Superlattices and Microstructures 120 (2018) 508–516

Contents lists available at ScienceDirect

Superlattices and Microstructures

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

Double Gaussian barrier distribution of permalloy ($Ni_{0.8}Fe_{0.2}$) Schottky contacts to n-type GaN

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ARTICLE INFO

Keywords:
GaN
Permalloy
Schottky contact
Current-voltage characteristics
Low-frequency noise

ABSTRACT

The temperature-dependent current-voltage (*I-V*) characteristics of permalloy ($Ni_{0.8}Fe_{0.2}$) Schottky contacts to n-type GaN have been investigated. Magnetization measurements revealed the ferromagnetic behavior of $Ni_{0.8}Fe_{0.2}$ film on n-type GaN. The Schottky barrier parameters, such as the barrier height and ideality factor, determined by thermionic emission depended on the measurement temperature, suggesting the presence of lateral inhomogeneity in the Schottky barrier. The experimental data modified by the thermionic emission model along with a Gaussian distribution of the barrier heights indicated the presence of a double Gaussian barrier distribution in the $Ni_{0.8}Fe_{0.2}$/n-type GaN Schottky contact. The mean barrier heights and standard deviations for each Gaussian distribution were 0.84 & 1.32 eV and 0.10 & 0.17 eV over temperature range of 125–200 K and 225–400 K, respectively. The noise spectral density of the current fluctuations measured as a function of frequency (*f*) at room temperature followed a $1/f^{\gamma}$ dependence with a γ value close to unity, irrespective of the applied forward bias. The 1/*f*-type noise was attributed to the barrier inhomogeneity existing at the $Ni_{0.8}Fe_{0.2}$/n-type GaN Schottky interface as revealed from the temperature-dependent *I–V* characteristics.

1. Introduction

Gallium nitride (GaN) has attracted considerable interest in the research and development of optoelectronic devices, and high speed and high power electronic devices owing to its high-frequency operation and high break-down field [1–3]. These devices include photo-diodes [4], light emitting diodes [5], laser diodes [6], high-electron mobility transistors [7], and hetero-junction field-effect-transistors [8]. In addition, GaN possesses very small spin-orbit coupling because of its wide band gap, which may be useful for spintronic applications [3,9,10]. In particular, GaN-based spintronic devices would be beneficial compared to that of GaAs-based devices because of the long spin transport length in this material [11–13].

Generally, ferromagnetic metals are a natural choice for spin injection into semiconductors [9,10,14,15]. In particular, an understanding of the nature of its contact is essential for efficient spin injection into a semiconductor and spin transport through an interface between ferromagnetic metals and semiconductors, which can provide fundamental and practical insight into the spin injection process. The temperature-dependent current-voltage (*I–V)* characterization allows a better perception of the detailed

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https://doi.org/10.1016/j.spmi.2018.06.019
Received 8 June 2018; Accepted 8 June 2018
Available online 14 June 2018

features of the ferromagnetic metal/semiconductor interface. Several attempts have been made to examine the temperature dependent electrical characterization of ferromagnetic metal/GaN Schottky barrier diodes [3,16–19]. Kumar et al. [3] investigated the temperature dependent *I–V* characteristics of the Fe/n-type GaN Schottky barrier diode over the range of 100–300 K, found that an inhomogeneous Fe/GaN interface affects the spin relaxation time in GaN in spintronic applications. They also observed the dominance of the diffusion currents, higher ideality factors, and lower barrier heights with a reduced level of barrier inhomogeneity in the temperature range, 100–200 K. Ejderha et al. [18] fabricated Co/n-type GaN Schottky diodes and found that the Schottky barrier parameters such as barrier height and ideality factor depend on the measurement temperature, indicating the presence of lateral inhomogeneity in the Schottky barrier. Adari et al. [19] analyzed the junction parameters and transport mechanism of ferromagnetic metals, such as Fe, Co, and Ni Schottky contacts to heavily doped GaN. They showed that thermionic emission with a Gaussian distribution for barrier inhomogeneity can explain the data for high bias voltages. They also reported that at low bias voltages, a direct tunneling transport mechanism contributes significantly to Fe/n-type GaN Schottky contact, providing the possibility for Fe Schottky diodes to be used for electrical spin injection and detection, whereas trap-assisted tunneling dominates current transport in Co/n-type GaN and Ni/n-type GaN Schottky diodes. Although there have been several reports available on the electrical characterization of ferromagnetic metal contacts to GaN, the reports on the magnetic properties of the ferromagnetic contacts to GaN are quite scarce [15,20,21] and in particular being focused on the Fe thin films on GaN. For instance, Gao et al. [15] investigated the impact of annealing on the morphological, structural and magnetic properties of the epitaxially grown Fe films on GaN from 300 to 950 °C and found thermally stable up to a temperature of 700 °C. Kim et al. [20] systematically investigated the changes in magnetic moment and in-plane magnetic anisotropy of Fe/GaN structure in correlation with the thickness of the Fe films on GaN. From the results obtained, it is expected to contribute towards the realization of future Fe/GaN spintronic devices. Garrido et al. [21] analyzed the morphological, magnetic and electrical properties of Fe Schottky contacts prepared in situ on *n*-GaN (0001) by molecular beam epitaxy and suggested the Fe/GaN contacts qualify for spin injection.

