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## Correlation of a generation-recombination center with a deep level trap in GaN

X. S. Nguyen,<sup>1,a)</sup> K. Lin,<sup>2</sup> Z. Zhang,<sup>3</sup> B. McSkimming,<sup>4</sup> A. R. Arehart,<sup>3</sup> J. S. Speck,<sup>4</sup> S. A. Ringel,<sup>3</sup> E. A. Fitzgerald,<sup>1,5</sup> and S. J. Chua<sup>1,2,6,a)</sup>

<sup>1</sup>Low energy electronic system IRG, Singapore MIT Alliance for Research and Technology Center, 1 CREATE way, Singapore 138602

<sup>2</sup>Institute of Materials Research and Engineering, 3, Research Link, Singapore 117602

<sup>3</sup>Department of Electrical and Computer Engineering, The Ohio State University, Columbus, Ohio 43210, USA

<sup>4</sup>Materials Department, University of California, Santa Barbara, California 93106-5050, USA

<sup>5</sup>Department of Materials Science and Engineering, Massachusetts Institute of Technology, Room 13-5153, 77 Mass. Ave., Cambridge, Massachusetts 02139, USA

<sup>6</sup>Department of Electrical and Computer Engineering, National University of Singapore, Block E4, Engineering Drive 3, Singapore 117583

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We report on the identification of a deep level trap centre which contributes to generation-recombination noise. A n-GaN epilayer, grown by MOCVD on sapphire, was measured by deep level transient spectroscopy (DLTS) and noise spectroscopy. DLTS found 3 well documented deep levels at  $E_c - 0.26$  eV,  $E_c - 0.59$  eV, and  $E_c - 0.71$  eV. The noise spectroscopy identified a generation recombination centre at  $E_c - 0.65 \pm 0.1$  eV with a recombination lifetime of  $65 \mu\text{s}$  at 300 K. This level is considered to be the same as the one at  $E_c - 0.59$  eV measured from DLTS, as they have similar trap densities and capture cross section. This result shows that some deep levels contribute to noise generation in GaN materials. © 2015 AIP Publishing LLC.

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GaN, a wide and large bandgap semiconductor, is an important material for high power high frequency devices.<sup>1–3</sup> GaN is typically grown on Sapphire, Silicon Carbide, or Silicon substrates. Due to the large lattice mismatch between GaN and the substrates, a large amount of dislocations are generated. Other defects are also created due to vacancies and formation of complexes. These defects affect the efficiency of light emission from the material and current collapse in GaN HEMT.<sup>4,5</sup> Therefore, it is important to find out their concentrations and the energy levels within the band-gap.

Noise spectroscopy (NS) measuring low frequency noise (LFN) in the range up to 1 kHz can identify the generation-recombination (G-R) contributions in causing fluctuations in the transistor channel current. It is therefore a very useful method to complement other techniques for analysing the quality of semiconductor materials and devices. Application of NS in GaN is widely used in analysing GaN HEMT and GaN MOS-HEMT performance<sup>1,4–6</sup> and traps in the AlGaIn and GaN layers of HEMT.<sup>5</sup> LFN is also used to identify trap levels in oxide-GaN interface in MOS-HEMT.<sup>6</sup> However, LFN has not been applied to characterize GaN epilayer. On the other hand, Deep Level Transient Spectroscopy (DLTS), invented by DV Lang,<sup>7</sup> has been widely used to study n-GaN and p-GaN grown by MOCVD and MBE on sapphire, SiC, and silicon. The deep level traps commonly seen are located at  $E_c - 0.25$  eV;  $E_c - 0.60$  eV; and  $E_c - 0.90$  eV in MOCVD grown GaN and at  $E_c - 0.25$  eV;  $E_c - 0.60$  eV; and  $E_c - 0.68$  eV in MBE grown GaN.<sup>8–10</sup> This work focuses on using LFN measurement to identify a G-R level

with a deep level measured by DLTS. While DLTS is able to yield trap parameters such as their capture cross-section, energy level, and concentration, G-R noise is able to measure the trap level, capture-cross section, and also its concentration. Thus, by matching the common parameters, the deep level is identified with the G-R trap. Moreover, noise spectroscopy is quite an effective technique when DLTS fails: levels with very small capture cross sections and levels in semi-insulators.<sup>11–13</sup>

In order to conduct DLTS and low-frequency noise and G-R noise measurement in n-GaN wafer, GaN Schottky diodes were fabricated. The structure of n-GaN Schottky diode is shown in Figure 1. Ammonia based molecular beam epitaxy was used to grow a layer of lightly doped GaN:Si with thickness of 500 nm on a heavily doped GaN:Si on a Lumilog standard c-plane GaN grown by MOVPE on sapphire with a threading dislocation density of about mid  $10^8 \text{ cm}^{-2}$ . To form the Schottky contact, a Ni/Au thin layer was deposited. The Ohmic contact was formed by depositing a Ti/Al/Ni/Au layer.

