Thin Solid Films 550 (2014) 564–568

Contents lists available at ScienceDirect

Thin Solid Films

journal homepage: www.elsevier.com/locate/tsf

Fermi-level depinning at metal/GaN interface by an insulating barrier

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ARTICLE INFO

Article history:
Received 18 March 2013
Received in revised form 10 November 2013
Accepted 12 November 2013
Available online 20 November 2013

Keywords:
Gallium nitride
Fermi level
Spintronics
Schottky contact

ABSTRACT

We have investigated Schottky contacts on GaN and observed that Fermi level pinning is dominant at the metal/GaN interface with a pinning factor of 0.23. A methodology to solve the problem by introducing a thin layer of MgO between the metal and the semiconductor is demonstrated here. It is observed that the insertion of a thin layer of the insulator prevents the metal wave-function penetration into the semiconductor band gap which in turn helps in the Fermi level depinning for GaN. We have particularly demonstrated the Fermi level depinning for ferromagnetic Schottky contact Fe and shown its usefulness for electrical spin injection and detection. The resistance-area product of an as deposited Fe/GaN contact is found to be too high for efficient spin injection and detection. It is improved considerably by using a 3 nm layer of MgO and the effective barrier height is reduced to 0.4 eV. We have further investigated the influence of low work function metal Gd and found it is possible to do barrier height engineering when deposited in conjunction with other metals.
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1. Introduction

GaN semiconductor has received a lot of attention for its immense potential for various devices and their applications [1–7]. GaN based heterostructures including alloys of various compositions with Al and In have found many usages. GaN based light emitting diodes have already found their applications in solid-state lighting. Blue laser is also a very attractive choice for high power applications in many areas [1,2]. GaN based high electron mobility transistor (HEMT) and metal–semiconductor field effect transistor (MESFET) have turned out to be the key elements in millimeter wave integrated circuits [3–7]. GaN based spintronic devices have the potential for room temperature operation owing to the long spin transport length [8]. It is envisaged that GaN may replace GaAs based devices in many applications. Ohmic and Schottky contacts are the two integral parts for any device. While p- and n-Ohmic contacts on GaN are reasonably well established, Schottky contacts are still being investigated particularly for transistors, spintronic and novel device applications. One of the major problems in Schottky contacts is the Fermi level pinning, where the barrier height is pinned with respect to the band-gap of the semiconductor independent of the work function of the metal. Here we have developed a methodology for Fermi level depinning at the metal/GaN interface, which may be useful for many devices. Schottky contacts form the gate terminal for HEMTs and MESFETs and can act as efficient spin-injector and detector for semiconductor spintronic devices. Though Ni Schottky contacts have been the choice for transistors, there is no such standard contact designed for spintronic applications. Here, we have investigated Fe, Co and Ni Schottky contacts on GaN and shown the effectiveness of Fermi level depinning using an insulating layer of MgO. It is also experimentally demonstrated by others that the presence of an insulating layer of MgO improves electrical injection and detection of spin polarized carriers in semiconductors [9]. These contacts can be used for efficient spin injection and detection–injection and detection in semiconductors. We have also fabricated and characterized control devices without insulating barrier to confirm the Fermi level depinning in these devices. The effect of low work-function metal Gd is also investigated. The same procedure for Fermi level depinning can be followed for devices using Schottky contacts with other metals.