Permalloy is a ferromagnetic Ni—Fe alloy with high magnetic permeability, low coercivity, near zero magnetostriction, and significant anisotropic magnetoresistance [22] widely employed in spintronics for spin current injection and detection. The properties of permalloy can be modified by altering the Fe to Ni ratio in the composition, making it attractive for tuning the performance of spintronic devices. Despite the prominent features of permalloy, however, there were no reports available on the fabrication and characterization of permalloy Schottky contacts to GaN. In the present work, GaN Schottky rectifiers were fabricated using permalloy ($Ni_{0.8}Fe_{0.2}$) films, investigated its magnetic properties and the nature of the $Ni_{0.8}Fe_{0.2}$/GaN interface was demonstrated using the temperature dependent *I–V* characteristics over the temperature range of 175–400 K. The $Ni_{0.8}Fe_{0.2}$/GaN structure exhibited ferromagnetic behavior at room temperature. The Schottky barrier inhomogeneity at the interface between $Ni_{0.8}Fe_{0.2}$ and n-type GaN with a double Gaussian barrier distribution leads to temperature dependency of the barrier height and ideality factor. Furthermore, the presence of barrier inhomogeneity of $Ni_{0.8}Fe_{0.2}$ Schottky contact to n-type GaN was confirmed by *1/f* noise measurements.

2. Experimental details

Fig. 1(a) presents a schematic diagram of the $Ni_{0.8}Fe_{0.2}$/n-type GaN Schottky diode. The Si-doped n-type GaN wafers (2 μm in thickness) grown on a C-plane Al_2O_3 sapphire substrate with a metal organic chemical vapor deposition (MOCVD) technique were used as the starting material. The carrier concentration in the n-type GaN layer was obtained as $4.07 \times 10^{17}\ cm^{-3}$, which was measured by Hall measurements and matched the value provided by the manufacturer. First, a n-type GaN wafer was degreased ultrasonically in warm trichloroethylene, followed by acetone and methanol for 5 min each. The wafer was then dipped into boiling aqua-regia at a HNO_3: HCl ratio of 1:3 for 10 min to remove the native oxide layer and rinsed in deionized (DI) water. The 25 nm-

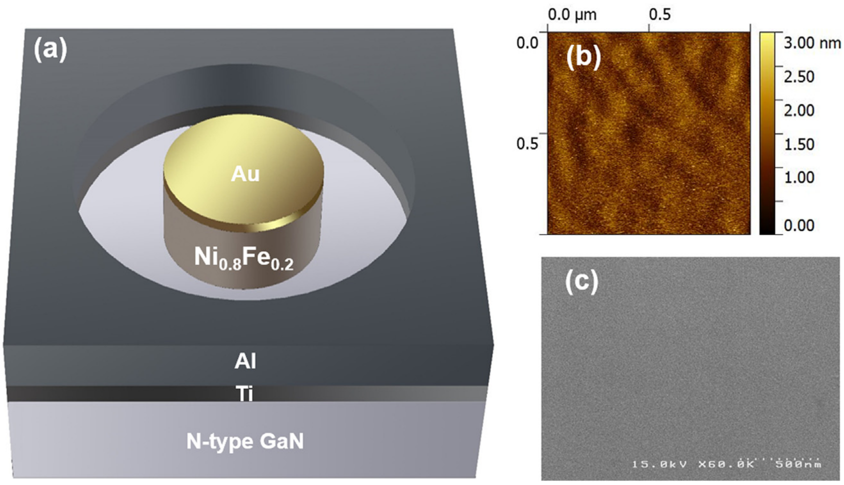

Fig. 1. (a) Schematic diagram of the $Ni_{0.8}Fe_{0.2}$/n-type GaN Schottky diode. Surface morphology of the $Ni_{0.8}Fe_{0.2}$ film with a Au capping layer observed by (b) AFM and (c) SEM.

