Electrical Characterization of RF Reactive Sputtered $p$–Mg-In$_x$Ga$_{1-x}$N/$n$–Si Hetero-Junction Diodes without Using Buffer Layer

Thi Tran Anh Tuan 1✉, Dong-Hau Kuo 2✉, Phuong Thao Cao 3✉, Van Sau Nguyen 1, Quoc-Phong Pham 3, Vinh Khanh Nhi 3 and Nguyen Phuong Lan Tran 4

1 School of Basic Sciences, Tra Vinh University, Tra Vinh 87000, Vietnam; thitrananhtuan@tvu.edu.vn (T.T.A.T.); nvsau@tvu.edu.vn (V.S.N.)
2 Department of Materials Science and Engineering, National Taiwan University of Science and Technology, Taipei 10607, Taiwan
3 School of Engineering and Technology, Tra Vinh University, Tra Vinh 87000, Vietnam; phongpham@tvu.edu.vn (Q.-P.P.); nghivinhkhanh@tvu.edu.vn (V.K.N.)
4 College of Engineering and Technology, Can Tho University, Can Tho 94000, Vietnam; tnplan@ctu.edu.vn

* Correspondence: dhkuo@mail.ntust.edu.tw (D.-H.K.); cpthao@tvu.edu.vn (P.T.C.);
Tel.: +886-2-27303291 (D.-H.K.)

Received: 30 August 2019; Accepted: 21 October 2019; Published: 25 October 2019

Abstract: The modeling of $p$–In$_x$Ga$_{1-x}$N/$n$–Si hetero junction diodes without using the buffer layer were investigated with the “top-top” electrode. The $p$–Mg-GaN and $p$–Mg-In$_{0.05}$Ga$_{0.95}$N were deposited directly on the $n$–Si (100) wafer by the RF reactive sputtering at 400 °C with single cermet targets. Al and Pt with the square size of 1 mm$^2$ were used for electrodes of $p$–In$_x$Ga$_{1-x}$N/$n$–Si diodes. Both devices had been designed to prove the $p$-type performance of 10% Mg-doped in GaN and InGaN films.

By Hall measurement at the room temperature (RT), the holes concentration and mobility were determined to be $N_p = 3.45 \times 10^{16}$ cm$^{-3}$ and $\mu = 145$ cm$^2$/V·s for $p$–GaN film, $N_p = 2.53 \times 10^{17}$ cm$^{-3}$, and $\mu = 45$ cm$^2$/V·s for $p$–InGaN film. By the $I$–$V$ measurement at RT, the leakage currents at −5 V and turn-on voltages were found to be 9.31 $\times$ $10^{-7}$ A and 2.4 V for $p$–GaN/$n$–Si and 3.38 $\times$ $10^{-6}$ A and 1.5 V for $p$–InGaN/$n$–Si diode. The current densities at the forward bias of 20 V were 0.421 and 0.814 A·cm$^{-2}$ for $p$–GaN/$n$–Si and $p$–InGaN/$n$–Si devices. The electrical properties were measured at the temperature range of 25 to 150 °C. By calculating based on the TE mode, Cheungs’ and Norde methods, and other parameters of diodes were also determined and compared.

Keywords: $p$–Mg-InGaN films; RF sputtering; $I$–$V$ measurement; Cheung’s method; Norde’s method; TE mode

1. Introduction

GaN and InGaN have excellent characteristics such as high conductivity and high mobility. The development and creation of $p$-layer GaN and InGaN materials involve one of the important technologies in designing electronic devices [1–5]. The investigation of high-quality doping in GaN and InGaN semiconductors by incorporating elements such as Zn, and Cu, Mg for $p$–GaN behavior, and its alloys had reported [4–6]. The success of Mg doping in forming $p$–In$_x$Ga$_{1-x}$N films is an important factor for developing electric devices, a photo detector, and solar cell devices [7–10]. Si wafer has often been used for the growth of GaN, InGaN, and their alloys for applications in photo-detector, solar cells, and electronic devices. The combination between $n$–InGaN layers and $n$–Si wafers were studied to improve the interface layers by using an assortment of approaches [11–14]. For fabricated electronic devices, the growth of the InGaN layer on $n$–Si wafers were studied to improve the interface layers by
using a variety of approaches [15–20]. Lee et al. studied electrical properties of a nanowire \( n\)
–GaN/\( p\)
–Si device by forming dielectrophoretic alignment. At the current density of 10–60 A/cm², the diode was well-defined with a forward voltage drop of 1.2–2.0 V and high resistance in the range of 447 KΩ [17]. Li et al. used the RF sputtering method to deposit the Mg-doped GaN films on the Si substrate and design the homo junction GaN diodes. By testing the \( I–V\) measurement, the turn-on voltages of diodes were 2.3 and 2.1 V for as-deposited and 500 °C-annealed sample, respectively [21]. Vinay Kabra et al. investigated the \( p\)
–ZnO/\( n\)
–Si hetero junction diode by using a dip coating technique. Their electrical properties showed the highly rectifying, with a rectification ratio of 101 at 3 V [22]. Mohd Yusoff et al. reported the \( p–n\) junction diode based on GaN grown on the AlN/Si (111) substrate and annealed samples at 700 °C. The ideality factors of their diodes decreased from 19.68 to 15.14, with the testing temperature increasing from 30 to 104 °C [23]. In previous work, the Mg–doped In\(_{0.05}\)Ga\(_{0.95}\)N films had been deposited on Si (100) substrates by RF reactive sputtering. The Mg–In\(_{0.05}\)Ga\(_{0.95}\)N films had the \( p–n\) type conduction at \( x \leq 0.075\). The \( p–Mg–In_{0.05}Ga_{0.95}N/n–GaN\) diode was shown the leakage current of \( 2.7 \times 10^{-6}\) A, turn-on voltage of 1.8 V, and breakdown voltage of 6.8 V at the RT [12].