2. Device fabrication and characterization

The samples are grown on a sapphire substrate using metalorganic chemical vapor deposition (MOCVD) technique. A thick undoped GaN buffer layer (7 μm) is grown first, which is followed by the growth of a heavily Si doped n-layer of 2 μm as the active area. The Schottky diodes are also fabricated on moderately doped GaN as control devices. However, we focus on heavily doped samples for electrical spin injection and detection in GaN. A ring shaped ohmic contact Ti/Al/Ni/Au (20/150/50/125 nm) is deposited by electron-beam (e-beam) evaporation under high vacuum and annealed using rapid-thermal-annealing technique at a temperature of 775 °C for 1 min. A second layer lithography is done to expose the center of the annular region and buffered hydrofluoric acid cleaned to remove the native oxide. Ferromagnetic contacts (Fe, Co and Ni) of 50 nm thickness and Ti/Au (10/125 nm) are then deposited by e-beam evaporation and lift-off technique for

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http://dx.doi.org/10.1016/j.tsf.2013.11.041

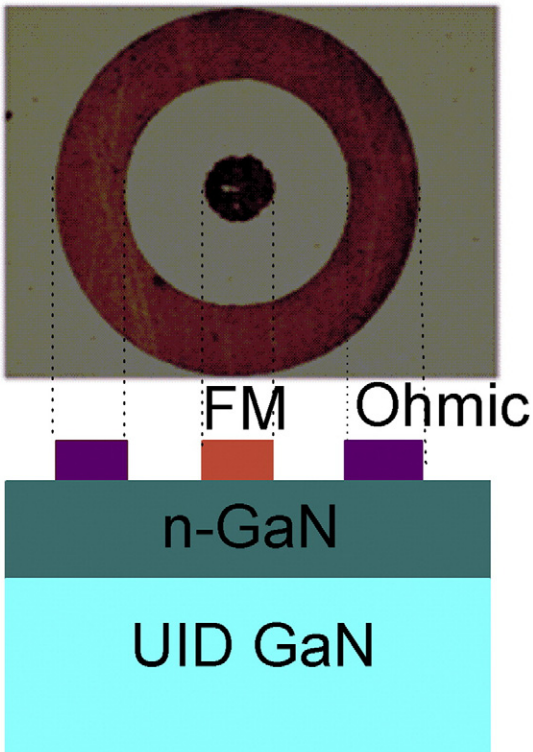

Fig. 1. (a) A schematic and a microphotograph of a typical Schottky diode.

the Schottky diodes. Another set of devices is fabricated with a thin layer of MgO (3 nm) in between Fe and GaN. A schematic of the device structure and micro-photograph of the device are shown in Fig. 1. Temperature dependent current–voltage *I*–*V* and capacitance–voltage *C*–*V* characteristics are measured using a probe station and source-measuring-units.

3. Results and discussion

The capacitance (*C*) versus reverse bias voltage (*V*) characteristics of the as-deposited Fe, Co and Ni Schottky diodes are measured at 100 kHz and temperature 300–475 K. The zero-bias barrier height Φ_{B0} and GaN doping concentration (N_D) are determined by plotting C^{-2} versus *V* as shown in Fig. 2, and using the depletion approximation [10],

$$\frac{1}{C^2}=\frac{2}{e\varepsilon_s A^2 N_D}\left(V_0+V\right) \tag{1}$$

where *A* is the effective area of the device, *e* is the electronic charge, ε_s is the electrical permittivity of GaN ($=9.5\,\varepsilon_0$), *T* is the temperature and V_0 is related to Φ_{B0} and effective density of states in the conduction band of GaN (N_C) through the equation,

$$\Phi_{BO}=V_0+\frac{K_BT}{e}+\frac{K_BT}{e}\ln\left(\frac{N_C}{N_D}\right) \tag{2}$$

where K_B is the Boltzmann's constant. The zero bias barrier height, as determined using Eqs. (1) and (2), is shown in Table 1. The doping density is estimated to be $N_D \sim 2\times10^{18}$ cm^{-3} for all the devices and it matches well with the Hall measurement data. Temperature dependent current–voltage (*I*–*V*) characteristics are shown in Fig. 3(a) and (b) for 300 K and 475 K, respectively. The forward bias characteristics are analyzed using ideal thermionic emission model [10,11],

$$I=AA*T^2\exp\left(\frac{-\Phi_{B0}}{K_BT}\right)\text{ x }\exp\left(\frac{eV}{nK_BT}\right) \tag{3}$$