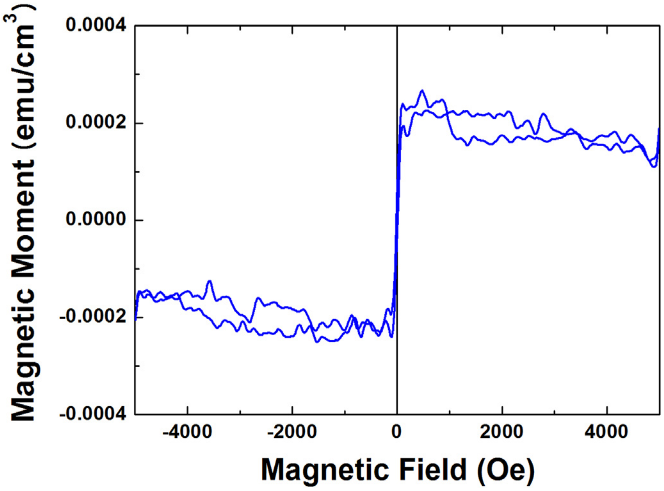

Fig. 2. Magnetization versus magnetic field (M–H) curve of the $Ni_{0.8}Fe_{0.2}$ film on n-type GaN at room temperature.

thick Ti and 100 nm-thick Al films were deposited sequentially on a portion of the sample defined by photolithography as Ohmic contacts by electron beam evaporation, followed by rapid thermal annealing at 650 °C in N_2 ambient for 3 min. After removing the native oxide, the circular Schottky electrodes with a diameter of 200 µm were formed by the sequential evaporation of 50 nm-thick $Ni_{0.8}Fe_{0.2}$ and 10 nm-thick Au films by electron beam evaporation. During the evaporation process, the chamber pressure was maintained at 1×10^{-6} Torr. The Au layer was used as a capping layer to prevent contamination of the $Ni_{0.8}Fe_{0.2}$ layer, resulting in stable contact probing. Atomic force microscope (AFM) and scanning electron microscope (SEM) examinations (Fig. 1(b) and (c), respectively) showed that the deposited layers had a smooth surface morphology with a root-mean-square (rms) roughness of 0.75 nm, indicating the growth of a continuous film. In addition, the Ni/Fe atomic ratio of the deposited film calculated from EDX quantitative analysis (data not shown), was estimated to be ∼4: 1, which was very close to the compositional ratio of the evaporation source. Magnetization measurements, which were carried out with the field applied parallel to the plane of the sample at room temperature using vibrating sample magnetometer (VSM, Lake-shore 7307), revealed that $Ni_{0.8}Fe_{0.2}$/n-type GaN structure showed ferromagnetic behavior after subtracting diamagnetic contribution from GaN substrate, as shown in Fig. 2. The *I–V* characteristics of the $Ni_{0.8}Fe_{0.2}$/n-type GaN Schottky diode were examined using a precision semiconductor parameter analyzer (Agilent 4155C). The low frequency noise measurements were taken using a battery-powered low noise current amplifier (Stanford Research 570) at room temperature within a shielded room to minimize the AC power source frequency coupling. An external multimeter was used to verify the biasing voltage applied to the $Ni_{0.8}Fe_{0.2}$/n-type GaN Schottky diode. At each biasing point, the gain was adjusted to ensure that the output fell within the suitable detection range of the dynamic signal analyzer (Agilent 35670A).

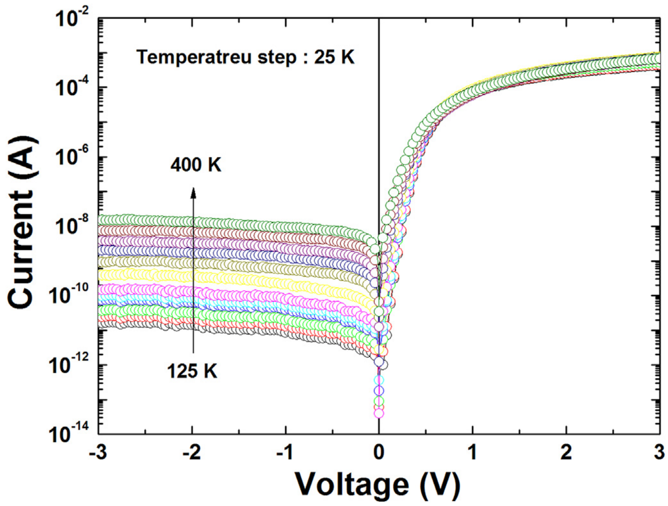

Fig. 3. Temperature dependent *I*−*V* characteristics of the $Ni_{0.8}Fe_{0.2}$/n-type GaN Schottky diode over the temperature range of 125–400 K.