All previous groups often investigated the \( p–Ga\)N films and their alloys by using MOCVD above 800 °C and other methods. The sputtered technique with the low temperature at and below 400 °C has been hardly declared. Furthermore, there is no report on the electrical properties of \( p–Mg–In_{x}Ga_{1–x}N/n–Si\) diodes without using buffer layers. In this study, to prove the success of Mg doping in the \( p–GaN\) and the \( p–In\)GaN films, the modeling of \( p–Mg–In_{x}Ga_{1–x}N/n–Si\) hetero junction diodes was designed by using the RF reactive sputtering. This method was chosen to design diodes due to the benefits of low sputtered-temperature, low cost, and safe working atmosphere [7,13,15]. The \( n–Si\) (100) wafer was also used for its low cost, large wafer size, and easy availability [18,22,24]. The electrical characteristics of devices were calculated by the thermionic emission (TE) mode at different testing temperatures [3,12,13].

2. Materials and Methods

Figure 1 shows the structural modeling of a \( p–In_{x}Ga_{1–x}N/n–Si\) hetero junction diode. This device was designed on the \( n–Si\) (100) wafer by modeling with the “top-top” electrode. The \( p–Mg–In_{0.05}Ga_{0.95}N\) and \( p–Mg–GaN\) films were deposited together on the \( n–Si\) (100) and SiO\(_2\)/Si (100) substrate. The \( n–Si\) (100) wafer had sheet resistance of \( ~1–10\) Ω·cm, diameter of 2 inches, thickness of \( ~550\) μm, and the polished surface. Sputtered-\( In_{x}Ga_{1–x}N\) films on SiO\(_2\)/Si substrate were used for testing Hall measurement and SEM analysis.

![Figure 1](image-url)

**Figure 1.** Structural modeling of \( p–In_{x}Ga_{1–x}N/n–Si\) hetero junction diode.

For the \( p–Ga\)N film, the sputtering cermet target was made by hot pressing with the mixture of metallic Mg, Ga powders, and GaN powder. The \([Mg]/([Ga]+[Mg])\) molar ratio in each cermet target was reserved at 10%. Similar for \( p–In\)GaN film, the \([Mg]/([In]+[Ga]+[Mg])\) molar ratio in each cermet target was also kept at 10%. The \([In]/([In]+[Ga]+[Mg])\) molar ratios was 5%. The \( p–Mg–In_{x}Ga_{1–x}N\) films (with \( x = 0\) and 0.05) were deposited on \( n–Si\) (100) substrates at 400 °C for 25 min by RF reactive
sputtering. Both Mg–In$_x$Ga$_{1-x}$N targets were sputtered with RF power of 150W under the gas mixture of Ar and N$_2$, which remained at 5 sccm for each.

The pure Aluminum (99.99%) and Platinum (99.99%) targets were used for making the electrodes for $p$–In$_x$Ga$_{1-x}$N/n–Si hetero junction diodes. By using steel masks with the square size of 1 mm$^2$, these electrodes were deposited at 200 °C, with RF power of 80W for 30 min on top of $p$–In$_x$Ga$_{1-x}$N films and n–Si substrate. The detail procedure for creating the $p$–GaN and $p$–InGaN films, made by RF reactive sputtering, can be referred to our previous works [10–12,21].

