Electrical Characteristics of Au/n-GaN Schottky Junction with a High-k SrTiO$_3$ Insulating Layer

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The electrical characteristics of Au/n-GaN Schottky junction (SJ) were improved by a place of high-k strontium titanate (SrTiO$_3$) insulating layer in the middle of Au and n-GaN. The electrical properties of Au/n-GaN SJ and Au/SrTiO$_3$/n-GaN metal/insulator/semiconductor (MIS) junction were explored by current-voltage and capacitance-voltage techniques. The MIS junction displayed an exquisite rectifying nature as compared to the SJ. The series resistance ($R_s$) and shunt resistance ($R_{sh}$) were found to be 30 $\Omega$, 4.69 $\times$ 10$^5$ $\Omega$ and 250 $\Omega$, 2.12 $\times$ 10$^5$ $\Omega$ for the SJ and MIS junction, respectively. The estimated barrier height (BH) and ideality factors of SJ and MIS junction were 0.67 eV, 1.44 and 0.83 eV, 1.78, respectively. Higher BH was achieved for the MIS junction than the SJ junction, suggesting the BH was effectively changed by the SrTiO$_3$ layer. Also, the ideality factor, BH and series resistance of the SJ and MIS junction were estimated by employing the Cheung’s function and compared each other. Observations reveal the ohmic behavior at lower voltage regions and space-charge-limited conduction at higher voltage regions in the forward bias I-V characteristic of the SJ and MIS junctions. Also, the reverse leakage current conduction mechanism of SJ and MIS junctions was explored.

Keywords: n-type GaN, Strontium titanate, Electrical properties, MIS junction, Barrier height, Ideality factor, Current conduction mechanism.

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1. INTRODUCTION

III-V wide bandgap semiconductors, mainly gallium nitride (GaN), are essential semiconductor materials for the development of metal/oxide/semiconductor field effect transistors, heterojunction field effect transistors, metal/insulator/semiconductor field effect transistors, high electron mobility transistors, and Schottky rectifiers [1, 2] because of their unique properties. However, Schottky junctions in GaN-based devices suffer from strange leakage current and lower breakdown voltage that limits the device concert and steadiness. Henceforth, it is imperative to realize good Schottky junctions with a low ideality factor, low leakage current and high barrier height by applying thin insulating/interlayer. Consequently, the complete investigation of fabrication and electrical characteristics of metal/insulator/semiconductor interface is crucial. Different research groups have concentrated on the creation of thin oxide/insulating or interlayer in the middle of the metal and n-type GaN semiconductor, and investigated its electrical characteristics using different approaches [3].

This work primarily emphasizes on the introduction of high-k strontium titanate (SrTiO$_3$) as an insulating layer between the metal and the semiconductor, and tested its outcome on the electrical properties of Au/n-GaN SJ. To achieve superior ultra-large-scale integration (ULSI) with high rectical and low-power consumption, high-k materials have fascinated large interest for future gate dielectrics. Therefore, SrTiO$_3$ is chosen as an insulator layer in the present work because it has high dielectric constant, small dielectric loss, large relative permittivity, high breakdown potency, and extremely good thermal strength [4]. Moreover, SrTiO$_3$ is one probable material that may be placed to use for tunable microwave device applications owing to its high dielectric nonlinearity and low dissipation factor [5]. So, the current work is devoted to the development of Au/SrTiO$_3$/n-GaN MIS junction with a high-k SrTiO$_3$ as an insulating layer and investigates its electrical characteristics. The electronic parameters of Au/SrTiO$_3$/n-GaN MIS junction were estimated by current-voltage (I-V) and capacitance-voltage (C-V) measurements. These parameters were compared with that of the conventional Au/n-GaN SJ. As well, the possible forward and reverse current conduction mechanisms of the Au/n-GaN SJ and Au/SrTiO$_3$/n-GaN MIS junction were described and explained.

