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Effects of thermal annealing on Ti/Al Ohmic contacts on quaternary n-$Al_{0.08}In_{0.08}Ga_{0.84}N$ alloy film

Alaa J. Ghazai[1*], H. Abu Hassan[2], Z. Hassan[2], and A. SH. Hussein[3]

[1]*Physics Department, Science College, Thi-Qar University, Iraq.*

[2]*Nano-Optoelectronics Research and Technology Laboratory, School of Physics, Universiti Sains Malaysia, 11800 Penang, Malaysia.*

[3]*Al-Faris State Company, Research and Development Department, Ministry of Industry and Minerals, Iraq.*

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Abstract

Ohmic contacts of Ti/Al have been fabricated on n-type $Al_{0.08}In_{0.08}Ga_{0.84}N$ to determine the specific contact resistivity (SCR) using transmission line method (TLM). The measurements are performed on Ti/Al contacts which have been annealed to various temperatures from 400-700 °C with times of 5, 15 and 35 minutes, where the electrical behaviors of each condition are compared. For relatively different annealing temperatures, substantial differences of the SCR values are observed between different duration samples. The changes in the surface morphology after the annealing treatment were examined using scanning electron microscopy (SEM). The study has resulted in producing contact from the Ti (200 nm)/Al (50 nm) metallization scheme with the lowest specific contact resistivity of ρ_c= 0.054 Ωcm^2 after annealing in nitrogen for 10 minutes (cumulated time of 15 minutes) at 400 °C.

Keywords: Quaternary AlInGaN, Ohmic contact, SCR, Annealing temperature, TLM.
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1. Introduction

The III-nitrides form a continuous alloy system with direct band gap ranging from 6.2 eV for (AlN) to 0.7 eV for (InN) [1-3]. The alloy system has long been viewed as a promising material system for optical device applications between visible and ultraviolet (UV) wavelength spectra; and also for various high temperature, high power and high frequency electronic devices, due to their direct wide bandgap characteristic.

In order to realize AlInGaN devices with good performance, it is essential to have high quality ohmic contacts to this wide bandgap material. In most of the work that has been carried out on ohmic contacts, high temperature annealing has been performed in order to achieve low specific contact resistivity [4]. This process is however, often not desirable, especially in heterostructure devices.

*) For correspondance, E-mail: alaaphys74@gmail.com

On the other hand, multi-layer metallization has been interesting to researchers because of its capability of producing phase formation, which promotes good ohmic contacts. Thus, the contact resistance for the Ti/Al bi-layer metallization was lowered by the factor of 1.6 using a DC magnetron sputtered Ti/Al (35/115 nm) bi-layer metallization [5]. The specific contact resistances between the range of 1.0×10^{-5} Ω.cm^2 to 1.0×10^{-8} Ω.cm^2 which are good enough for optical and electronics devices have been reported [6, 7].

In this work, we report our initial investigation of the Ti/Al bi-layer contacts on the n-type doped $Al_xIn_yGa_{1-x-y}N$ grown on silicon (111) substrate using molecular beam epitaxy (MBE) technique. The electrical stability of the contacts at various annealing temperatures (400–700 °C) was investigated.

2. Experimental Procedure

A commercial $Al_{0.08}In_{0.08}Ga_{0.84}N$ alloy grown on silicon substrate Si (111) was employed. The contact resistance was measured using the transmission line method (TLM). For metallization, the $Al_{0.08}In_{0.08}Ga_{0.84}N$ samples were first cleaned to remove native oxides which maybe presence in the semiconductor that can increase the contact resistance of ohmic contacts. To provide oxide free and defect free for device application the controlling of metal/semiconductor interface is very important. The native oxide was removed in the NH_4OH:H_2O=1:20 solution for 10 min, then rinsed with distilled water. Subsequently, the samples were dipped into HF: H_2O=1:50 solution for 10 s then rinsed with distilled water. The cleaned samples were then chemically etched in boiling aqua regia of HCL: HNO_3=3:1 for 10 min to reduce the amount of oxygen (O) and carbon (C) contamination of the $Al_{0.08}In_{0.08}Ga_{0.84}N$ surface. Wafers were then blown dry with compressed air after cleaning and are ready for the next fabrication step. First, titanium (Ti) with 50 nm was RF-sputtered onto the $Al_{0.08}In_{0.08}Ga_{0.84}N$ through a metal mask, followed by the evaporation of 200 nm capping layer of Al. Fig. 1 shows the metal mask used to fabricate the transmission line method (TML) pads before and after metallization.