In this work, our diodes were designed at the low sputtered-temperature and high pressure. The holes’ concentration, electrical conductivities, and mobilities of $p$–Mg–In$_x$Ga$_{1-x}$N films and n–Si wafer were measured by a Hall measurement (HMS–2000, Ecopia, Tokyo, Japan). Scanning electron microscopy (SEM, JSM–6500F, JEOL, Tokyo, Japan) was used to observe the surface morphology of $p$–In$_x$Ga$_{1-x}$N films. Energy dispersive spectrometer (EDS, JSM–6500F) equipped on SEM was used for composition analysis of films. The $I$–$V$ characteristics of $p$–In$_x$Ga$_{1-x}$N/n–Si diodes were measured by using Semiconductor Device Analyzer (Agilent, B1500A, Tokyo, Japan) with the diode resistance was set of 1.95 eV [22,24–26]. Therefore, the electrons’ injection from $n$–Si into $p$–In$_x$Ga$_{1-x}$N will be easier than the holes’ injection from $p$–In$_x$Ga$_{1-x}$N into n–Si because the energetic barrier $\Delta E_c$ of holes is many times higher than the barrier $\Delta E_c$ of electrons. With the existing space charge layer at the forward bias, the current is limited. However, the depletion width will decrease because of the low potential barrier, and the current will increase easily by increasing the voltage [6,27,28].

3. Results and Discussion

3.1. Structural and Electrical Characteristics

The carrier concentration ($N_p$) and carrier mobility ($\mu$) of n–Si wafer were found to be $N_p = 4.7 \times 10^{15}$ cm$^{-3}$ and $196$ cm$^2$/Vs when measuring the Hall effect at room temperature (RT). The holes concentration ($N_p$) and mobility ($\mu$) were also determined to be $N_p = 3.45 \times 10^{16}$ cm$^{-3}$, $\mu = 145$ cm$^2$/Vs for $p$–GaN film, and $N_p = 2.53 \times 10^{17}$ cm$^{-3}$, $\mu = 45$ cm$^2$/Vs for $p$–InGaN film, respectively. By SEM analysis, the thicknesses of Pt and Al layers were ~250 nm and the thickness of both $p$–In$_x$Ga$_{1-x}$N films was ~0.6 μm.

3.2. The Energy Band Diagram

Figure 2 displays the energy band diagram of a $p$–In$_{0.5}$Ga$_{0.95}$N/n–Si diode as an example. Our band gap ($E_g$) of Mg-doped In$_{0.5}$Ga$_{0.95}$N (Mg of 10%) films at 400 °C-deposition were 2.92 eV. The $E_g$ was reduced by increasing In content in In$_x$Ga$_{1-x}$N [10,21]. In a similar result, Wagner et al. reported the composition dependence of the band gap energy of the strained In$_x$Ga$_{1-x}$N layers grown by MOCVD. The energy $E_g$ of In$_x$Ga$_{1-x}$N decreased from 3.43 to 3.28 eV with the increasing in ratio from 0.02 to 0.15 [25]. The band gap values of n–Si was also found to be 1.12 eV. The electron affinities $\chi$ of $p$–InGaN and n–Si were 4.20 eV and 4.05 eV, respectively [6,24]. According to the band gap values of $p$–In$_{0.5}$Ga$_{0.95}$N and n–Si (2.92 and 1.12 eV), the barrier $\Delta E_c$ for electrons was followed by $\Delta E_c = \chi_{p$–GaN} − \chi_{Si}$ and the barrier $\Delta E_v$ for holes was calculated by $\Delta E_v = E_{g(\text{InGaN})} − E_{g(Si)} + \Delta E_c$ (Figure 2). As a result, the energy band diagram showed a small conduction band offset of 0.15 eV and a large valance band offset of 1.95 eV [22,24–26]. Therefore, the electrons’ injection from n–Si into $p$–In$_x$Ga$_{1-x}$N will be easier than the holes’ injection from $p$–In$_x$Ga$_{1-x}$N into n–Si because the energetic barrier $\Delta E_c$ of holes is many times higher than the barrier $\Delta E_c$ of electrons. With the existing space charge layer at the forward bias, the current is limited. However, the depletion width will decrease because of the low potential barrier, and the current will increase easily by increasing the voltage [6,27,28].

3.3. I–V Measurements

Figure 3 shows the current density–voltage characteristics of $p$–GaN/n–Si (device-A) and $p$–InGaN/n–Si (device-B) tested at RT based on a 1-mm$^2$ contact. The applied voltage of measurement was extended from −20 V to +20 V for both devices. The current densities and the leakage current densities are found in the area of 1 cm$^2$. 

Coatings 2019, 9, 699
At the bias range of (−5 V, +5 V), the leakage current of diodes at −1 V and the turn-on voltages at RT were $1.43 \times 10^{-7}$ A, 1.5 V (device-A) and $2.58 \times 10^{-7}$ A, 2.4 V (device-B). Our devices had an improvement in the turn-on voltage with the increase in content in the p–InGaN layer.