2. EXPERIMENTAL DETAILS

Si-doped GaN films (2 $\mu$m thick) were employed for the fabrication of Au/(SrTiO$_3$)/n-GaN metal/insulator/semiconductor (MIS) junction. The growing n-GaN films, cleaning process and fabrication methods were followed as stated in [3]. The schematic configuration of a fabricated Au/SrTiO$_3$/n-GaN MIS junction is shown in Fig. 1a. To correlate the electrical properties of the Au/SrTiO$_3$/n-GaN MIS junction, the Au/n-GaN Schottky junction (SJ) was also prepared on the same GaN substrate as a reference junction. Using a Keithley source measurement unit (Model No: 2400) and automated deep level transient spectrometer (DLTS-83D), the electrical properties of the Au/SrTiO$_3$/n-GaN MIS junction and Au/n-GaN SJ were measured in the dark, respectively.

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3. RESULTS AND DISCUSSION

Fig. 1b displays the I-V curves of the SJ and MIS junction measured at room temperature. The SJ and MIS junction exhibit a good rectifying nature (Fig. 1b). The reverse leakage currents of SJ and MIS junction are measured to be $1.8 \times 10^{-6}$ and $9.5 \times 10^{-8}$ A at $-1$ V, respectively. The MIS junction exhibits a lower reverse leakage current than the SJ, thus indicating that the electrical properties of MIS junction are improved. This is due to the place of high-$k$ SrTiO$_3$ thin insulating layer between the Au and $n$-GaN layers.

![Fig. 1 - Schematic diagram of Au/SrTiO$_3$/n-GaN MIS junction (a), I-V characteristics of Au/n-GaN SJ and Au/SrTiO$_3$/n-GaN MIS junction (b)](image)

The barrier height (BH) and ideality factor of Au/n-GaN SJ and Au/SrTiO$_3$/n-GaN MIS junction are derived. The reverse saturation current of the Au/n-GaN SJ and Au/SrTiO$_3$/n-GaN MIS junction was obtained from the plot of $I(I - \exp(-qV/kT))$ versus voltage (plot not shown here). The BHs of the SJ and MIS junction are found to be $0.67$ eV and $0.83$ eV, respectively. The estimated BH of MIS junction is greater than the SJ, implying that the BH can be modified by SrTiO$_3$ interlayer. Both junctions showed that BH rises in forward-bias which may be because of the enhance in quasi-Fermi level of the majority carriers on the GaN surface. Thus, the majority of the electrons to be injected directly into the metal which makes a thermionic current through a few electrons are trapped by interface states. As a result, the BH rises thus decreasing the junction current [3]. The ideality factor of SJ and MIS junction are evaluated from the slope of the In-I-V plot. The evaluated ideality factor values of SJ and MIS junction are 1.44 and 1.78, respectively. The SJ and MIS junction show that the determined ideality factor values are more than one. The reasons may be due to (1) barrier inhomogeneity, (2) recombination-generation, (3) image-force effect, (4) tunneling effect and (5) voltage drop present at the insulating layer [6, 7]. Another possibility may be the inhomogeneous BH for greater values of ideality factor. The creation of an electric dipole layer at SrTiO$_3$/n-GaN interface may be accountable for the departure of the ideality factor from unity [8].

In order to estimate the device consistency and effectiveness, the series resistance ($R_s$) and shunt resistance ($R_{sh}$) of the junction play an important role. The values of $R_s$ and $R_{sh}$ can be determined from the plots of junction resistance ($R = \epsilon V/dI$) versus bias voltage (V) for the SJ and MIS junction as shown in Fig. 2a, b. The calculated $R_s$ of the SJ and MIS junction are $30 \, \Omega$ and $250 \, \Omega$, respectively. The shunt resistance ($R_{sh}$) is also derived for the SJ and MIS junction and the corresponding values are $4.69 \times 10^7 \, \Omega$ and $2.12 \times 10^9 \, \Omega$, respectively. Results indicate that both the SJ and MIS junction have low $R_s$ and high $R_{sh}$ which are needed for ideal devices.