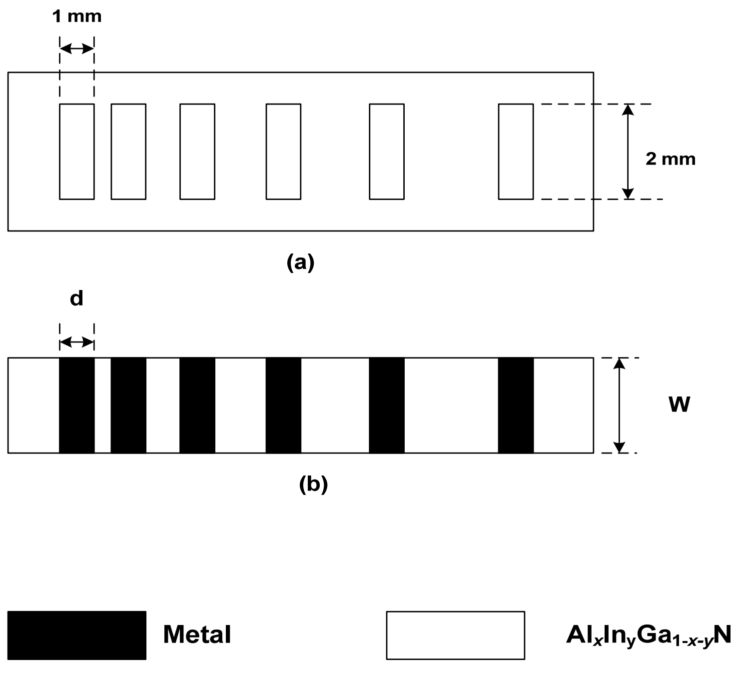

Fig. 1: The metal mask used to fabricate the transmission line method (TML) pads a) before metallization, b) after metallization.

The TLM pads were designed to be 2 mm (W, width) × 1 mm (d, length) in size and with spacing (l) between the pads were 0.3, 0.4, 0.6, 0.9, and 1.3 mm. The specific contact resistivity, ρ_c were determined from the plot of the measured resistance against the spacing between the TLM pads. The linear-square method was used to fit a straight line to the experimental data. The samples were annealed under flowing nitrogen gas environment in the furnace at 400, 500, 600, and 700 °C for 5 min. Similar heat treatments were carried out for additional annealing times of 10 and 20 min to investigate the thermal stability of the contacts. The nitrogen gas was purged at a mass flow rate of 5 L min^{-1}. The changes in the surface morphology after the annealing treatment were examined using scanning electron microscopy (SEM).

3. Results and Discussion

3.1 Calculation of Specific Contact Resistivity (SCR)

The total resistance R_T between two points of a sample having a metallic conductor laying on a semiconductor to make an ohmic contact can be divided into three components. It is the resistance of the metallic conductor R_m, the contact resistances R_c and the semiconductor resistance R_s; therefore, the total resistance is given as

$$R_T = 2R_m + 2R_c + R_s \tag{1}$$

The semiconductor resistance, R_s is determined by the sheet resistance, R_{sh} of the semiconductor layer. It does not include the resistance of the metal-semiconductor contact only, but it also includes a portion of the metal immediately above the metal-semiconductor interface. A part of the semiconductor below that interface, current crowding effect and any interfacial oxide or other layer that may be present between the metal and the semiconductor are also included. The specific contact resistivity ρ_c determines the use of the rectangular transmission line method (TLM) that has widely been used in the characterization of ohmic contacts to semiconductors. TLM consists of rectangular metal pads placed at different distances as shown in Fig. 2. The resistance R_i ($R_i = R_T$) is measured between two contact pads with spacing l_i, and can be written as:

$$R_i = \frac{R_{sh} l_i}{W_c} + \frac{2R_{sk} l_t}{W_c} \tag{2}$$

$$R_i = \frac{R_{sh} l_i}{W_c} + 2R_c \tag{3}$$

where l_i is the spacing between two pads, W_C is the width of the contact pad, R_c is the resistance due to the contact, R_{sh} is sheet resistance of the semiconductor layer outside the contact region, R_{sk} is the sheet resistance of the layer directly under the contact, and L_t is the transfer length.

