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Letter

Tunneling coefficient for GaN Schottky barrier diodes

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ABSTRACT

In this report, the tunneling coefficient (C_T) for GaN Schottky barrier diodes is extracted for analytical computation of the reverse leakage current. The extraction method is based up on fitting experimental data to the analytical equation by adjusting Schottky barrier height (ϕ_{BN}) to account for defects. The tunneling coefficient $(7.1 \pm 0.74) \times 10^{-12}$ cm^2 V^{-2} for GaN Schottky contacts is found to be independent of the size of the contact inspite of the presence of defects.

1. Introduction

Gallium Nitride (GaN) is an attractive material for Schottky power rectifiers due to its high breakdown electric field [1]. In recent years, substantial effort has been focused on the study of electrical properties of GaN Schottky diodes [2]. The leakage current density must be studied to determine the level of the power dissipation of these devices in the reverse blocking mode. The dominant mechanisms of the reverse leakage current are defined as a function of electric field and Schottky Barrier Height from the analytical formula of the field emission model, the thermionic emission model, and the barrier lowering model [3]. With increasing reverse bias voltage, the leakage current increases significantly due to the tunneling process induced by the high electric field at the Schottky interface. It is also well known that GaN material has a high defect density. Several groups have suggested that defects, in particular dislocations, might play an important role in the reverse bias leakage current [4,5]. If many defects are present near the surface region, electrons can go through the reduced barrier height by defect-assisted tunneling [2]. Due to the barrier thinning caused by the unintentional surface-defect donors, the tunneling transport mechanism enhances which leads to large leakage currents through Schottky interfaces [6]. Hsu et al. [7] found that reverse current distribution is highly nonuniform and most current flows through screw and mixed dislocations. Miller et al. [8] also studied the temperature dependence of the reverse leakage current and concluded that field emission is the dominant mechanism for lower temperatures. For temperatures of 275–400 K, thermally activated two-step trap assisted mechanism was identified. Bhatnagar et al. [9] have proposed a leakage current model for SiC Schottky barrier diodes based on localized Schottky barrier height reduction due to the presence of epitaxial layer defects at the metal interface. A similar model is applicable to GaN Schottky barrier diodes.

With addition to defects, electric field enhancement is also taking place at the edges of power devices. This high electric field enhances leakage current due to Schottky barrier lowering and tunneling. Therefore tunneling coefficient (C_T) can be used to model the leakage current enhanced by the high electric field at the edges and the defects.

A tunneling coefficient (C_T) of 8×10^{-13} cm^2 V^{-2} for Silicon Carbide Schottky rectifiers has been found to yield an increase in leakage current by six orders of magnitude in agreement with the experimental data [10]. A similar analytical model is desirable for GaN Schottky barrier diodes, but the tunneling coefficient (C_T) is not known for GaN. Today's simulators such as Synopsys-TCAD cannot simulate leakage current properly, because they do not have a model for Schottky Barrier Lowering and Tunneling for GaN. In this paper, the tunneling coefficient is extracted for analysis of the reverse leakage current density for GaN Schottky barrier diodes.

2. Experimental

Schottky barrier diodes were fabricated on 0.5 μm n-type GaN grown on a bulk GaN wafer with a 2 μm n+GaN buffer layer grown

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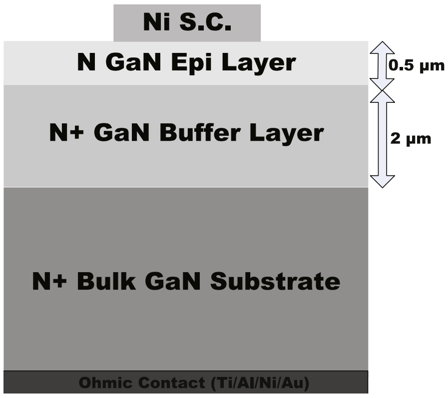

Fig. 1. Structure of the GaN Schottky diode.