With the wide voltage of (−20 V, +20 V), Figure 3 also shows the breakdown voltage was beyond the largest instrument capacity of −20 V for both diodes. The leakage currents also were found to be $9.31 \times 10^{-7}$ and $3.38 \times 10^{-6}$ A at −5 V for (device-A) and (device-B), respectively. At the forward bias of 20 V, the current densities of diodes were 0.421 and 0.814 A·cm$^{-2}$ for device-A and device-B, respectively. Higher holes concentration in the p–InGaN layer with the performance of the in ratio in p–InGaN leads to the higher current density of device-B. In addition, with the high conduction of electrodes, the forward current of diodes increased rapidly at the bias of (−20 V, +20 V). The rectification ratio (on/off) of diodes were also found to be $3.22 \times 10^4$ (device-A) and $6.61 \times 10^4$ (device-B), respectively.

Figure 4 shows the semilogarithmic $I$–$V$ characteristics of diodes under the forward bias, which were tested at the RT temperature. All parameters of diodes can be calculated by the thermionic-emission (TE) mode (for $qV > 3 kT$). They are given by the equations below [3,11,12].

\begin{align*}
I &= I_0 \exp \left(\frac{q}{nkT} (V - IR_s) \right) \quad (1) \\
\phi_b &= \frac{kT}{q} \ln \left( \frac{AA^*T^2}{I_0} \right) \quad (2) \\
n &= \frac{q}{kT} \left( \frac{dV}{d\ln I} \right) \quad (3) \\
A^* &= \frac{4\pi q k^2 m^*}{\hbar^3} \quad (4)
\end{align*}
where $A^*$ is the effective Richardson constant, $R_s$ is the series resistance, $n$ is the ideality factor, $I_o$ is the saturation current, $q$ is the electronic charge, $A$ is the area of diode, $\phi_B$ is the barrier height, $m_e$ is the free electron mass, $m^*$ is the effective electron mass, and $h$ is the Plank constant [29–31]. In base Equation (4), the theoretical value of $A^*$ was 26.4 A·cm$^{-2}$·K$^{-2}$ for $p$–GaN ($m^* = 0.22m_e$), and 23 A·cm$^{-2}$·K$^{-2}$ for $p$–InGaN ($m^* = 0.19m_e$) [6,12,13].

As shown in Figure 4, the barrier height of diodes can be calculated from $I_o$ as the saturation current. Based on Equation (2), and from the plot of ln$I$ versus $V$, the saturation current $I_o$ can be determined by intersecting the interpolated straight lines from the linear region with the current axis [12,20].

![Figure 4. The I–V characteristics of device-A and device-A under the forward bias tested at room temperature.](image)

Figure 5a,b show the semi logarithmic I–V characteristics of diodes were tested at the temperature range from 25 to 150 °C. From Figure 5, the leakage current of diode at $-5$ V increased from $9.39 \times 10^{-7}$ A (device-A) and $3.38 \times 10^{-6}$ (device-B) at 25 °C to $3.25 \times 10^{-5}$ A (device-A) and $2.64 \times 10^{-4}$ A (device-B) at 150 °C. Based upon Equations (1)–(3), the barrier height values were found to increase from 0.54 to 0.69 eV (device-A), and 0.50 to 0.62 eV (device-B), whereas the ideality factor $n$ decreased from 5.9 to 4.8 (device-A), and 5.1 to 3.6 (devices-B) with testing temperatures ranging from 25 to 150 °C. These achieved parameters of diodes made by RF sputtering are similar to some previous works with the GaN-diodes made by MOCVD and techniques [1,3,18,28].

Similar to the analysis of the parameters for Schottky diodes, the effect of series resistance $R_s$ will influence and change the ideality factor $n$. They can be determined by using Cheung’s method. It is given by the equation below [13,32,33].

$$\frac{dV}{d(lnI)} = \frac{nkT}{q} + IR_s$$  \hspace{1cm} (5)

Based on Equation (5) and the plot of the $dV/d(lnI)$ versus $I$ from Figure 6, the series resistance $R_s$ and ideality $n$ can be calculated from the slope and the intercept [11,33,34]. Table 1 shows all detailed parameters of the I–V measurement for both devices tested at different temperatures. With the high indium content, the $R_s$ and $n$ values of device-B were smaller than device-A. They showed 412 Ω and 5.3 at 25 °C and decreased them to 133 Ω and 3.8 at 150 °C.

By comparison, with Cheung’s method, the modified Norde function was also used to define the effective barrier height of diodes. It is followed by the equation below [12,13,34–36].

$$F(V, I) = \frac{V}{\gamma} - \frac{kT}{q} \ln\left( \frac{I}{AA^*T^2} \right)$$  \hspace{1cm} (6)

The effective barrier height $\phi_B$ is followed by the equation below.

$$\phi_B = F(V_{\text{min}}) + \frac{V_{\text{min}}}{\gamma} - \frac{kT}{q}$$  \hspace{1cm} (7)
where the $F(V_{\text{min}})$ is the minimum value of $F(V,I)$, $\gamma$ is the first integer (dimensionless) greater than $\eta$, and $V_{\text{min}}$ is the corresponding voltage at $F(V_{\text{min}})$.