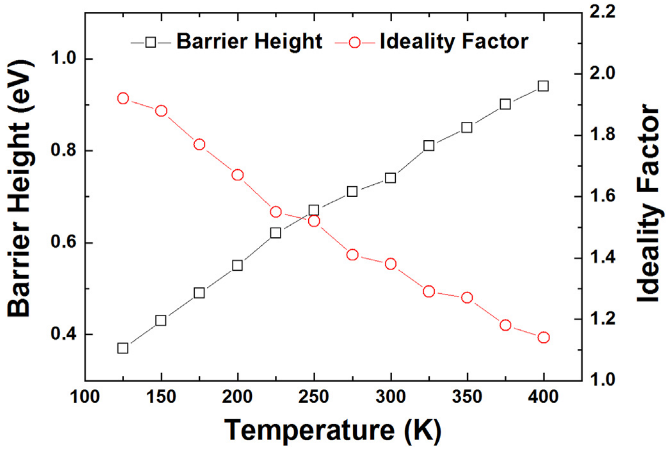

Fig. 4. Plot of the barrier height as a function of the ideality factor obtained at different temperatures for the $Ni_{0.8}Fe_{0.2}$/n-type GaN Schottky diode.

3. Results and discussion

Fig. 3 presents the *I–V* characteristics of the $Ni_{0.8}Fe_{0.2}$/n-type GaN Schottky diode as a function of temperature over the range of 125–400 K. The device clearly showed good rectifying behavior, in which the current increased with increasing temperature. At all temperatures, the device showed a weak voltage dependence of the reverse bias current and an exponential increase in the forward bias current, which are characteristic of a rectifying interface. Based on thermionic emission theory, the barrier heights and ideality factors were calculated at each temperature from a linear fit of the straight-line portion of the ln(*I*)–*V* plot. The barrier height and ideality factor of the $Ni_{0.8}Fe_{0.2}$/n-type GaN Schottky diode ranged from 0.37 eV to 1.92 to 0.94 eV and 1.14 for the temperature range, 125–400 K, respectively, as shown in Fig. 4. Namely, the barrier height and ideality factor were strongly dependent on the temperature. In particular, the barrier height and ideality factor increased and decreased, respectively, with increasing temperature, suggesting the domination of current transport other than thermionic emission mechanism. Such a temperature dependence of the barrier height and ideality factor could be attributed to the presence of barrier inhomogeneity at the Schottky interface, which may be due to the poor interface quality associated with surface and bulk defects, non-stoichiometry in the interfacial layer, non-uniform distribution of interfacial charges, and non-uniform interfacial layer thickness [23–25]. In general, an inhomogeneous Schottky barrier is composed of low and high barrier height local patches with nanoscale dimensions. The current at the lower temperature is dominated by the lower barrier height patches with a high ideality factor because the current flows preferably through the lower barrier height patches. As the temperature is increased, the current tends to flow through the higher barrier height patches, causing the ideality factor to decrease and the barrier height to increase.

The ideality factor, being much larger than the unit associated with the image-force effect, have been reported frequently in non-ideal Schottky diodes, where the contacts might be patchy, usually characterized by the lateral inhomogeneity of the barrier height [23]. The thermionic emission model would still be valid in the case of patchy contacts with lateral dimensions smaller than the depletion width. On the other hand, the potential fluctuations need to be included in the model by considering the total junction current as the sum of the currents flowing through all the individual areas of the spatial regions with different barrier heights [24]. As a result of the barrier inhomogeneity at the metal/semiconductor interface, the barrier height is not constant but follows a Gaussian distribution with different mean barrier heights and standard deviations. Therefore, the temperature dependence of the barrier height in the present device can be interpreted in terms of inhomogeneous Schottky contact by assuming a Gaussian distribution of the barrier height with a mean barrier height $\overline{\Phi_{b0}}$ and a standard deviation $\sigma_{0,}$ expressed as [26–28]:

$$\Phi_{ap} = \overline{\Phi_{b0}} - \frac{q\sigma_0^2}{2kT} \tag{1}$$

where Φ_{ap} is the apparent barrier height obtained experimentally from *I-V* characteristics (Fig. 3). Based on Eq. (1), a plot of Φ_{ap} versus $q/2$ kT of a $Ni_{0.8}Fe_{0.2}$/n-type GaN Schottky diode clearly showed the presence of two distinct linear regions, as shown in Fig. 5, revealing the existence of two Gaussian distributions of barrier heights in the $Ni_{0.8}Fe_{0.2}$/n-type GaN Schottky diode. The standard deviation and the mean barrier height, which were extracted from a linear fit of the data were calculated to be 0.10 and 0.84 eV in region-I, and 0.17 and 1.32 eV in region-II, respectively. Since σ_0 is a measure of the barrier homogeneity, the lower the value of σ_0 the more the homogeneous barrier height. The values of $\sigma_0 = 0.17$ and 0.10 eV are not small compared to the mean values of $\overline{\Phi_{b0}} = 1.32$ and 0.84 eV in region II and region I, respectively, indicates the presence of inhomogeneities. This inhomogeneity considerably affects the *I–V* characteristics, especially at low temperatures.

Fig. 6 shows the Richardson plot of $\ln(I_0/T^2)$ versus 1/T of the $Ni_{0.8}Fe_{0.2}$/n-type GaN Schottky diode, in which the saturation current, I_0, was obtained from a linear fit of the straight line portion of the ln(*I*)–*V* plot at $V = 0$. The Richardson constant (A^{**}) and the mean zero voltage barrier height $\overline{\Phi}_{b0}$ can be calculated from the intercept and slope of the Richardson plot, respectively. The plot clearly shows two different linear regions with different slopes in the temperature range of 125–255 K and 275–400 K, which is

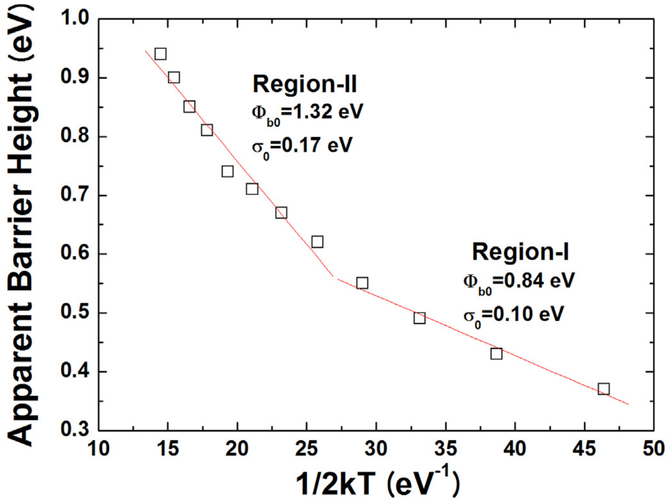

Fig. 5. Plot of the barrier height versus $q/2\,kT$ of the $Ni_{0.8}Fe_{0.2}$/n-type GaN Schottky diode.

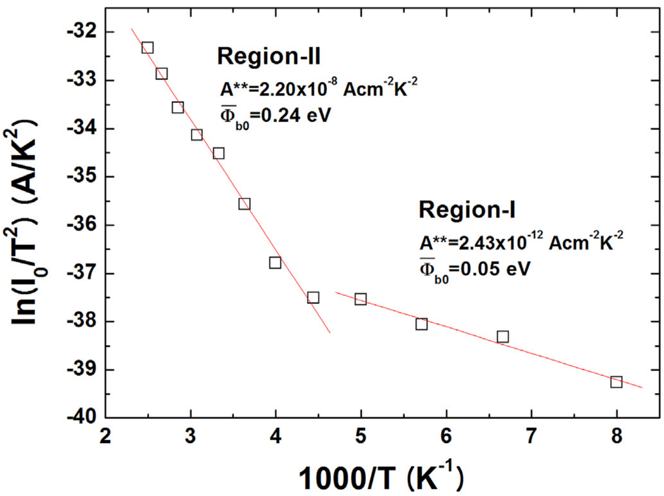

Fig. 6. Richardson plot of $\ln(I_0/T^2)$ versus 1/T for the $Ni_{0.8}Fe_{0.2}$/n-type GaN Schottky diode.