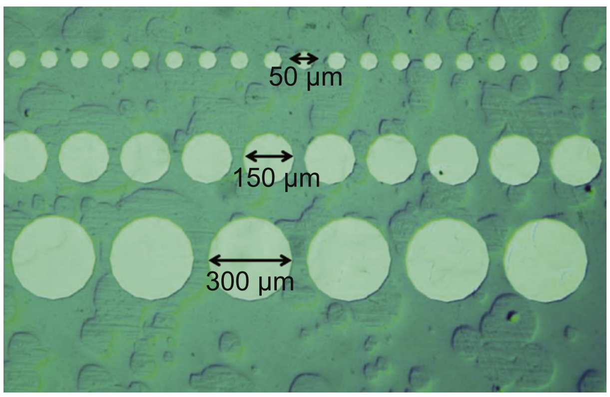

Fig. 2. The 50 μm, 150 μm and 300 μm Schottky contact patterns on the GaN wafer.

by metal-organic chemical vapor deposition (MOCVD). The wafer was cleaned using Trichloroethylene (TCE) (5 min), Acetone (5 min), Methanol (5 min) and HCl:H_2O (1:1), 5 min, followed by DI water flushing/N_2 blow dry. After cleaning, the ohmic contact of Ti(20 nm)/Al(200 nm)/Ni(50 nm)/Au(50 nm) was deposited by E-beam on the back of the wafer and annealed at 750 °C in N_2 for 30 s by rapid thermal annealing (RTA). Nickel Schottky contacts with thickness of 100 nm were deposited by DC magnetron sputtering through a shadow mask. A cross-section of the diode is shown in Fig. 1. Three sizes of the Schottky diodes with diameters of 50 μm, 150 μm and 300 μm were fabricated as shown in Fig. 2. Defects can be seen in this figure. Current–voltage (*I–V*) and capacitance–voltage (*C–V*) measurements were performed to obtain the doping concentration of the epitaxial layer and the barrier height of the Schottky contact as shown in Fig. 3 [11]. It should be noted that the barrier height measured by *I–V* measurement is approximately 0.1 eV smaller than the one obtained from *C–V* measurement for the 50 μm diameter Ni Schottky contact diode. The difference in barrier height values measured by *I–V* and *C–V* measurements is due to the image force lowering and indicates the presence of a very thin interfacial layer between the metal and GaN [12–14].

3. Tunneling coefficient extraction

The reverse leakage current of a Schottky barrier diode increases due to both the Schottky barrier lowering and the tunneling processes induced by the high electric field at the Schottky interface with increasing reverse bias [3]. The leakage current has been reported to increase by approximately five orders of magnitude [15]. To explain this rapid increase, it is necessary to include the field emission (tunneling) component of the leakage current.