Fig. 2 shows R_i as a function of l_i which produces a straight line with the slope R_{sh}/W_C, and $2R_C$ is yielded from the intercept at y-axis. The intercept at x-axis gives L_x:

$$L_x = \frac{2R_{sk} lt}{R_{sh}} \tag{4}$$

where $L_x \approx 2L_t$ with the assumption that $R_{sh}=R_{sk}$. On the other hand, the assumption of an electrically long contact $d >> L_t$ enabled the relationship $\rho_c=R_{sh}L_t^2$ to be invoked which leads to $\rho_c=R_cWL_t$ [8].

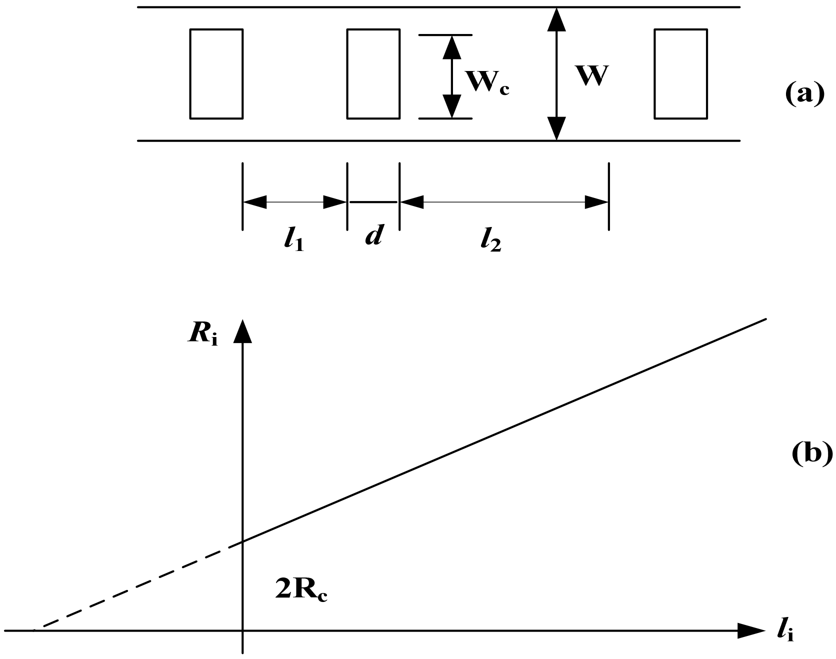

Fig. 2: (a) Rectangular TLM pattern and (b) plot showing the variation of the resistance with respect to the gap distance.

Fig. 3 shows the *I-V* characteristics for Ti/Al contacts of $Al_{0.08}In_{0.08}Ga_{0.84}N$ layer at thermal annealing temperature from (400-700 °C) which revealed that the sample with thermal treatment of 400 °C under annealing durations of 10 minutes (cumulated 15 minutes) has Ohmic behavior. This particular annealing temperature was considered the optimum annealing temperature for AlInGaN-based ohmic devices which produced the lowest SCR. Lowering the contact resistance and improved linearity may come from more intimate contact of metal with semiconductor or any new phases having lower work function. Intimate contact leads to more current flow across the interface by breaking up some of interfacial contamination between metal and semiconductor [8].

The specific contact resistivities of Ti/Al contact on $Al_{0.08}In_{0.08}Ga_{0.84}N$ epilayer are summarized in Table 1. From Fig. 3 and Table 1, the contact specific resistivity ρ_c reaches a minimum of 0.054 $\Omega.cm^2$ when the annealing temperature is 400 °C with cumulated time of 15 minutes. Increasing the annealing time degraded the contacts due to the formation of an insulating Al_xO_y layer on the surface of the Al for higher annealing time [4, 9]. As a result, measurements of the contact resistance at the $Al_{0.08}In_{0.08}Ga_{0.84}N$ interface became more difficult and caused the contact resistance to be artificially high.