The setup for noise measurement is shown in Figure 1(b). In the setup, the device was biased by a battery voltage source to eliminate extraneous noise. The device was probed in the EM shielded box. The current through the device was amplified using a Stanford SR 560 low noise current amplifier. Next, the current signal was analysed using HP 35670 Dynamic signal analyser to obtain the power spectral density (PSD) which was displayed on a computer.

The main parts of DLTS system are (1) Boonton 7200 capacitance meter, (2) TTPX probe station, (3) HP 33220—function generator, (4) Oscilloscope, and (5) data acquisition box. The temperature of the sample being probed can be

<sup>a)</sup>Authors to whom correspondence should be addressed. Electronic addresses: xuansang@smart.mit.edu and elecjs@nus.edu.sg.

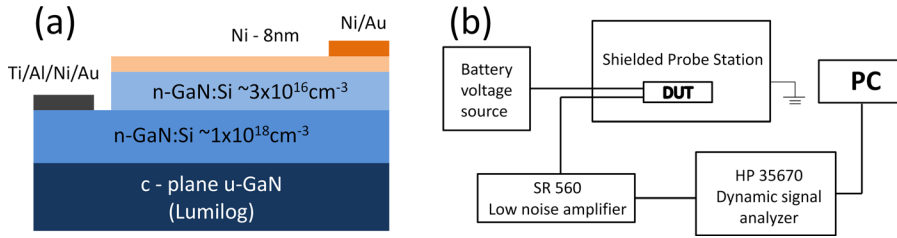


FIG. 1. (a) Structure of the GaN Schottky diode and (b) the noise measurement setup.

cooled down to 78 K by flowing of liquid  $N_2$ . All devices were connected to the PC using GPIB cables. The DLTS measurement was controlled by a Labview program.

In order to prepare for noise and DLTS measurements, I-V and C-V characteristic of the Schottky diode were measured and presented in Figure 2. The leakage current of the diode is measured to be  $10^{-5} A/cm^2$  at  $-4 V$  biased. At a forward bias of  $1 V$ , the current density is about  $1 A/cm^2$ . Following Cheung and Cheung,<sup>14</sup> the series resistance and ideality factor were calculated from the I-V plot using the equation given below

$$\frac{dV}{d \ln(I)} = R_S I + n \frac{kT}{q}, \quad (1)$$

where  $R_S$  is the series resistance and  $n$  is the ideality factor. Using Eq. (1), the ideality factor was calculated to be 1.09 and  $R_S$  is  $68 \Omega$ . These results show that the Ohmic and Schottky contacts are suitable for making noise and DLTS measurements.

The C-V characteristic shows the typical curve in Fig. 2(c) with the value of the capacitance of about  $40 pF$  at  $0 V$  biased. Using the following equation:<sup>15</sup>

$$N(X_d) = \frac{\rho(X_d)}{q} = \frac{C^3}{q\epsilon A^2 \left(\frac{dC}{dV}\right)}, \quad (2)$$

the carrier concentration,  $N$ , was calculated to be  $3.2 \times 10^{16} cm^{-3}$ . The electronic charge  $q = 1.602 \times 10^{-19} C$ ,  $A = 0.089 mm^2$  is device area,  $\epsilon = 8.9$  is permittivity of GaN,  $X_d = A\epsilon_S/C \mu m$  is the depletion width of the Schottky junction. This value of carrier concentration obtained from C-V measurement agrees well with that determined separately by Hall measurement. This value will be used later in the G-R noise and DLTS calculations.

The low-frequency noise in a GaN Schottky diode is due to the fluctuation of electron density and electron mobility. Under forward bias, the fluctuation of electron density is partly due to trapping and de-trapping of electrons from the deep level defects. This random capture and emission of carriers are the source of the generation-recombination (G-R)

noise. The capture and emission processes involve free electrons and electron-traps and/or free holes and hole-traps. These traps can be either interface traps, or bulk traps present in the GaN layer. The noise voltage spectral density versus frequency, shown in Figure 3(a), includes a  $1/f$  noise and an additional Lorentzian at low frequencies. The Lorentzian is G-R noise which occurs due to the presence of local centers in the band gap of the semiconductor. The voltage power spectrum density (PSD) of the fluctuations in the number of carriers is found to be<sup>12</sup>

$$S_V(f) = \frac{B}{f} + A \frac{1}{1 + (2\pi f)^2 \tau^2} + 4k_B T R_S \quad (V^2/Hz). \quad (3)$$

Here,  $B$  and  $A$  are the amplitudes of the  $1/f$  and G-R processes in the volume of the semiconductor,  $f$  is frequency,  $\tau$  is the characteristic time constant of the G-R processes,  $T$  is temperature, and  $R_S = 68 \Omega$  is sample resistance. The deviation of the spectrum from  $1/f$  dependence is fitted to a Lorentzian function according to Eq. (3) and the result shown in the inset of Figure 3(a). This allows the time constant of the G-R process,  $\tau$ , to be extracted at a certain temperature. It is seen that within the temperature of  $300 K$ ,  $\tau$  is found to be  $65 \mu s$ .