**Figure 5.** Forward and reverse $(I-V)$ characteristics of (a) device-A and (b) device-B tested in the temperature range of 25–150 °C.

**Figure 6.** Plots of $dV/d\ln(I)$ versus $I$ for (a) device-A and (b) device-B tested in the temperature range of 25 to 150 °C.
Figure 7a,b shows the plot of $F(V,I)$ versus $V$ of hetero junction diodes as a function of the different temperatures tested. By using Equations (6) and (7), the barrier height values were determined to be 0.56 eV (device-A) and 0.53 eV (device-B) at 25 °C, and reached 0.71 eV (device A) and 0.64 eV (device B) at 150 °C (Table 1).

![Graph showing $F(V)$ versus $V$ for device-A and device-B](image)

**Figure 7.** The $F(V)$ versus $V$ plot for (a) device-A and (b) device-B tested in the temperature range of 25 to 150 °C.

### 4. Discussion

Table 1 showed the detailed comparisons of the $I$–$V$ measurements for both hetero junction diodes. The smallest leakage current of $9.31 \times 10^{-7}$ A at $-5$ V was found in device-A tested at RT, while the smallest turn-on voltage was ~1.5 V. The highest current density of 0.814 A·cm$^{-2}$ were found in device-B at the forward bias of 20 V. At the reverse bias, the breakdown voltage of both devices was strongly blocked with the value at $-20$ V. The forward current increased quickly with the occurrence of the in content in the $p$–InGaN layer. With a higher holes carrier concentration of $2.53 \times 10^{17}$ cm$^{-3}$ and a smaller band gap of 2.92 eV, device-B showed the small turn-on voltage of 1.5 V, barrier heights of 0.5 eV (Cheung’s method), and 0.53 eV (Norde method), compared with all parameters of device-A [20].

The ideality factor $n$ of diodes decreased quickly, from 5.9 at 25 °C for device-A to 3.6 at 150 °C for device-B. For the Schottky diode, the turn-on voltage is often small, and the ideality factor $n$ is $<2$ [2,3,13]. In our diodes, the ideality factors had high values because of the present high series’ resistances, which were calculated from the slope of the linear region in Cheung’s method. In addition, from the band diagram in Figure 2, the barrier $\Delta E_v$ for holes was larger than that of $\Delta E_c$. Therefore, a higher valance band offset will have a high potential barrier, large turn-on voltage, high ideality factor, and high series resistance $R_s$. The high ideality factor of our diodes at RT also has been attributed to the high structural defect density, which serves as the trap-assisted generation-recombination centers. This procedure also influences the current transportation of hetero junction diodes [13,17,20]. The $R_s$ values also reduced from 876 Ω at 25 °C (device-A) to 133 Ω at 150 °C (device-B). The generations of
series resistance, interface states, and the voltage drop across the interfacial layer caused the slight difference between the ideality factor \( n \) calculated from the \( \ln I \) vs \( V \) and \( dV/d\ln(I) \) vs. \( I \) plots (Table 1).

Both hetero junction diodes had remarkable improvements as compared with some other homo and hetero junction diodes made by different techniques. Their deposition had epitaxial growth and was conducted at high temperatures above 800 °C by MOVCD [18, 19, 27-39]. Our devices had displayed the special \( I-V \) characteristics, which can be attributed to the low-temperature deposited at ~400 °C without using a buffer layer. Both our diodes showed the breakdown voltage above 20 V for a 1 mm²-sized contact.

| Temp (°C) | Leaksage Current (A) at −5 V | Barrier Height \( \phi_B \) (eV) | From \( I-V \) | Cheungs’ Function \( dV/d\ln(I) \) versus \( I \) |
|-----------|-----------------------------|--------------------------|-------------|-----------------------------|
| Device-A  |                             |                          |             |                             |
| 25        | \( 9.31 \times 10^{-7} \)    | 0.54                     | 5.9         | 876                         | 6.4               |
| 75        | \( 4.02 \times 10^{-6} \)    | 0.57                     | 5.6         | 683                         | 5.8               |
| 100       | \( 1.03 \times 10^{-5} \)    | 0.63                     | 5.4         | 549                         | 5.5               |
| 125       | \( 1.91 \times 10^{-5} \)    | 0.66                     | 5.0         | 467                         | 5.3               |
| 150       | \( 3.26 \times 10^{-5} \)    | 0.69                     | 4.8         | 413                         | 5.1               |
| Device-B  |                             |                          |             |                             |
| 25        | \( 3.38 \times 10^{-6} \)    | 0.50                     | 5.1         | 486                         | 5.3               |
| 75        | \( 9.92 \times 10^{-5} \)    | 0.53                     | 4.8         | 292                         | 4.9               |
| 100       | \( 3.43 \times 10^{-5} \)    | 0.57                     | 4.6         | 233                         | 4.7               |
| 125       | \( 7.81 \times 10^{-5} \)    | 0.60                     | 4.1         | 173                         | 4.2               |
| 150       | \( 2.64 \times 10^{-4} \)    | 0.62                     | 3.6         | 133                         | 3.8               |