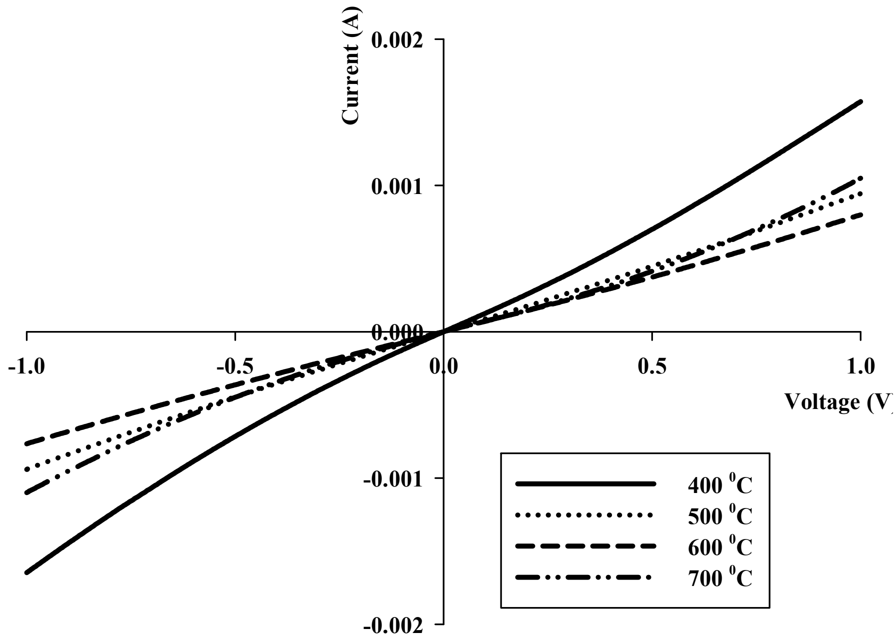

Fig. 3: I-V characteristics for Ti/Al contacts of $Al_{0.08}In_{0.08}Ga_{0.84}N$ layer at thermal annealing temperature from (400-700 °C) for 15 minutes.

Table 1: Specific contact resistivities of the Ti/Al contact on the $Al_{0.08}In_{0.08}Ga_{0.84}N$ epilayer.

Annealing Temperature	Specific Contact Resistivity (Ωcm^2)		
	Time/(cumulated time)		
	5 min	10 min/(15 min)	20 min/(35 min)
400 C	0.644	0.054	5.85
500 C	1.96	1.88	-
600 C	4.7	2.82	-
700 C	6.08	5.57	-

The lowest specific contact resistivity of 0.054 $\Omega.cm^2$ is due to the formation of either TiN or AlN, as follows: First, the chemical reaction at the Ti/ $Al_{0.08}In_{0.08}Ga_{0.84}N$ interface would form a thin layer of TiN which have a low work function of 3.74 eV [4], and hence satisfying the condition to form an ohmic contact to n- $Al_{0.08}In_{0.08}Ga_{0.84}N$. Second, Al which is a low work function metal of 4.28 eV, diffuse through Ti during annealing and reaches the n- $Al_{0.08}In_{0.08}Ga_{0.84}N$ surface. The Al then reacts with the surface of the AlInGaN to form a thin AlN layer at the interface. This processes results in N vacancies, which yields heavily doped interface, resulting in a tunneling current responsible for the ohmic contact formation. However, with increasing annealing temperatures from 500 to 700 °C the specific contact resistivity increased, this is due to the degradation of the interface between the contact and sample surface. In addition, at high annealing temperature, islands are formed on the surface from the metals themselves which created the much rougher surfaces that can be seen in Fig. 4 which shows the SEM imaging for Ti/Al contacts of $Al_{0.08}In_{0.08}Ga_{0.84}N$ layer at thermal annealing temperature from (400-700 °C) for 10 minutes (cumulated 15 minutes). The segregation of the metal contact can be seen with increasing thermally treatment which leads to high SCR and non ohmic behavior.