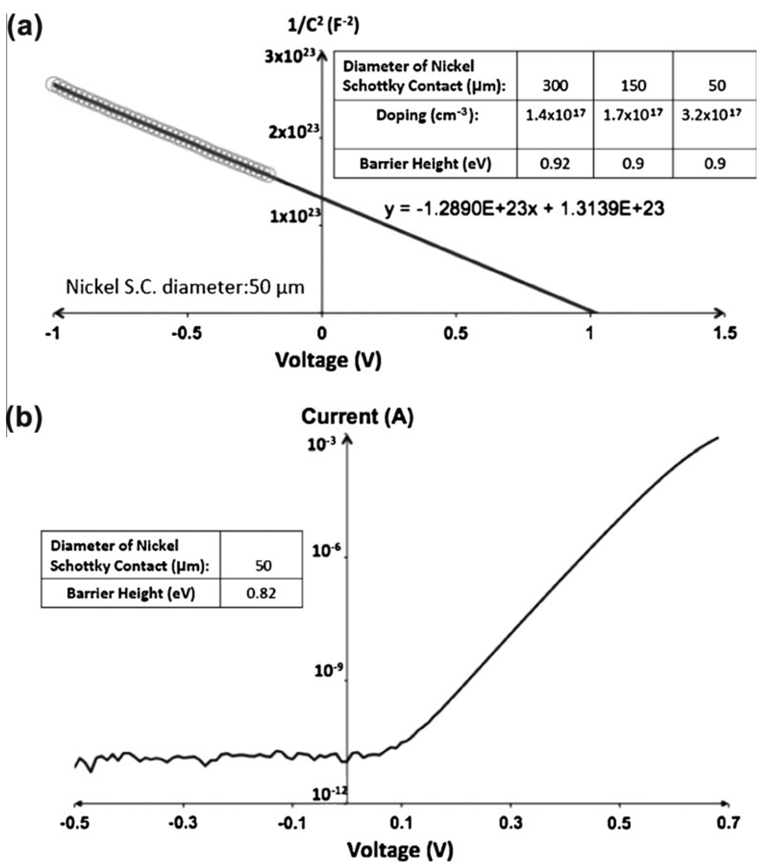

Fig. 3. (a) Capacitance–voltage. (b) Current–voltage characteristics of GaN Schottky diodes.

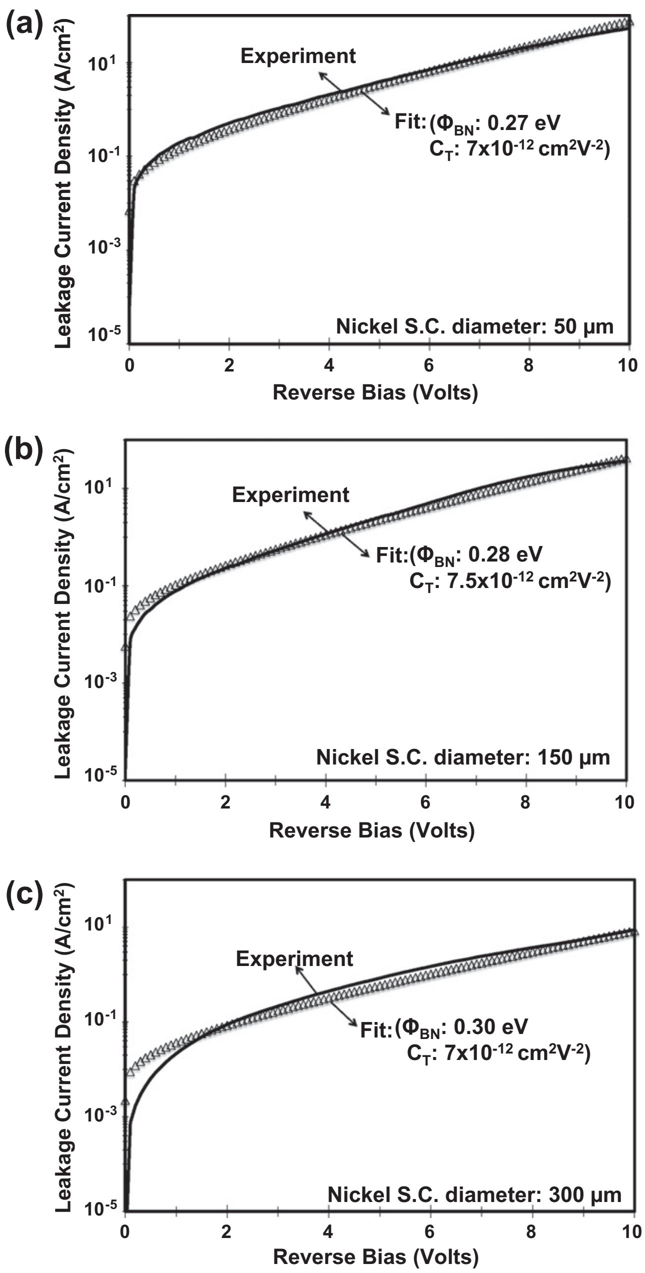

Fig. 4. Fitting curves for (a) 50 μm, (b) 150 μm and (c) 300 μm diameter Nickel Schottky contacts.