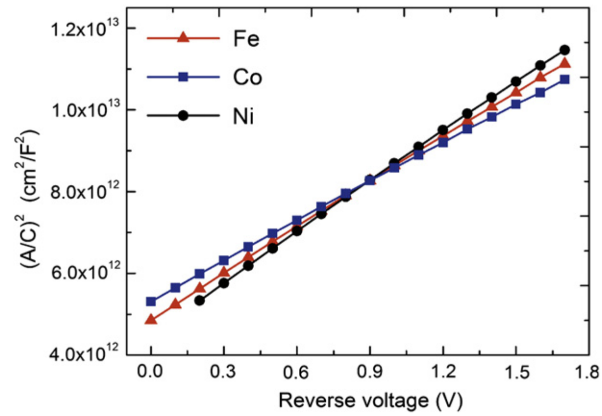

Fig. 2. Room temperature capacitance (*C*) versus reverse bias voltage (*V*) characteristics of FM/n-GaN Schottky diodes at 100 kHz frequency. The extracted doping concentration N_D matches well with the Hall measurement data.

where *A*∗ is the Richardson's constant, and *n* is the ideality factor. The voltage independent prefactor in Eq. (3) corresponds to the reverse saturation current. Φ_{B0} and *n* as determined from experimental data and Eq. (3) show a strong variation with temperature (Table 1). The Richardson's plot is also non-linear and a single characteristic barrier height for the Schottky diodes cannot be extracted. The difference in estimation of barrier height between *I*–*V* and *C*–*V* measurements can be explained using barrier inhomogeneity during current flow [12–14]. The barrier inhomogeneity in the Schottky diode under study is confirmed using Tung's theoretical prediction of linear dependence of Φ_{B0} on *n* (Fig. 3(c)) [13]. It is observed that with an appropriate correction for barrier inhomogeneity, barrier height measured using *I*–*V* characteristics matches well with that determined using *C*–*V* measurements, and it remains weakly dependent on the metal work function. The Richardson's plot also becomes linear when the effect of barrier inhomogeneity is taken into account which further confirms the presence of barrier inhomogeneity in these devices.

The extracted barrier height is relatively large and weekly dependent on the metal work function, which can be attributed to the Fermi level pinning at the metal/semiconductor interface. According to the intrinsic model, the Schottky pinning parameter *S*, defined as $d\Phi_{B0}$ / d*W* (where *W* is the metal work function), is mainly determined by the continuum of metal-induced-gap-states (*MIGS*) which are evanescent states of the metal wave functions continued into the forbidden gap of the semiconductor. To ascertain Fermi level pinning at the metal/GaN junction, Schottky barrier heights extracted from the *C*–*V* analysis are plotted as a function of metal work function in Fig. 4. The Schottky barrier heights for Pt, Pd, Ag, and Au are also plotted alongside against the metal work function, which are obtained from literature [15,16]. It can be seen that there is no clear trend in the barrier height with increasing metal work function indicating that Fermi level pinning is dominant in these devices. The barrier height is weekly dependent on the metal work function having $S=0.23$. The effect of Fermi level pinning at the metal/GaN contacts is also investigated by several other groups [16–20] whose inferences are summarized in Table 2. To depin the Fermi level, we have deposited a thin layer of MgO between Fe

Table 1
Schottky parameters extracted from temperature dependent diode characteristics.

Ferromagnet *T* (K)	Fe (300–475 K)	Co (300–475 K)	Ni (300–475 K)
Φ_{B0} (*eV*) (*C*–*V* data)	1.30–1.25	1.50–1.43	1.12–1.02
Φ_{B0} (*eV*) (*I*–*V* data)	0.75–1.02	0.85–1.15	0.55–0.80
n (*I*–*V* data)	2.20–1.40	2.25–1.40	2.34–1.45

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