![Fig. 2 - Junction resistance ($R$) versus bias voltage for the (a) Au/n-GaN SJ and (b) Au/SrTiO$_3$/n-GaN MIS junction](image)

Furthermore, the Au/n-GaN SJ and Au/SrTiO$_3$/n-GaN MIS junction (Fig. 1b) reveal non-linearity in the forward bias I-V curves at the upper voltage region, which is owing to the effect of series resistance ($R_s$) and interface state density. To assess the BH, ideality factor and $R_s$ of the SJ and MIS junction in the non-linearity region of I-V curves, Cheung’s functions were executed [9]. The $dV/dln(I)$ and $H(I)$-I plots are drawn for the SJ and MIS junction and are depicted in Fig. 3a, b. From $dV/dln(I)$-I plot, the ideality factor and series resistance were evaluated as $1.87$ and $19 \, \Omega$, and $4.16$ and $565 \, \Omega$ for the SJ and MIS junction, respectively. Whereas the $R_s$ and BH are determined to be $18 \, \Omega$ and $0.61$ eV, and $595 \, \Omega$ and $0.84$ eV from $H(I)$-I plot for the SJ and MIS junction, respectively. The $R_s$ values derived from the $dV/dln(I)$-I plot are almost comparable to those determined from the $H(I)$-I plot, which confirms that Cheung’s functions are reliable and applicable. Results present that the BHs evaluated by $H(I)$-I plot are nearly similar with those derived by the forward-bias In(lnI)-V graph. Nevertheless, the ideality factors derived by $dV/dln(I)$-I plot are somewhat different from those derived by forward-bias In(lnI)-V plot. This may be caused by the effect of both $R_s$ and interfacial layer on the I-V characteristics, although only $R_s$ effects the $dV/dln(I)$-I plot [9, 10].
In order, the majority of the carriers injected charge carriers \[ \text{PFE} \] and Schottky emission (SE) mechanisms, the reverse leakage current mechanism is investigated in the Au/SrTiO\(_3\)/n-GaN MIS junction. The reverse leakage current is due to the trap-filled" limit. As a result, the strong electron injection, electrons escape from the traps and contribute to the space-charge-limited current (SCLS) [15]. Clearly, the observation reveals that a clear variation from an Ohmic-type conduction at lower voltage range (region-I) to a space-charge-limited conduction at higher voltage range (region-II and region-III) for both the SJ and MIS junctions.

