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Effect of thermal annealing on electrical and structural properties of *Ni/Au/n-GaN* Schottky contacts

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ABSTRACT

The effects of thermal annealing on the electrical and structural properties of *Ni/Au* Schottky contacts to *n*-type *GaN* were investigated by current–voltage (*I–V*) and capacitance–voltage (*C–V*) characteristics, atomic force microscopy (*AFM*), and X-ray photoelectron spectroscopy (*XPS*) depth profile analysis. The metallization patterns on *GaN* grown by metal organic chemical vapor deposition (*MOCVD*) on a (0001) sapphire substrate were formed using the photolithography and lift-off techniques. The Schottky barrier height (*SBH*) for these contacts was obtained from *I–V* and *C–V* measurements. The value of *SBH* of the as-deposited contacts was found to be 0.560 ± 0.004 eV (from *I–V*) and 0.622 ± 0.018 eV (from *C–V*) with an ideality factor of 1.856 ± 0.085. The values of *SBH* obtained from the *C–V* measurements were found to be higher than that of obtained from the *I–V* measurements. This case was attributed to the presence of the lateral inhomogeneities of the barrier height. However, the values of *SBH* slightly increase after the annealing temperatures at 100, 200, 300, 400 and 500 °C. The *SBH* of the *Ni/Au* Schottky contact for the other annealing temperature of 600 °C was 0.617 ± 0.005 eV. The highest value of *SBH* for *Ni/Au* Schottky contact was obtained after annealing at 700 °C and the value was 0.910 ± 0.019 eV. The variations in the chemical composition of the contacts with the annealing process were examined by *XPS* depth profile analysis.

1. Introduction

Recently, group III-nitride semiconductors have been intensively studied for optoelectronic devices as well as high-temperature and high-power electronic devices due to their properties of wide band gap, high electron saturation velocity, large breakdown field and thermal stability [1–6]. Visible light-emitting diodes, ultraviolet (*UV*) photodetectors and high-electron-mobility transistors (*HEMTs*) have been fabricated by several researchers [5–9]. High quality ohmic and Schottky contacts are demanded in all of these devices. One of the key questions for both types of contacts is the poor reproducibility of the results obtained in different laboratories for similar metallization [10–12]. Another fundamental problem for Schottky contacts is the occurrence of high reverse leakage currents [10–12]. The barrier height of metal contacts to group III-nitride semiconductors strongly depends on the difference between the work function of the metal and the electron affinity of the semiconductor for *GaN* and other highly ionic semiconductors. Titanium-based metallization schemes have been used to form ohmic contacts to *GaN* [12–14]. During annealing solid phase reactions between *Ti* and *GaN* have been reported. Nitrogen out-diffusing from the *GaN* lattice to form *TiN* and residual nitrogen vacancies act as donors in *GaN* [13]. The interfacial area thus becomes heavily doped providing the configuration needed for tunneling contacts [13].

Schottky barrier heights (*SBHs*) of a variety of elemental metals including *Au* [11], *Pt* [15], *Pd* [16], *Ni* [3] have been investigated. Published reports indicated that a barrier height was in between 0.53 and 1.05 eV which is dependent on the types of metals used. Wang et al. [15] investigated the thermal annealing effects on Schottky barrier height of the *Pt/n-GaN* Schottky contacts. They reported that the as-deposited *Pt/n-GaN* Schottky contact has a *SBH* and ideality factor of 0.82 eV and 1.40 respectively. The *SBH* of *Pt/n-GaN* Schottky contact was slightly increased after annealing at 500 °C and then degreased greatly after annealing above 600 °C. The temperature dependence change of the *SBHs* was attributed to changes of surface morphology of *Pt* films on the surface and variation of nonstoichiometric defects at the interface vicinity. Further improvements should be made in the Schottky contact to extract *GaN* robust material stability and to realize the long term integrity of *GaN* related devices. Therefore, various rare metals, alloys and

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multilayer systems have also been investigated and thermal annealing of the diodes in particular has been reported to be quite effective in some cases [17–22]. Dobos et al. [19] investigated the structural and electrical properties of *Au* and *Ti/Au* contacts on *n-GaN* and showed that the contacts were rectifying up to 700 °C, and the highest barrier height of 1.07 eV was obtained for *Au* single layer. Nickel also has a relatively large work function of 5.15 eV [23]. *Ni* is chemically more active than *Pt*, which can provide better adhesion on *GaN* [18]. The Schottky barrier height of *Ni/Au/n-GaN* contacts has been obtained with the values in between 0.58 and 1.07 eV by several research groups [20–22]. The obtained variation in the barrier height is mainly attributed to differences of material characteristics and measurement methods used [16–20].

However, the realization of these devices not only depends on the quality of the material properties, but also relies seriously on the performance of metal contacts. Fabrication of electrical contacts to these devices requires the deposition of metals on semiconductors with subsequent annealing. Interfacial reactions between metals and *GaN* are important since the electrical properties of such contacts are influenced by the phases formed directly on the *GaN* surface because of process annealing or high-temperature service. High quality, thermally stable contacts to *GaN*-based semiconductors are required for the fabrication of reliable and high-performance devices. The structure of metal/semiconductors interfaces is of vital importance to all microelectronic and opto-electronics devices.