represented as region-I and region-II, respectively. The Richardson constant and zero voltage mean barrier heights were 2.43×10^{-12} Acm^{-2} K^{-2}, and 0.05 eV in region-I and, 2.20×10^{-8}Acm^{-2} K^{-2} and 0.24 eV in region-II, respectively. The Richardson constants obtained were much smaller than the theoretical value for n-type GaN (26.4 Acm^{-2}K^{-2}) [3,29]. The large deviation of the Richardson constant from the theoretical value could be attributed to the calculation using the temperature dependent *I–V* characteristics, which are affected by the lateral inhomogeneity of the Schottky barrier with potential fluctuations. According to the implicit assumption of this method, the Richardson plot would be useful only if the barrier height is independent of temperature. On the other hand, the dependence of the barrier height on temperature contradicts this assumption and leads to erroneous and non-physically meaningful derived parameters.

A more reliable Richardson constant can be obtained using the modified Richardson plot by eliminating the effect of the Schottky barrier inhomogeneity. When considering the Gaussian distribution of the barrier heights, the conventional Richardson plot of $\ln(I_0/T^2) = \ln(AA^{**}) - ((q\overline{\Phi}_{b0})/kT)$ can be modified as [27]:

$$\text{In}\left(\frac{I_0}{T_2}\right) - \frac{(q\sigma_0)^2}{2(kT)^2} = \text{In}(AA^{**}) - \frac{q\overline{\Phi}_{b0}(T=0)}{kT} \tag{2}$$

Fig. 7 presents the modified Richardson plot of $\ln(I_0/T^2)$ - $(q\sigma_0)^2/2(KT)^2$ versus 1/T of the $Ni_{0.8}Fe_{0.2}$/n-type GaN Schottky diode, in which the slope and y-axis intercept of the linear fit to the data correspond to a zero voltage mean barrier height and Richardson constant, respectively. Owing to the double Gaussian distributions of barrier height of the $Ni_{0.8}Fe_{0.2}$/n-type GaN Schottky diode, two distinct regions represented as region-I and region-II were clearly visible. From a linear fit of the data, zero voltage mean barrier height and Richardson constant were determined to be 0.81 eV and 2.96 Acm^{-2}K^{-2} in region-I, and 1.36 eV and 36.8 Acm^{-2}K^{-2} in

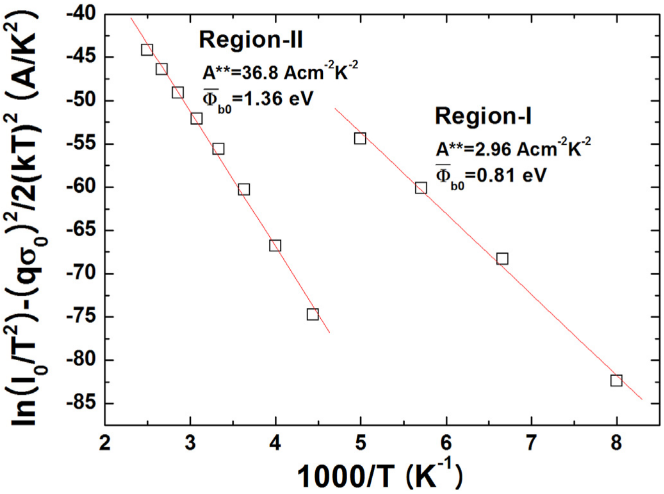

Fig. 7. Modified Richardson plot of $\ln(I_0/T^2)$ - $(q\sigma_0)^2/2(KT)^2$ versus 1/T of the $Ni_{0.8}Fe_{0.2}$/n-type GaN Schottky diode.

region-II, respectively. The zero voltage mean barrier heights were very close to those extracted from the Φ_{ap}- 1/2 kT plot (Fig. 5). Moreover, the values of Richardson constant calculated from the modified Richardson plot were comparable to the theoretical value of the Richardson constant for n-type GaN (26.4 $Acm^{-2}K^{-2}$).

