni/n-GaNSchottkydiodes from references [16] fitted to *ET* dependence on temperature is shown. As is seen in Figure 6 the theoretical*ET* versus *T* dependence reflects well the apparent barrier height dependence on temperature. An abnormal temperature dependence of the barrier height the authors of [16] have explained by invoking three sets of Gaussiandistributions of barrier heights at 320–160 K, 160–80 K, and 80–40 K (see inset of Figure 6).

Figure 7 shows the fit of temperature-dependent SBHfor Pd/Au/n-GaN from [12] and Ag/p-GaN/ SDs [14] with the theoretical *ET* versus *T* dependence. One can see that theoretical curves both for n-type and p-type GaN describe very well the strong temperature dependence of apparent SBH observed for these diodes. Such the SBH behaviour in [12] was attributed to barrier inhomogeneities by assuming a Gaussian distribution of barrier heights at the interface.Temperature variation of the experimental value of the SBHderived from the reverse bias characteristics from 0.17 eV at 80 K to 0.84 eV at 360 K for the Ag/p-GaN SD; the authors of [14] ascribed to the charge transport tunnelling mechanism.

It is worth mentioning that the strong temperaturedependence of the apparentSchottky barrier height is also peculiarity for SDs made on the basis of other semiconductors.

For instance in Figure 8 we represent the temperature dependence of SBH assessed from *I-V/T* data for SD made on n-type Si [27] and on p-type Si [28] ones. As can be seen the theoretical curves *ET* versus *T* computed using(6) and (7) and inherent for silicon parameters describe the experimental SBH dependence on temperature very well. The temperature dependence of the apparent SBH in these SDs by authors of [27, 28] have been explained invoking the Schottky barrier height inhomogeneity model [29]. Under their opinion, in presence of inhomogeneitiesof SBH electrons at low temperatures are able to surmount the lower barriers, and therefore the current transport will be dominated by current flowing through the patches of lower Schottky barrier height. As the temperature increases, an increasing number of electrons will have sufficient energy to surmount the higher barriers; consequently, the dominant barrier height will increase with increasing both temperature and bias voltage. However, actual decrease in barrier height with increasing bias is observed for many diodes (see, e.g., [30] and references therein). We want to emphasize that PhATtheory predicts the SBH decrease as a bias voltage increases. This assertion is proved by *ET* dependence on temperature computed for different values of field strength (see Figures 6 and 8).

The physical essence of the apparent barrier heightdependence both on temperature and bias voltage in the framework of the PhAT theory is comprehensible. According to thismodel, the apparent SBH/(activation energy) depends on the quantity of phonons taken part in the tunnelling process. At low temperatures the number of phonons according to the equation n = [exp(_ω/kT) − 1]−1will be less in determining lower energy activation and herewith barrierheight. At higher temperatures the number of phonons is greater, and apparent SBH will be higher. Likewise is explicable dependence of SBH on bias voltage. At high voltages for the tunnelling less quantity of phonons is required then at low ones. Hence, at low bias voltages the apparent SBH will be higher. Thus, the actual barrier height can be determined fromthe*C-V* measurements but not from*I-V/T* measurements using thermionic emission theory.