In this work, we have investigated the thermal annealing effects on the electrical and structural properties of the *Ni/Au* contacts on *n-GaN*. Annealing treatment was performed at a temperature ranging from 100 to 800 °C in increments of 100 °C for 2 min in argon ambient. The thermal stability of the *Ni/Au* Schottky contacts was evaluated by considering the change of the *SBH* with the annealing temperature. The variations in the chemical composition of the contacts with the annealing temperature were examined by *XPS* depth profile analysis.

2. Experimental procedure

In this study, unintentionally doped (uid) *n*-type *GaN* epitaxial layers grown by metalorganic chemical vapor deposition (*MOCVD*) on a sapphire (0001) substrate were used. The structure of the samples consists of a 2.5 μm thick *n*-type *GaN* layer on top of a 3.5 μm thick nucleation *GaN* layer on a sapphire substrate.

The *GaN* samples were cleaned consecutively acetone, methanol, trichloroethylene, deionised water (18 MΩ) 5 min. using ultrasonic agitation in each step. The samples were then dried with high-purity nitrogen. After cleaning organic residuals, the substrates were dipped in aqua regia to remove the native oxide from the front surface of the substrate and boiling *KOH* solution (0.5 M) to reduce the surface roughness, respectively. Stripe of a bilayer of *Ti/Al* (25 nm/105 nm) was deposited using magnetron dc sputtering for *Ti* and thermal evaporation for *Al* on *n-GaN* as ohmic contact. The contact was annealed at 850 °C for 1 min in flowing high purity (5 N) argon gas in a quartz tube furnace. The *Ni/Au* (30 nm/50 nm) metallization was then deposited using magnetron dc sputtering for *Ni* and thermal evaporation for *Au.* Conventional photolithography lift-off technique was used to deposit metalized dots with a diameter of 0.5 mm for Schottky contacts. All contact metals were deposited in the same environment without breaking the vacuum using a high vacuum metallization system (NANOVAK-NVTS400) and back pressure better than 1×10^{-6} mTorr and 20 mTorr during the thermal evaporation and sputtering process respectively. AZ 400K Developer, AZ 5214 E image reversal photoresist and optical mask with UV lamp were used in conventional photolithography technique. Following the metallization, metals lift-off was performed in acetone.

In order to study the thermal annealing effects of *Ni/Au* Schottky contacts on *n-GaN*, samples were annealed in a quartz tube furnace for 2 min. in flowing argon (5N) ambient from 100 to 800 °C with step of 100 °C. Prior to the all annealing process, tube furnace carefully swept with high argon flow to prevent undesired oxidation of metals at high temperatures and residual humidity effects (if exist).

The current–voltage (*I–V*) and capacitance–voltage (*C–V*) measurements of the *Ni/Au/n-GaN* Schottky contacts were accomplished by employing a computer-controlled *HP 4140B* picoamperemeter and *Agilent E4980A* Impedance Analyzer, respectively. The surface morphology of the annealed Schottky contacts was investigated using atomic force microscopy (*AFM*). The variations in the chemical composition of the contacts with the annealing process were examined by *XPS* depth profile analysis. Prior to *XPS* measurements the *GaN* substrates were ex situ degreased in isopropanol, next washed in distilled water and dried in air, then were mounted with copper strips on molybdenum plates. The *XPS* spectra for the as-deposited and annealed *SBDs* were recorded using a Thermo Scientific system equipped with a monochromatic $Al\ K_{\alpha}$ source and 180° double focusing hemispherical analyzer. X-ray spot size was 250 μm, take-off angle 60° and back pressure better than 8×10^{-8} mTorr. *XPS* depth profiles recorded by alternating sputtering with argon ion-sputter (2 keV energy). The ion beam was raster over an area of 1×1 mm^2. Due to the insulating nature of substrate, a defocused low energy electron gun was used to stabilize the surface potential. *XPS* peak refinement and peak defining were performed with Avantage Data System.

3. Results and discussion

3.1. Electrical properties of Ni/Au Schottky contacts on n-GaN

Fig. 1 shows the forward and reverse *I–V* characteristics of the as-deposited and annealed *Ni/Au/n-GaN* Schottky diodes. For the as-deposited *Ni/Au* Schottky contact, the leakage current at -1.0 V is 7.82×10^{-5} A. For the diode annealed at temperature 400 °C, 500 °C and 600 °C, the leakage currents are 3.11×10^{-5}, 1.50×10^{-5} and 1.71×10^{-6} A at -1.0 V, respectively. It can be seen from Fig. 1 that the thermal annealing effect was small under the annealing temperature of 500 °C. However, the annealing effect on the leakage current reduction was revealed to be more significant at the annealing temperature of 700 °C. The reverse leakage current was drastically reduced to the order of 10^{-7} A. Therefore, the annealing temperature of 700 °C is crucial for the studied *Ni/Au* Schottky contacts.

The experimental *I–V* curves were analyzed using the thermionic emission theory (*TET*). According to the *TET*, the current

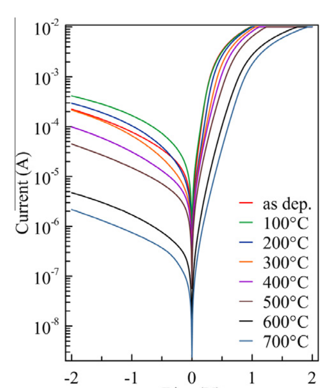

Fig. 1. The current–voltage characteristics of the as-deposited and annealed (*Ni/Au*)/*n-GaN* Schottky diodes.