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Electrical characterization of Ni/$Al_{0.09}Ga_{0.91}N$ Schottky barrier diodes as a function of temperature

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ABSTRACT

The current–voltage characteristics (*I–V*) of Ni/$Al_{0.09}Ga_{0.91}N$ Schottky barrier diodes (*SBDs*) prepared with a photolithography and lift-off techniques were investigated in the wide temperature range of 100–310 K. The *I–V* characteristics of the devices were analyzed on the basis of the thermionic emission (TE) theory. An abnormal decrease in the experimental effective barrier height and an increase in ideality factor with a decrease in the temperature were observed. The temperature dependence of the effective Schottky barrier height (SBH) was explained with the presence of the laterally barrier height inhomogeneity at the metal-semiconductor interface. In addition, the modified Richardson plots were used to determine experimental Richardson constants in the three temperature regions.

1. Introduction

GaN-based semiconductors with a wide band-gap have been extensively used for high power electronic device applications due to their unique physical properties, such as a large breakdown field, a high thermal conductivity, and a high saturated electron velocity [1–5]. Especially, an improvement in the quality of epitaxial layers grown by metalorganic chemical vapor deposition (MOCVD) and molecular beam epitaxy (MBE) technologies have made possible the realization of a number of GaN-based devices. Several research groups [6–8] demonstrated encouraging operations of high electron mobility transistors (HEMTs) and metal-semiconductors field effect transistors (MESFETs) with outstanding high dc transconductance and high cut-off frequency. Experimental studies of the gate current leakage in AlGaN HEMTs show that the excess gate leakage strongly influences the gate control and power consumption [8]. The noise performance of $Al_xGa_{1-x}N$/GaN HEMTs is also dependent on gate leakage current. Therefore, Schottky contacts with a sufficient barrier height and low leakage current are critical factors for the realization of GaN-based HEMTs. It is well known that the barrier height is most important parameter of the metal/semiconductor contact, electron current controls with both width of the depletion region and effective SBH in the semiconductor across the interface [9]. In order to fabricate reliable and high-performance electronic devices, it is still indispensable to clarify electronic properties at metal/GaN and AlGaN interfaces, such as a relatively large gate leakage current, drain current instability accompanied with the current collapse after a bias stress, and somewhat poor reproducibility of those characteristics.

The future improvement of aforementioned devices is based on a good understanding of the MS interface of Schottky contact. Analysis of the *I–V* characteristics of Schottky barrier diodes (SBDs) only at room temperature does not give detailed information about their conduction process or nature of barrier formation at the *MS* interface. The temperature dependence of the *I–V* characteristics allows us to understand different aspects of conduction mechanisms. Recently, several research groups have reported

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on AlGaN/GaN SBDs [10–15]. Jung et al. [13] have studied electrical and structural characterizations of AlGaN/GaN heterostructures. This device with Pt/Au Schottky contact displayed a barrier height of 0.76 eV and an ideality factor of 4 at 20 °C. They reported that a high ideality factor can be attributed the trap-assisted tunneling or surface barrier thinning. Lim et al. [14] have investigated temperature dependence of current–voltage characteristics and apparent barrier height for Ni/AlGaN/GaN-based SBDs with lateral geometry. They have concluded that temperature dependence of barrier height can be explained by invoking inhomogeneous Schottky contacts. Recently, Arehart et al. [15] have investigated the carrier trapping properties and current transport behavior of Ni/n-$Al_{0.30}Ga_{0.70}N$ Schottky diodes by a combination of deep level optical spectroscopy (DLOS), thermally based deep level transient spectroscopy (DLTS), current–voltage–temperature (*I*–*V*–*T*), and internal photoemission (IPE) measurements. They have stated that the dominant current transport mode of Ni/AlGaN SBDs can be explained by a thermionic-field and field emission model based on the results of DLTS, DLOS, DLTS and *I*–*V*–*T* measurements.