For Schottky diodes having interface states in equilibrium with a semiconductor, the ideality factor becomes greater than unity, as proposed by Card and Rhoderick [30]. The energy distribution of the interface states (N_{ss}) can be evaluated from the forward bias I–V characteristics by considering the voltage dependence of the ideality factor $n(V)$ and the effective barrier height and is given by:

$$N_{SS} = \frac{1}{q}\left\{\frac{\varepsilon_i}{\delta}[n(V)-1]-\frac{\varepsilon_S}{W_d}\right\} \tag{3}$$

where δ is the thickness of the interfacial layer, W_d is the width of the space-charge region, ε_i and ε_s are the permittivity of the insulator layer and semiconductor, respectively, and $n(V)$ is the voltage dependent ideality factor given by $n(V) = V/(kT/q)\ln(I/I_0)$. For n-type semiconductors, the energy of the interface states with respect to the bottom of the conduction band (E_C) at the surface of the semiconductor is expressed as:

$$E_C - E_{SS} = q\Phi_e - qV \tag{4}$$

where V is the voltage drop across the depletion layer and Φ_e is the effective barrier height given by:

$$\Phi_e = \Phi_b + \beta V \tag{5}$$

where β is the voltage coefficient of the effective barrier height given by:

$$\beta = \frac{d\Phi_e}{dV} = 1 - \frac{1}{n(V)} \tag{6}$$

Fig. 8 shows the energy distribution of N_{ss} determined from the forward bias I–V characteristics of the $Ni_{0.8}Fe_{0.2}$/n-type GaN Schottky diode at the temperatures ranging of 125–400 K. The profiles show that N_{ss} decreases with increasing temperature. For example, the N_{ss} values ranged from $6.51 \times 10^{14} eV^{-1}cm^{-2}$ in (E_C - 0.13 eV) to $6.23 \times 10^{13} eV^{-1}cm^{-2}$ in (E_C - 0.34 eV) and from $3.06 \times 10^{14} eV^{-1}cm^{-2}$ in (E_C - 0.49 eV) to $7.69 \times 10^{12} eV^{-1}cm^{-2}$ in (E_C - 0.89 eV) at 125 and 400 K, respectively. Such a temperature dependence of N_{ss} could be associated with the atomic restructuring and reordering at the metal semiconductor interface [31,32]. Furthermore, N_{ss} decreased exponentially with bias from the midgap towards the bottom of the conduction band, irrespective of the measurement temperatures. This could be due to the variation of the ideality factor as a function of temperature caused by the lateral inhomogeneity of the Schottky barrier in the $Ni_{0.8}Fe_{0.2}$/n-type GaN interface [33].

To better understand the carrier transport through the $Ni_{0.8}Fe_{0.2}$/n-type GaN interface, $1/f$ noise measurements were carried out, which can be directly related to the interface quality [34]. Fig. 9 shows the spectral power density of the current fluctuation (S_I) as a function of frequency for the $Ni_{0.8}Fe_{0.2}$/n-type GaN Schottky diode measured at room temperature. The $1/f$ noise measurements were performed over the frequency range of 10 Hz to 1.6 kHz and forward biases varying from 0.2 to 1.0 V with a step of 0.2 V. The $1/f$ noise followed a Hooge-type equation given by Refs. [35,36]:

$$S_I = \frac{\alpha I^\beta}{f^r} \tag{7}$$

where α is the magnitude of noise, I is the DC current, f is the frequency, and β and γ are constant exponents. The current spectral power density was inversely proportional to frequency at all voltages measured. Moreover, at a particular frequency, an increase in

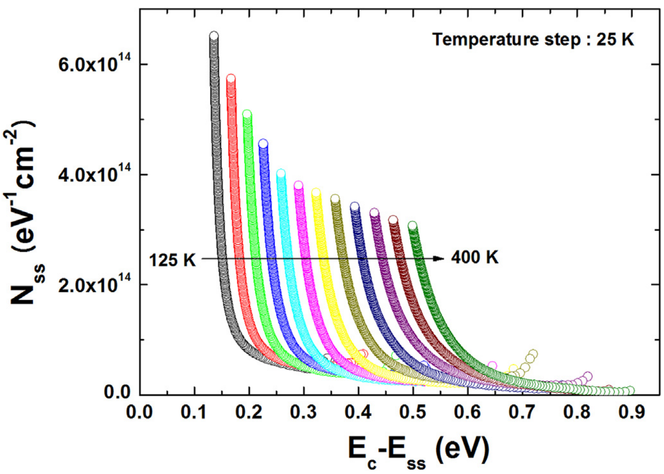

Fig. 8. Plot of N_{ss} as a function of E_C-E_{SS} obtained over temperature range of 125–400 K for the $Ni_{0.8}Fe_{0.2}$/n-type GaN Schottky diode. N_{ss} was derived from the forward bias $I-V$ characteristics.