The trap level is found from the Arrhenius plot of  $\ln(\tau T^2)$  vs  $1/T$  is following the equation develop by Scholz *et al.*:<sup>16,17</sup>

$$\ln(\tau T^2) \approx \frac{\Delta E}{k_B T} - \ln \left( \frac{4K^2 \sigma_n}{gh^3} \left[ 6\pi^3 m_e^{3/2} m_h^{1/2} \right]^{1/2} \right), \quad (4)$$

$\Delta E = E_C - E_T$ ,  $E_T$  is the trap energy,  $g = 1$  is the ground state degeneracy factor. The value of  $\Delta E$  was determined from the slope of the Arrhenius plot, shown in Figure 3(b). The value of capture cross section  $\sigma_n$  was determined from y-intercept follows Eq. (4). The trap energy level  $\Delta E$  is extracted and found to be as at  $E_C - (0.65 \pm 0.10) eV$ . Capture cross-section  $\sigma_n$  was found as  $\sim 10^{-14} cm^2$ .

The density of the trap was calculated from amplitude of G-R processes in the volume of the semiconductor using following equation:<sup>12</sup>  $A = 4N_T/VN_d^2$ , where  $A$  is the amplitude

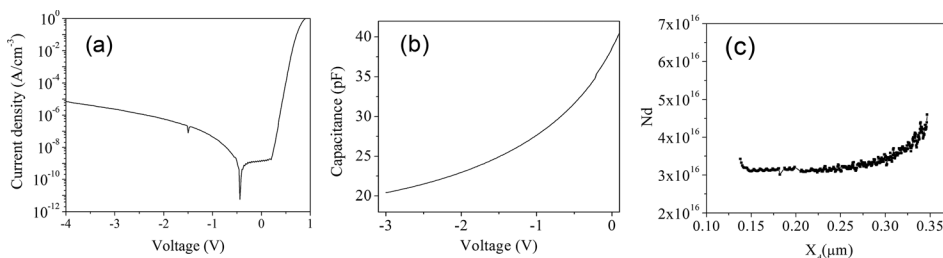


FIG. 2. I-V (a) and C-V (b) characteristic of n-GaN Schottky diode, and (c) carrier concentration of the top layer of n-GaN.

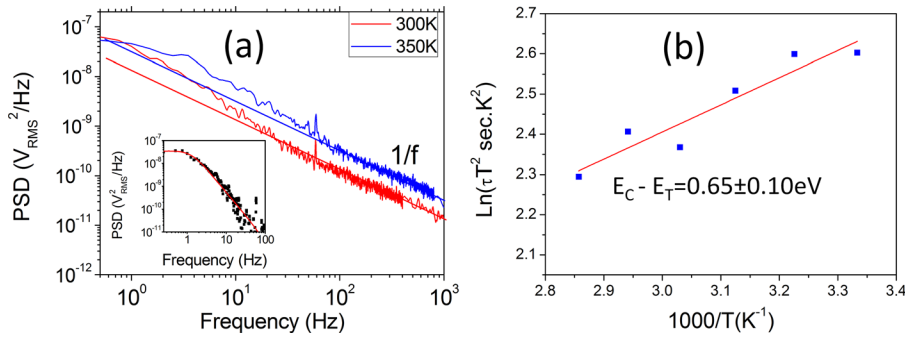


FIG. 3. Low-frequency noise spectrum of GaN Schottky diode under 1 V forward bias at 300 K and 350 K. (a)  $1/f$  and G-R noise and (b) Arrhenius plot of deep level traps in GaN. Inset in (a) is the Lorentzian fitting of LFN at 300 K after subtracting the  $1/f$  noise.