The leakage current density with the thermionic emission model can be written as [10]:

$$J_L = AT^2\left(e^{-q\phi_{BN}/kT}\right)\left(e^{q\Delta\phi_{BN}/kT}\right)\left(e^{C_T E_M^2}\right) \tag{1}$$

where C_T is the tunneling coefficient, A is the Richardson constant (24 A cm^{-2} K^{-2}, [16]), T is the temperature, k is Boltzmann's constant, ϕ_{BN} is the Schottky barrier height, $\Delta\phi_{BN}$ is the reduction of the barrier height due to the image force lowering phenomenon. The Schottky barrier lowering is given by:

$$\Delta\phi_{BN} = \sqrt{\frac{qE_M}{4\pi\epsilon_S}} \tag{2}$$

where E_M is the maximum electric field at the metal–semiconductor interface given by:

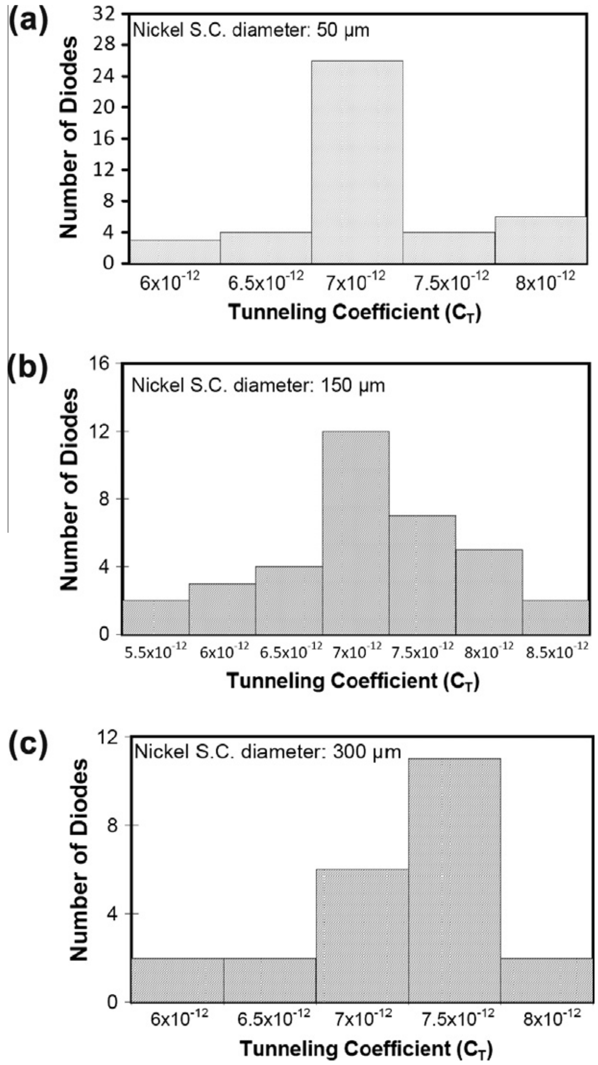

Fig. 5. C_T distribution curves for (a) 50 μm, (b) 150 μm and (c) 300 μm diameter Nickel Schottky contacts.

$$E_M = \sqrt{\frac{2qN_D(V_R + V_{bi})}{\epsilon_S}} \tag{3}$$

The tunneling coefficient (C_T) for GaN Schottky barrier diodes was extracted by fitting the above analytical equations to the experimentally measured reverse I–V characteristics of the GaN Schottky barrier diodes. The leakage current at small reverse bias voltages varies widely among the diodes due to the presence of defects [2]. However, the rate of increase in leakage current with increasing voltage was found to be similar indicating that a single C_T value is applicable in spite of the presence of defects. To extract C_T, the Schottky barrier height (ϕ_{BN}) was adjusted for each diode to account for defects. Examples of fitting curves for different size Schottky barrier diodes with mean C_T values are shown in Fig. 4. A good fit for the increase in leakage current with voltage is observed in all cases validating the use of the above analytical model for the reverse leakage current. Presence of defects results in lowering of the Schottky barrier height in localized regions resulting in different values for the effective barrier height for each diode [9] [17]. More than 100 diodes were measured in this study. The statistical distribution of the extracted C_T values for different diameter Nickel Schottky contacts is provided in Fig. 5. From this data, the mean value and standard deviation for C_T was extracted (Table 1). The mean value (7×10^{-12} cm^2 V^{-2}) of the extracted C_T is found

Table 1
C_T values for different size Nickel Schottky contact diodes.