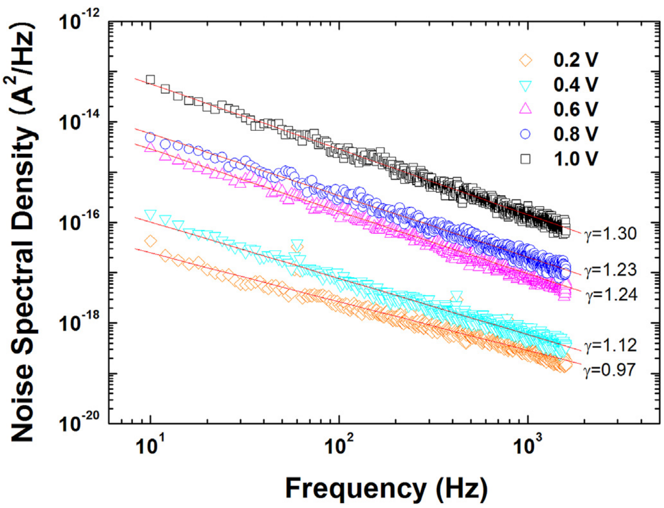

Fig. 9. Spectral power density of the current fluctuations as a function of frequency measured at different forward bias voltages (0.2–1.0 V with a voltage step of 0.2 V).

applied bias led to an increase in current noise power spectral density. This suggests that the current spectral power density measured from the $Ni_{0.8}Fe_{0.2}$/n-type GaN Schottky diode exhibited a f^{γ} dependency. From power law fits to the experimental data, γ were extracted be in the range of 0.97–1.30, which were close to 1. For a Schottky diode with a homogenous barrier, where interface states are distributed continuously over a wide range, the $1/f$ noise spectra revealed Lorentzian behavior, *i.e.*, S_I is constant at the low frequency region and S_I varies with f^2 at the higher frequency region [17]. On the other hand, for the Schottky diode, where barrier height has a Gaussian distribution, the $1/f$ noise spectra can be described by $S_I \propto f^{-1}$, instead of the Lorentzian type. Therefore, the extracted γ values being close to 1 suggest that the barrier inhomogeneity prevails in the $Ni_{0.8}Fe_{0.2}$/n-type GaN Schottky diode, which is consistent with the temperature dependency of the barrier height and ideality factor extracted from the temperature dependent *I–V* characteristics (Fig. 3). When considering the exponential increase in current with respect to the barrier height, as described by thermionic emission theory, any small variation of the barrier height gives rise to large current fluctuations, which could be the origin of the $1/f$ noise occurring in the present device.

4. Conclusions

I–V and $1/f$ noise measurements were performed to examine the barrier nature of the $Ni_{0.8}Fe_{0.2}$/n-type GaN Schottky contact having ferromagnetic property. The temperature dependent behavior of the barrier height and ideality factor indicated the presence of lateral inhomogeneity in the Schottky barrier. The calculations based on thermionic emission theory combined with the assumption that the Schottky barrier height has a Gaussian distribution revealed the existence of two Gaussian distributions of barrier heights in the $Ni_{0.8}Fe_{0.2}$/n-type GaN Schottky contact. From the Φ_{ap} versus $q/2\,kT$ plot, the mean barrier heights and standard deviations of each Gaussian distribution in the $Ni_{0.8}Fe_{0.2}$/n-type GaN Schottky contact were calculated to be 0.10 and 0.84 eV in the lower temperature regions (125–200 K), and 0.17 and 1.32 eV in the higher temperature regions (225–400 K), respectively. From the modified Richardson plot, the Richardson constant values obtained as 2.96 and 36.8 $Acm^{-2}K^{-2}$ in the temperature ranges 125–200 K and 225–400 K were comparable with the theoretical value of 26.4 $Acm^{-2}K^{-2}$ for *n*-GaN. The noise spectral density of the current fluctuations measured at room temperature followed a $1/f^{\gamma}$ dependence with a γ value close to unity, which also indicates the inhomogeneous nature of the $Ni_{0.8}Fe_{0.2}$/n-type GaN interface.

Acknowledgments

This study was supported by the National Research Foundation of Korea grant (NRF-2017R1A2B2003365) funded by the Ministry of Education of the Republic of Korea, and by a grant from the R&D Program for Industrial Core Technology (Grant No. 10045216) funded by the Ministry of Trade, Industry and Energy, Republic of Korea. This paper was also supported by the selection of research-oriented professor of Chonbuk National University in 2018.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.spmi.2018.06.019.

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