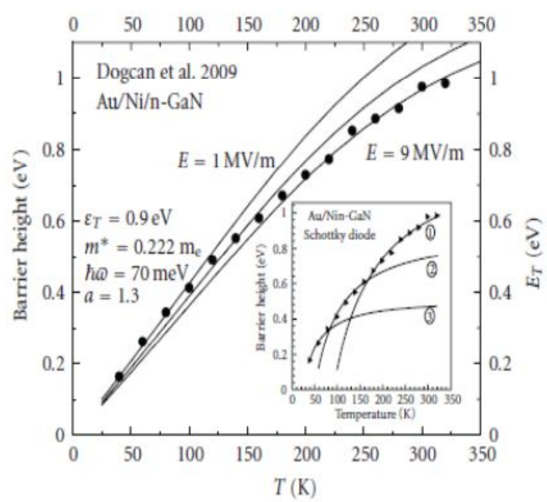


Figure 6: Temperature dependence of the barrier height for Au/Ni/n-GaN from [16] (symbols), fitted to the theoretical ET versus T (solid lines) computed for field strengths of 1, 5, 9 (MV/m). Note that theoretical ET is higher at lower fields. The inset shows barrier height versus T from the same work. The continuous curves in the inset correspond to Φbcomputed by authors of [16] using TE model for the three Gaussian distributions of the barrier height.

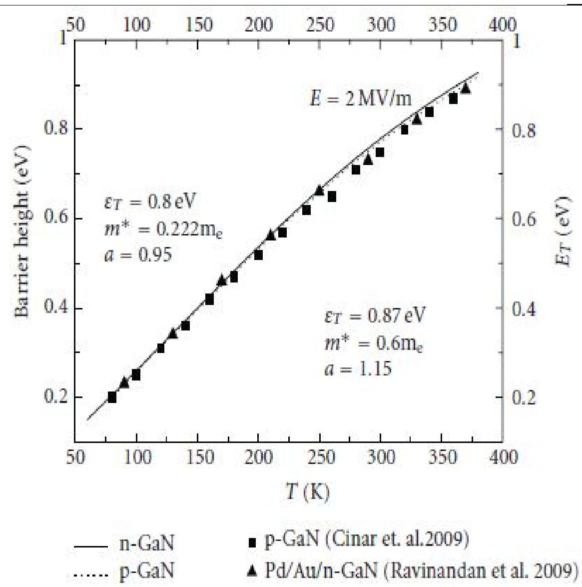


Figure 7: Variation of the barrier height with temperature for Pd/Au/n-GaN from [12] and Ag/p-GaN [14] (symbols), fitted to the ET versus T exposed by solid line for n-type and dot line for p-type GaN

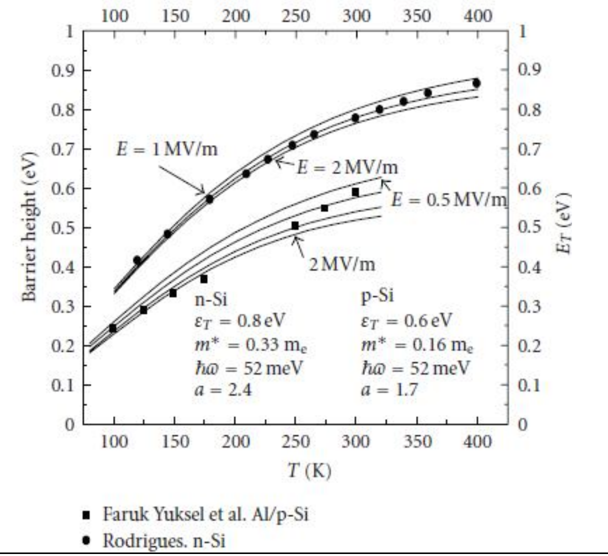


Figure 8: Temperature dependence of the barrier height for n- Si from [26] and Al/p-Si [27] symbols, fitted to the ET versus T dependences (solid lines).

3.CONCLUSION

In conclusion, the phonon-assisted tunnelling modeldescribes well the peculiarities of reverse-bias current temperature dependence in Schottky diodes fabricated either on GaN epitaxial layer or on GaN nanowires. The fit of experimental data to computed tunnelling rate allows to estimate the field strength at which the free charge carriers are generated, and the density of charged states near the interface between metal and semiconductor. In the terms of this model the bias voltage and temperature dependence of apparent SB height evaluated from *I-V/T* measurements is explained as well. Thus, phonon-assisted tunnellingmechanism must be taken into account in explaining the reverse leakage current characteristics for diodes with Schottky barriers.

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