Size of Nickel Schottky contact (μm)	Number of measured diodes	Mean value of ϕ_{BN} (eV)	ϕ_{BN} standard deviation	Mean value of C_T ($cm^2 V^{-2}$)	C_T standard deviation
50	43	0.28	±0.03	6.91×10^{-12}	$\pm 0.52 \times 10^{-12}$
150	35	0.30	±0.01	7.10×10^{-12}	$\pm 0.74 \times 10^{-12}$
300	23	0.31	±0.01	7.20×10^{-12}	$\pm 0.53 \times 10^{-12}$

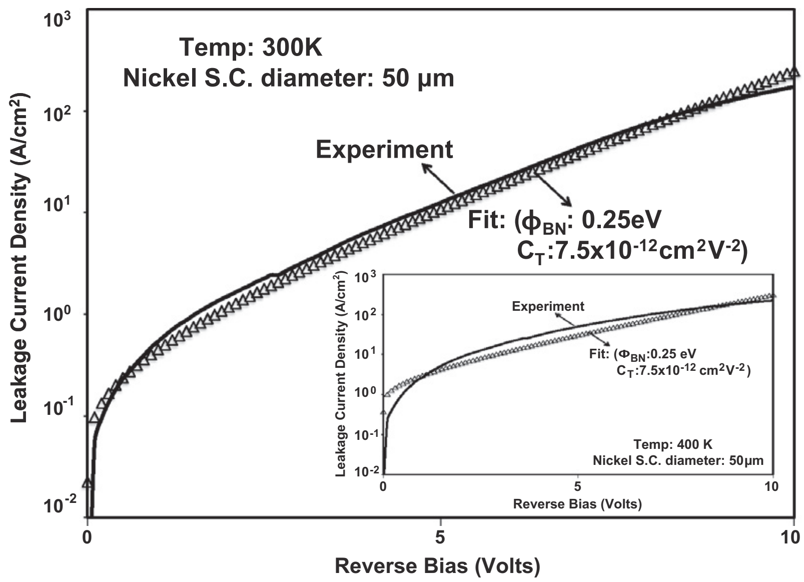

Fig. 6. C_T fitting curves for 50 μm diameter Nickel Schottky contact at 300 K and 400 K.

to be independent of the size of the GaN Schottky diode. The mean value of the (ϕ_{BN}), shown in Table 1, was extracted and observed that it is also independent of the size of the GaN Schottky diode. From this data, it can be concluded that there is a uniform defect distribution across the wafer. It can also be concluded that leakage is due to the enhanced electric field at the edges of the diodes and results in an increase in the leakage current. Due to the increase in leakage current, it looks like the value of ϕ_{BN} is reduced.

To further validate the model, measurements of the leakage current are provided at two temperatures in Fig. 6 for the same GaN Schottky diode. It can be observed that the analytical model (Eq. (1)) can be used to predict the experimentally observed increase in the leakage current with no change to the barrier height or the tunneling coefficient.

4. Conclusion

By looking at the extracted mean C_T values for different size GaN Schottky barrier diodes in Table 1, it can be concluded that the extracted C_T is independent of the size of the contact in spite of the presence of defects. Based upon this, the tunneling coefficient ($(7.1 \pm 0.74) \times 10^{-12}$ $cm^2 V^{-2}$) extracted in this paper can be generally utilized for analytical computation of the increase in leakage current with reverse voltage for GaN Schottky barrier diodes. The extracted C_T value for GaN is found to be an order of magnitude higher than the one for SiC.

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