Further, in view of Poole-Frenkel emission (PFE) or Schottky emission (SE) mechanisms, the reverse leakage current mechanism is investigated in the Au/n-GaN SJ and the Au/SrTiO\(_3\)/n-GaN MIS junction. The theoretical values of PFE and SE field lowering coefficients \( \beta_{PF} \) and \( \beta_{SE} \) can be calculated from the equation \[ 2\beta_{SC} = \beta_{PF} = (q\beta_{SE}E_0)^{1/2} \] [15]. \( \beta_{PF} \) is always twice the theoretical values of PFE and SE field lowering coefficients \( \beta_{PF} \) and \( \beta_{SE} \) can be calculated from the equation \[ 2\beta_{SC} = \beta_{PF} = (q\beta_{SE}E_0)^{1/2} \] [15]. \( \beta_{PF} \) is always twice the theoretical values of PFE and SE field lowering coefficients \( \beta_{PF} \) and \( \beta_{SE} \) can be calculated from the equation \[ 2\beta_{SC} = \beta_{PF} = (q\beta_{SE}E_0)^{1/2} \] [15]. \( \beta_{PF} \) is always twice the theoretical values of PFE and SE field lowering coefficients \( \beta_{PF} \) and \( \beta_{SE} \) can be calculated from the equation \[ 2\beta_{SC} = \beta_{PF} = (q\beta_{SE}E_0)^{1/2} \] [15]. \( \beta_{PF} \) is always twice the theoretical values of PFE and SE field lowering coefficients \( \beta_{PF} \) and \( \beta_{SE} \) can be calculated from the equation \[ 2\beta_{SC} = \beta_{PF} = (q\beta_{SE}E_0)^{1/2} \] [15]. \( \beta_{PF} \) is always twice the theoretical values of PFE and SE field lowering coefficients \( \beta_{PF} \) and \( \beta_{SE} \) can be calculated from the equation \[ 2\beta_{SC} = \beta_{PF} = (q\beta_{SE}E_0)^{1/2} \] [15]. \( \beta_{PF} \) is always twice the theoretical values of PFE and SE field lowering coefficients \( \beta_{PF} \) and \( \beta_{SE} \) can be calculated from the equation \[ 2\beta_{SC} = \beta_{PF} = (q\beta_{SE}E_0)^{1/2} \] [15]. \( \beta_{PF} \) is always twice the theoretical values.
value of the $\beta_{SC}$. The derived theoretical values of $\beta_{FW}$ and $\beta_{SC}$ obtained for the SJ are $2.46 \times 10^{-3} \text{ eVm}^{1/2}\text{V}^{-1/2}$ and $1.25 \times 10^{-3} \text{ eVm}^{1/2}\text{V}^{-1/2}$, respectively. Similarly, for the MIS junction they are $0.43 \times 10^{-3} \text{ eVm}^{1/2}\text{V}^{-1/2}$ and $0.21 \times 10^{-3} \text{ eVm}^{1/2}\text{V}^{-1/2}$, respectively. A plot of $\ln(I_d)$ versus $V_{d/2}$ was drawn for the Au/n-GaN SJ and Au/SrTiO$_3$/n-GaN MIS junction and is illustrated in Fig. 6. The determined experimental slope value is $2.52 \times 10^{-3} \text{ eVm}^{1/2}\text{V}^{-1/2}$ for the Au/n-GaN SJ, which agrees well with the theoretical slope of the PFE.

Table 1 – The barrier height, ideality factor, series resistance and shunt resistance of Au/n-GaN SJ and Au/SrTiO$_3$/n-GaN MIS junction

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Au/n-GaN SJ</th>
<th>Au/SrTiO$_3$/n-GaN MIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>I-V method</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barrier height (eV)</td>
<td>0.67</td>
<td>0.83</td>
</tr>
<tr>
<td>Ideality factor (n)</td>
<td>1.44</td>
<td>1.78</td>
</tr>
<tr>
<td>Leakage current (A) at 1 V</td>
<td>$1.8 \times 10^{-6}$</td>
<td>$9.5 \times 10^{-8}$</td>
</tr>
<tr>
<td>Series Resistance, $R_s$ (Ω)</td>
<td>30</td>
<td>250</td>
</tr>
<tr>
<td>Shunt resistance, $R_{sh}$ (Ω)</td>
<td>$1.8 \times 10^6$</td>
<td>$2.12 \times 10^{-9}$</td>
</tr>
<tr>
<td>Cheung’s method</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$dV/d(inJ)$ vs. I</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Series resistance (Ω)</td>
<td>19</td>
<td>565</td>
</tr>
<tr>
<td>Ideality factor (n)</td>
<td>1.87</td>
<td>4.16</td>
</tr>
<tr>
<td>$H(I)$ vs. I</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barrier height (eV)</td>
<td>0.61</td>
<td>0.84</td>
</tr>
<tr>
<td>Series resistance (Ω)</td>
<td>18</td>
<td>595</td>
</tr>
<tr>
<td>C-V method</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Built-in potential (V)</td>
<td>0.75</td>
<td>0.86</td>
</tr>
<tr>
<td>Barrier height (eV)</td>
<td>0.77</td>
<td>0.92</td>
</tr>
</tbody>
</table>