K.E.F. Keskenler et al. made the \( n–ZnO/p–Si \) hetero junction diode by using a sol-gel spin technique [38]. The leakage current, barrier height, ideality factor, and series resistance of their diode were determined to be \( 4 \times 10^{-6} \) A at −1 V, 0.71 eV, 2.03, and 42.1 Ω at RT. Chirakkara et al. investigated the \( n–ZnO/p–Si \) (100) diode by pulsed laser deposition without using a buffer layer [39]. By \( I-V \) testing at the temperature range of 300–390 K, the barrier height increased from 0.6 (300 K) to 0.76 eV (390 K). Seng et al. reported the \( n-ZnO/p-GaN \) diode formed by the RF technique [40]. Their diode had showed the turn-on voltage of 2 V, the leakage current of \( 1.6 \times 10^{-5} \) A, and the series resistances of 102 Ω. Hsueh et al. investigated the \( n-Mg_{x}Zn_{1-x}O/p-GaN \) hetero-junction diode. Their ideality factors decreased from 3.86 to 7.00, with testing temperature increasing from 25 to 125 °C [41]. Compared to our previous works, for the sputtering-made \( n-In_{x}Ga_{1-x}N/p-Si \) devices with the similar area of 1-mm², the leakage current densities at −5 V were \( 5.96 \times 10^{-5} \) A·cm⁻² for \( n–GaN/p–Si \) and \( 2.81 \times 10^{-4} \) A·cm⁻² for \( n–In_{x}Ga_{1-x}N/p–Si \), respectively [20].

At this time, there is rarely a report about the Mg-doped–\( n_{i}Ga_{1-x}N \) film made by RF sputtering below 400 °C deposition and designed diode on the \( n–Si \) wafer. With the improvement of doping Mg in \( n_{i}Ga_{1-x}N \) film, our devices had the stable \( I-V \) characteristics up to the testing temperature of 150 °C. The \( p–In_{x}Ga_{1-x}N/n–Si \) diodes with the strong breakdown voltage of 20 V and leakage current of \( \sim 10^{-7} \) A will create the opportunity to develop the power devices.

5. Conclusions

\( p–In_{x}Ga_{1-x}N/n–Si \) diodes were successfully investigated by directly depositing the \( p-GaN \) and \( p–Mg\)-doped–\( n_{i}Ga_{0.05}N \) films on \( n–Si(100) \) wafers without using a buffer layer. The highest current density of \( 0.814 \) A·cm⁻² at 20 V and the smallest turn-on voltage of 1.5 V were found for \( p–InN_{x}Ga_{1-x}N/p–Si \) devices. Pt and Al for Ohmic contacts contributed to the high current density at the forward bias of hetero junction diodes. Both diodes also displayed the good \( I-V \) characteristics up to the testing temperature of 150 °C and the breakdown voltages of 20 V. By calculating the equations based on the TE mode as well as Cheungs’ and Norde method, the obtained electrical parameters were also compared. They can be referred to develop cost-effective solutions in electronic devices.
Coatings 2019, 9, 699

Author Contributions: Data Curation, P.T.C. and T.T.A.T.; Methodology, Writing—Original Draft, Investigation, P.T.C. and T.T.A.T.; Formal Analysis, Funding Acquisition, Writing—Review and Editing, P.T.C., T.T.A.T., V.S.N., Q.-P.P., V.K.N. and N.P.L.T.; Supervision, D.-H.K.