In this work, the current–voltage characteristics of Ni/$Al_{0.09}Ga_{0.91}N$ SBDs fabricated with photolithography and lift-off techniques on $Al_{0.09}Ga_{0.91}N$ epitaxial layer grown by MOCVD on a high purity semi insulating 4H-SiC substrate were investigated over the temperature range of 100–310 K. The values of the effective barrier height and the ideality factor were obtained from the forward-biased *I*–*V* curves by using the thermionic emission (TE) theory. The temperature dependence of the effective Schottky barrier height (SBH) of Ni/$Al_{0.09}Ga_{0.91}N$ SBDs was interpreted on the basis of existence of three set Gaussian distributions of SBHs around mean values due to the effective SBH inhomogeneities at the metal/semiconductor interface.

2. Experimental procedure

In this study, unintentionally doped (uid) n-type $Al_{0.09}Ga_{0.91}N$ epitaxial layers grown by MOCVD on a 4H-SiC substrate were used. As shown in Fig. 1, the epistructure of the wafer consists of 2 nm thin layer of GaN cap layer for protection purposes, uid $Al_{0.09}Ga_{0.91}N$ layer with a thickness of 21 nm, AlN layer with a thickness of 3.0 nm, Fe doped GaN buffer layer with a thickness of 1.8 μm, and a 4H-SiC high-purity semi-insulating substrate with a resistivity of 10^5 Ω cm. The substrates were cleaned consecutively with acetone, methanol, trichloroethylene, deionised water (18 MΩ) 5 min. using ultrasonic agitation in each step. The substrates 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 then, boiled in a 0.5 M KOH solution to reduce the surface roughness. The Ti/Al (25 nm/105 nm) metallization was deposited using magnetron dc sputtering for Ti and thermal evaporation for Al in the same environment without breaking the vacuum and a photolithography/lift-off process was used to pattern the contacts. The contacts were annealed at 850 °C for 1 min in flowing high purity (6 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 and a photolithography/lift-off process was used to pattern to form Schottky contacts with a diameter of 0.5 mm (Fig. 1).

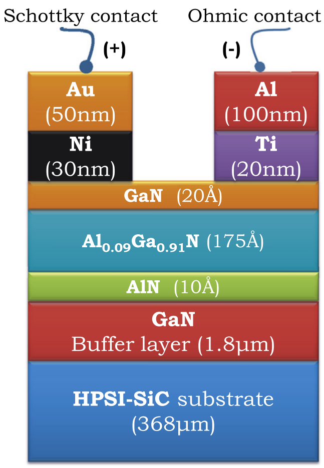

Fig. 1. Cross section of Ni/$Al_{0.09}Ga_{0.91}N$ SBD.

The *I*–*V*–*T* measurements of the Ni/$Al_{0.09}Ga_{0.91}N$ SBDs were accomplished by employing a computer-controlled HP 4140B picoamperemeter and liquid nitrogen cooled cryostat in the temperature range of 100–310 K by steps of 10 K in the dark. The temperature accuracy is better than ±1 K in the temperature range of 100–310 K.

3. Results and discussion

3.1. The current–voltage measurements of Ni/$Al_{0.09}Ga_{0.91}N$ Schottky barrier diodes

Fig. 2 shows the experimental semi-logarithmic forward and reverse bias *I*–*V* characteristics of Ni/$Al_{0.09}Ga_{0.91}N$ SBDs in the temperature range of 100–310 K. It can be seen in Fig. 2 that Ni/$Al_{0.09}Ga_{0.91}N$ SBD has a good rectifying property at the temperature range studied and they are obviously temperature-dependent. Furthermore, an increase of the current was observed by increasing temperature as predicted by the TE theory.

According to the TE theory, the forward bias current–voltage characteristics of a Schottky barrier diode for forward voltage in excess of a few kT/q can be expressed as [9]

$$I = I_s \exp\left[\frac{qV}{nkT}\right] \tag{1}$$

where I_s is the saturation current and given by

$$I_s = AA^*T^2 \exp\left(-\frac{q\Phi_{b0}}{kT}\right) \tag{2}$$

where V, n, T, A, A^*, q, k, and Φ_{b0} are the applied bias voltage, the ideality factor, the temperature in Kelvin, the effective diode area, the effective Richardson constant, the electronic charge, the Boltzmann constant, and the effective SBH at zero bias determined from the *I*–*V* data, respectively. The theoretical value of the effective Richardson constant can be calculated using $A^* = 4\pi qm^*k^2/$