Hence, the current conduction mechanism is dominated by PFE in the SJ. However, in the case of MIS junction (Fig. 6), it is detected by two distinct regions, thus indicating that two different conduction mechanisms occur in the reverse bias region. The determined experimental slope values in region I (lower-bias region) and region II (higher-bias region) are $3.94 \times 10^{-3} \text{ eVm}^{1/2}\text{V}^{-1/2}$ and $1.99 \times 10^{-3} \text{ eVm}^{1/2}\text{V}^{-1/2}$, respectively, for the MIS junction. The derived experimental slope value in the lower bias region is nearly matched to the theoretical slope value of the PFE, indicating the PFE is dominant. This may be the occurrence of a high density of structural defects or trap levels in the dielectric film employed here, which could be accountable for the improved performance of the trapping/detrapping of charge carriers [16]. Whereas, the determined experimental slope in the higher bias region is closer to the theoretical slope value of the SE. This indicates that the SE is dominant in the higher bias region where current conduction ensues via the contact interface rather than from the bulk material which attributable to the non-uniformity and subatomic structure of the dielectric layer [17, 18].

4. CONCLUSIONS

The Au/SrTiO$_3$/n-GaN MIS junction was fabricated by place of a high-k strontium titanate (SrTiO$_3$) in between the Au and n-GaN layers, and its electrical properties were explored by I-V and C-V approaches. The results of MIS junction correlate with the SJ results. The MIS junction revealed a good rectifying nature than the SJ junction. The BH and ideality factor values were determined as 0.67 eV, 1.44 for the SJ junction and 0.83 eV, 1.78 for the MIS junction, respectively. Higher BH was obtained for the MIS junction as compared to the SJ junction. This indicates that the SrTiO$_3$ insulating layer rehabilitated the effective BH. Results indicate the ohmic nature and space-charge-limited conduction at lower and higher voltage regions of forward bias I-V characteristic of the SJ and MIS junction. Analysis suggests that the Schottky emission is ruled by the reverse leakage current mechanism in the SJ. Nevertheless, for the MIS junction, the Schottky emission and Poole-Frenkel conduction mechanism were dominant in the lower and higher bias regions, respectively.
Електричні характеристики переходу Шоткі Au/n-GaN з ізоляційним шаром High-k SrTiO₃

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Електричні характеристики переходу Шоткі Au/n-GaN (SJ) вдосконалювались з використанням ізольючного шару високоомного титану стронцію (SrTiO₃) в серединні шарів Au i n-GaN. Розглянуто електричні властивості Au/n-GaN SJ та Au/SrTiO₃/n-GaN метал/ізолятор/напівпровідник (MIS) переходу методами струм-напруга і ємність-напруга. MIS пере‌хід показав вишукану випрямлювальну характеристику порівняно з SJ. Встановлено, що послідовний опір та опір шунту становлять 30 Ω, 4.69 • 10⁶ Ω та 250 Ω, 2.12 • 10⁸ Ω, відповідно, для SJ та MIS переходу. Розрахувано висоту бар'єру i коефіцієнти ідеальності SJ і MIS переходу становлять 0.67 еВ, 1.44 i 0.83 еВ, 1.78, відповідно. Більш значення висоти бар'єру було досягнуто для MIS переходу у порівнянні з SJ, що свідчить про те, що висота бар'єру ефективно змінювалася за допомогою шару SrTiO₃. Крім того, коефіцієнт ідеальності, висота бар'єру i послідовний опір SJ і MIS переходу оцінювалися за допомогою функції Ченга i порівнювалися між собою. Спостереження показують омічну поведінку в областях з низькою напругою i провідність, обмежену об'ємним зарядом, в областях з високою напругою у прямому зсуві I-V характеристики для SJ і MIS переходу. Крім того, досліджено механізм провідності зворотного струму витоку SJ i MIS переходу.

Ключові слова: GaN n-типу, Титанат стронцію, Електричні властивості, MIS пере‌хід, Висота бар'єру, Коефіцієнт ідеальності, Механізм провідності струму.

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