Funding: This research was funded by the Ministry of Science and Technology of the Republic of China under grant number 107-2221-E-011-141-MY3.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Baik, K.H.; Irokawa, Y.; Ren, F.; Pearton, S.J.; Park, S.S.; Park, S.J. Temperature dependence of forward current characteristics of GaN junction and Schottky rectifiers. Solid State Electron. 2003, 47, 1533–1538. [CrossRef]
2. Jang, J.S.; Kim, D.; Seong, T.Y. Schottky barrier characteristics of Pt contacts to n-type InGaN. J. Appl. Phys. 2006, 99, 073704. [CrossRef]
3. Reddy, V.R.; Prasanna, B.P.; Padma, R. Electrical Properties of Rapidly Annealed Ir and Ir/Au Schottky Contacts on n-Type InGaN. J. Metall. 2012, 1, 1–9. [CrossRef]
4. Cao, X.A.; Lachode, J.R.; Ren, F. Implanted p–n junction in GaN. Solid State Electron. 1999, 43, 1235–1238. [CrossRef]
5. Hickman, R.; Vanhove, J.M.; Chow, P.P.; Klaassen, J.J. GaN PN junction issues and developments. Solid State Electron. 2000, 44, 377–381. [CrossRef]
6. Tuan, T.T.A.; Kuo, D.H.; Albert, D.S.; Li, G.Z. Electrical properties of RF-sputtered Zn-doped GaN films and p-Zn-GaN/n-Si hetero junction diode with low leakage current of 10⁻³ A and a high rectification ratio above 10⁵. Mater. Sci. Eng. B 2017, 222, 18–25. [CrossRef]
7. Islam, M.R.; Sugita, K.; Horie, M.; Islam, A.Y. Mg doping behavior of MOVPE InₓGa₁₋ₓN (x~0.4). J.Cryst. Growth 2009, 311, 2817–2820. [CrossRef]
8. Yohannes, K.; Kuo, D.H. Growth of p-type Cu-doped GaN films with magnetron sputtering at and below 400 °C. Mater. Sci. Semicond. Process. 2015, 29, 288–293.
9. Ager, J.W.; Miller, N.; Jones, R.E. Mg-doped InN and InGaN Photoluminescence, Capacitance–Voltage and thermo-power measurements. Phys. Status Solidi 2008, 245, 873–877. [CrossRef]
10. Kuo, D.H.; Li, C.C.; Tuan, T.T.A.; Yen, C.L. Effects of Mg Doping on the Performance of InGaN Films Made by Reactive Sputtering. J. Electron. Mater. 2014, 44, 210–216. [CrossRef]
11. Tuan, T.T.A.; Kuo, D.H.; Li, C.C.; Li, G.Z. Effect of temperature dependence on electrical characterization of p-n GaN diode fabricated by RF magnetron sputtering. Mater. Sci. Appl. 2015, 6, 809–817.
12. Tuan, T.T.A.; Kuo, D.H.; Li, C.C.; Yen, W.L. Electrical and structural properties of Mg-doped InₓGa₁₋ₓN (x ≤ 0.1) and p-InGaN/n-GaN junction diode made all by RF reactive sputtering. Mater. Sci. Eng. B 2015, 193, 13–19.
13. Tuan, T.T.A.; Kuo, D.H.; Li, C.C.; Yen, W.L. Schottky barrier characteristics of Pt contacts to all sputtering-made n-type GaN and MOS diodes. Mater. Sci. Mater. Electron. 2014, 25, 3264–3270. [CrossRef]
14. Oh, M.; Lee, J.J.; Lee, L.K.; Oh, H.K. Electrical characteristics of Mg-doped p-GaN treated with the electrochemical potentiostatic activation method. J. Alloys Compd. 2014, 585, 414–417. [CrossRef]
15. Umeno, M.; Egawa, T.; Ishikawa, H. GaN-based optoelectronic devices on sapphire and Si substrates. Mater. Sci. Semicond. Process. 2001, 4, 459–466. [CrossRef]
16. Liou, B.W. Design and fabrication of InₓGa₁₋ₓN/GaN solar cells with a multiple-quantum-well structure on Si/Si(111) substrates. Thin Solid Films 2011, 520, 1084–1090. [CrossRef]
17. Lee, S.Y.; Kim, T.H.; Suh, D.I.; Park, J.E. An electrical characterization of a hetero-junction nanowire (NW) PN diode (n-GaN NW/pSi) formed by dielectrophoresis alignment. Phys. E 2007, 36, 194–198. [CrossRef]
18. Zebbar, N.; Kheireddine, Y.; Mokeddema, K.; Hafdadallah, A.; Kechouanea, M.; Aida, M.S. Structural optical and electrical properties of n-ZrO/p-Si heterojunction prepared by ultrasonic spray. Mater. Sci. Semicond. Process. 2011, 14, 229–234. [CrossRef]
19. Gad, A.E.; Hoffmann, M.W.G.; Hernandez, R.F. Coaxial p-Si/n-ZnO nanowire heterostructures for energy and sensing applications. Mater. Chem. Phys. 2012, 135, 618–622. [CrossRef]
20. Tuan, T.T.A.; Kuo, D.H.; Lin, K.; Li, G.Z. Temperature dependence of electrical characteristics of n-InₓGa₁₋ₓN/ p-Si heterojunctions made totally by RF magnetron sputtering. Thin Solid Films 2015, 589, 182–187. [CrossRef]
21. Li, C.C.; Kuo, D.H. Material and technology developments of the totally sputtering-made p/n GaN diodes for cost-effective power electronics. Mater. Sci. Mater. Electron. 2014, 25, 1942–1948. [CrossRef]
22. Kabra, V.; Aamir, L.; Malik, M. Low cost, p-ZnO/n-Si, rectifying nano heterojunction diode: Fabrication and electrical characterization. *Beilstein J. Nanotechnol.* **2014**, *5*, 2216–2221. [CrossRef] [PubMed]