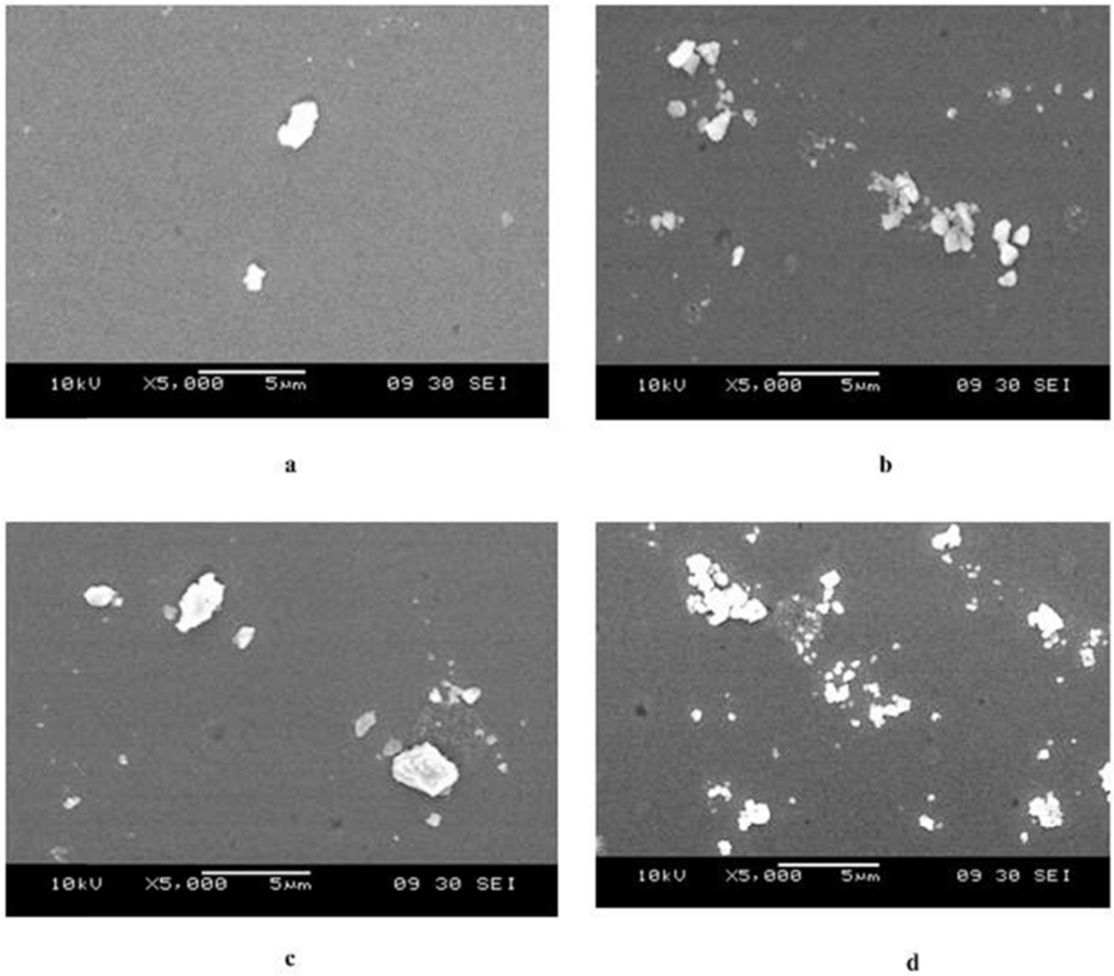

Fig. 4: SEM images for Ti/Al contacts of $Al_{0.08}In_{0.08}Ga_{0.84}N$ layer at thermal annealing temperatures of (a) 400 °C (b) 500 ºC (c) 600 ºC and (d) 700 ºC.

4. Conclusion

Ti/Al contacts were fabricated using RF-sputtering method on n-type $Al_{0.08}In_{0.08}Ga_{0.84}N$ semiconductor to determine the capability of this specific contact to serve as ohmic contact. Then, the as-deposited contacts were thermally annealed in nitrogen ambient at temperatures ranging from 400-700 °C. The changes in the surface morphology after the annealing treatment were examined using scanning electron microscopy (SEM). The duration of the annealing process were also varied to analyze the changes in the ohmic characteristics. The study has resulted in producing a contact from Ti (200 nm)/Al (50 nm) metallization scheme with a lowest specific contact resistivity of ρ_c= 0.054 Ωcm^2 after annealing in nitrogen for 10 minutes at 400 °C.

Acknowledgments

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