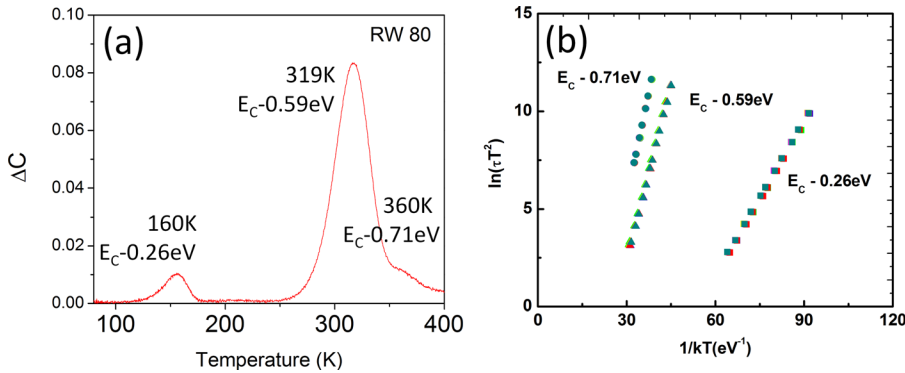


FIG. 4. (a) DLTS spectrum for rate window  $e_n = 80 \text{ s}^{-1}$  and (b) corresponding Arrhenius plot of deep level traps in n-GaN Schottky diode.

of the G-R process in the volume of the semiconductor,  $N_T$  is the trap density,  $V$  is the sample volume, and  $N_d$  is the donor concentration. The trap density was found to be  $N_T \sim 10^{14} \text{ cm}^{-3}$  with  $A = 1.342 \times 10^{-7}$ .

The n-GaN Schottky diode was characterized by DLTS to obtain the deep trap parameters. These traps are found to be electron traps. The DLTS measurement of the change in the diode capacitance  $\Delta C$  was carried out from 80 K to 400 K. Figure 4(a) shows the DLTS spectrum at a rate window of  $80 \text{ s}^{-1}$  which determines the value of  $e_n$ . As seen in the DLTS spectrum, three peaks located at about 160 K, 320 K, and 360 K were observed. Each peak represents a deep level trap in the GaN layer. In DLTS, the variation of the emission rate of a trap,  $e_n$ , with temperature,  $T$ , is given by<sup>18</sup>

$$\ln\left(\frac{T^2}{e_n}\right) = (E_C - E_T) \frac{1}{k_B T} - \ln(\sigma_n \gamma_n), \quad (5)$$

where  $E_C$  and  $E_T$  are the conduction band edge and the trap energy, respectively,  $\sigma_n$  is the trap cross-section, and  $\gamma_n$  is a constant related to the effective mass of the electron. In DLTS measurement, assuming the capture cross-section  $\sigma_n$  is temperature independence. In order to identify the trap parameters,  $\ln(T^2/e_n)$  versus  $1/kT$  was plotted and shown in Figure 4(b).  $e_n$ , which is the reciprocal of the trap lifetime,  $\tau$ , is obtained from the value of the rate window and  $T$  is the temperature at which the peak in  $\Delta C$  versus temperature occurs. The slope of the Arrhenius plot gives the energy level. The y-intercept of the plot shows the capture cross-

section of the traps. In Figure 4(b), three deep level traps were found to be located at  $E_C - 0.26 \text{ eV}$ ,  $E_C - 0.59 \text{ eV}$ , and  $E_C - 0.71 \text{ eV}$ . Among these traps, the one at  $E_C - 0.59 \text{ eV}$  is the dominant one. Table I shows the peak temperature and the corresponding rate window which determine  $e_n$  of the peak located at  $E_C - 0.59 \text{ eV}$ .

The concentration and capture-cross section of this trap are found to be  $8 \times 10^{14} \text{ cm}^{-3}$  and  $1.8 \times 10^{-14} \text{ cm}^{-2}$ , respectively. This trap corresponds to the trap located at  $E_C - (0.65 \pm 0.10) \text{ eV}$  found in LFN measurement as they have similar trap densities and capture cross section.

This paper shows that noise spectroscopy can be used to identify the deep levels measured from DLTS that contribute to G-R noise. DLTS is able to characterize the energy level, trap density, and trap lifetime or emission rate of the traps. From G-R noise measurement, the energy level, trap density, and capture cross-section can also be identified. The measurements made on the n-GaN sample showed that of the 3 deep levels measured by DLTS at  $E_C - 0.26 \text{ eV}$ ,  $E_C - 0.59 \text{ eV}$ , and  $E_C - 0.71 \text{ eV}$ , the one at  $E_C - 0.59 \text{ eV}$  contributes to the G-R noise as their trap densities and capture cross section match closely to one from values another obtained by DLTS and noise spectroscopy.

This research was supported by the National Research Foundation Singapore through the Singapore MIT Alliance for Research and Technology's LEES IRG research programme.

TABLE I. Peak temperature and the corresponding rate window of the peak located at  $E_C - 0.59 \text{ eV}$ .

Peak temperature, K	302	314	319	331	343	359
Rate window, $e_n$ , $\text{s}^{-1}$	20	50	80	200	400	1000

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