23. Mohd, M.Z.; Baharin, A.; Hassan, Z.; Abu, H.; Abdullah, M.J. MBE growth of GaN pn-junction photodetector on AlN/Si substrate with Ni/Ag as Ohmic contact. *Superlattices Microstruct.* **2013**, *56*, 35–44. [CrossRef]

24. Cho, S.G.; Nahm, T.U.; Kim, E.K. Deep level states and negative photoconductivity in n-ZnO/p-Si hetero-junction diodes. *Appl. Phys.* **2014**, *14*, 223–226. [CrossRef]

25. Wagner, J.; Ramakrishnan, A.; Behr, D.; Maier, M. Composition dependence of the band gap energy of In$_x$Ga$_{1-x}$N layers on GaN ($x \leq 0.15$) grown by metal-organic chemical vapor deposition. *MRS. Internet. J. Nitri. Semi. Res.* **1999**, *4*, 106–111. [CrossRef]

26. Bedia, F.Z.; Bedia, A.; Benyoucef, B.; Hamzaoui, S. Electrical characterization of n-ZnO/p-Si heterojunction prepared by spray pyrolysis technique. *Phys. Procedia* **2014**, *55*, 61–67. [CrossRef]

27. Baydogan, N.; Karacasu, O.; Cimenoglu, H. Effect of annealing temperature on ZnO:Al/p-Si heterojunctions. *Thin Solid Films* **2012**, *520*, 5790–5796. [CrossRef]

28. Li, J.L.; Schubert, E.F.; Graff, J.W.; Osinsky, A.; Schaaff, W.F. Low-resistance ohmic contacts to p-type GaN. *Appl. Phys. Lett.* **2000**, *76*, 2728–2730. [CrossRef]

29. Ponce, A.R.; Olguín, D.; Calderón, H.I. Calculation of the effective masses of II-VI semiconductor compounds. *Superficies y Vacío* **2003**, *16*, 26–28.

30. Suzuki, M.; Ueno, T. First-Principles Calculation of Effective Mass Parameters of Gallium Nitride. *Jpn. J. Appl. Phys.* **1995**, *34*, 3442–3446. [CrossRef]

31. Crowell, C.R. The richardson constant for thermionic Emission in schottky barrier diodes. *Solid State Electron.* **1965**, *8*, 395–399. [CrossRef]

32. Kumar, A.; Vinayak, S.; Singh, R. Micro-structural and temperature dependent electrical characterization of Ni/GaN Schottky barrier diodes. *Curr. Appl. Phys.* **2013**, *13*, 1137–1142. [CrossRef]

33. Cheung, S.K.; Cheung, N.W. Extraction of Schottky diode parameters from forward current-voltage characteristics. *Appl. Phys. Lett.* **1986**, *49*, 85–87. [CrossRef]

34. Benamara, Z.; Akkal, B.; Talbi, A.; Gruzza, B. Electrical transport characteristics of Au/n-GaN Schottky diodes. *Mater. Sci. Eng. C* **2006**, *26*, 519–522. [CrossRef]

35. Tuan, T.T.A.; Kuo, D.H. Characteristics of RF reactive sputter-deposited Pt/SiO$_2$/n-InGaN MOS Schottky diodes. *Mater. Sci. Semicond. Process.* **2015**, *30*, 314–320. [CrossRef]

36. Norde, H. A modified forward I-V plot for Schottky diodes with high series resistance. *J. Appl. Phys.* **1979**, *50*, 5052–5055. [CrossRef]

37. Urgessa, Z.N.; Dobson, S.R.; Talla, K.; Murape, D.M. Optical and electrical characteristics of ZnO/Si heterojunction. *Phys. B* **2014**, *439*, 149–152. [CrossRef]

38. Keskenler, E.F.; Tomakina, M.; Doğan, S. Growth and characterization of Ag/n-ZnO/p-Si/Al heterojunction diode by sol–gel spin technique. *J. Alloy Compd.* **2013**, *550*, 129–132. [CrossRef]

39. Chirakkara, S.; Krupanidhi, S.B. Study of n-ZnO/p-Si (100) thin film heterojunctions by pulsed laser deposition without buffer layer. *Thin Solid Films* **2012**, *520*, 5894–5899. [CrossRef]

40. Shen, Y.; Chen, X.; Yan, X.S. Low-voltage blue light emission from n-ZnO/p-GaN heterojunction formed by RF magnetron sputtering method. *Curr. Appl. Phys.* **2014**, *14*, 345–348. [CrossRef]

41. Hsueh, K.P. Temperature dependent current–voltage characteristics of n-Mg$_2$Zn$_{1-x}$O/p-GaN junction diodes. *Microelectron. Eng.* **2011**, *88*, 1016–1018. [CrossRef]

© 2019 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).