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Investigation of deep defects using generation-recombination noise

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Noise spectroscopy is an effective tool to characterize the quality of semiconductor bulk and surface and a figure of merit for device quality as a whole. In certain cases, low-frequency noise can be used for the evaluation of device reliability. Further, measurements of the noise characteristics of GaAs materials are a useful technique when it comes to studying deep defects exhibiting a thermally activated capture. In the paper we present the technique of noise spectroscopy and illustrate it with some applications. They include photocapacitive and noise measurements on a deep DX-like defect which gives rise to persistent photoconductivity in Mg-doped *p*-type GaN films. We also apply DLTS, photoconductivity and noise spectroscopy to characterize *n*-type bulk GaAs and an EL2-related metastable defect. The third example illustrates experimental results on the photoconductivity and noise of forward and reverse biased $Al_{0.3}Ga_{0.7}N$/GaN-based Schottky barriers. In the light of these results the nature and origin of the responsible centers are discussed.

Keywords: generation-recombination noise, deep defects, GaN, AlGaN, GaAs.

1. Introduction

It is well known that fabrication of both *n*- and *p*-type low-resistivity wide-bandgap semiconductors is difficult because of charge compensation by native defects and the fact that even standard dopants in these materials have quite deep energy levels [1–5]. GaN (bandgap $E_g = 3.4$ eV), AlN ($E_g = 6.2$ eV) and AlGaN, the bandgap of which ranges between the two values, are examples of wide-bandgap semiconductors that are suitable for a wide range of applications if problems related to especially *p*-type doping can be solved. Possible avenues towards fabricating low-resistivity wide bandgap semiconductor materials include avoiding charge compensation by increasing the solubility of the dopant, increasing the mobility of the carriers and identifying impurities with lower binding energies. A few methods to enhance the *p*-type conductivity have been reported, such as annealing of GaN:Mg in an oxygen ambient and co-doping, but much work must still be done in order to ensure further progress [6, 7]. Since the presence of native or process induced defects can have detrimental effects on the performance of materials and devices made from them, the knowledge of formation mechanisms and kinetics properties of such defects is of primary importance. Also, the challenge of obtaining good p-type conductivity layers requires the investigation of defects and their role in the compensation mechanism. The adaptability of spectroscopical techniques to investigate deep levels (on the order of 1–2 eV from either band edge) and the application of techniques such as photoluminescence (PL), photoconductivity (PC), deep-level transient spectroscopy (DLTS) methods, allow us to detect defects in a wide energy range. Persistent PC is a useful tool to model the effect of defect bands and extended defects responsible for the yellow, red and green photoluminescence bands in GaN [4]. Noise spectroscopy can be quite an effective technique in cases where DLTS and other common methods fail, namely for energy levels with very small capture cross-sections and ones with thermally activated capture. Methods for extracting characteristic parameters for local levels from noise spectroscopic data are particularly effective when the carrier capture cross-section depends exponentially on temperature. The simplest source of generation-recombination (g-r) noise is a two-level system (TLS). The electronic noise arising from DX-centers in AlGaAs has been interpreted according to this model [8]. It has been shown that the g-r noise $S(f)$ arising from a single TLS exhibits a peak at the frequency $f_p = 1/2\pi\tau_p$ with the value:

$$f_p S(f_p) = \frac{1}{4\pi^2} \frac{\tau_e \tau_c}{(\tau_e + \tau_c)^2} \tag{1}$$

Here $1/\tau_p = 1/\tau_e + 1/\tau_c$ where τ_e and τ_c are the emission and capture lifetimes which are thermally activated. They have the form:

$$\tau \sim T^{-2} \exp\left(\frac{E}{k_B T}\right) \tag{2}$$

To determine τ_e and τ_c one usually uses the assumption that one of the two lifetimes, τ_e or τ_c is much larger than the other. Assuming as it is often the case that $\tau_e \gg \tau_c$ we have $f_p = 1/2\pi\tau_c$ and $f_p^2 S(f_p) = 1/8\pi^3\tau_e$. The smaller of the two activation energies (which is usually the capture energy) can be obtained from the slope of $T^2\tau_c$ versus $1/T$ in a semi-log scale. The slope of $T^2/f_p^2 S(f_p) \sim T^2\tau_e$ gives the larger of the two activation energies.

The $1/f$ noise is a conductance fluctuation in which the noise spectrum is inversely proportional to the frequency. For a homogeneous material, the noise power spectrum density for a $1/f$ noise process is given by:

$$S_v = \frac{V^2\alpha}{Nf} \tag{3}$$

where α is a dimensionless constant referred to as the Hooge parameter, and N is the total number of free carriers. The Hooge parameter is used for assessing the relative noise in different materials. Despite the fact that the causes of the $1/f$ noise are not completely understood, the magnitude of the $1/f$ noise is affected by defect traps located in the bulk material or at the surface.

The experimental setup consists of measuring voltage fluctuations across the sample which have been amplified with a preamplifier to be analyzed with a HP Fast-Fourier Transform spectrometer. A current source together with a series resistor supplied the constant current necessary for the non-thermal noise measurements.

In this review we summarize results obtained using noise spectroscopy to supplement other characterization techniques in order to investigate three cases of metastable defects in GaN, GaAs, and AlGaN, respectively. Our work demontrates that noise measurements can be a poweful tool for chacaterization of deep defects in wide bandgap materials.

2. 1/*f* and generation-recombination noise in GaN:Mg

Persistent photoconductivity (PPC) has been observed in GaN films but its origin is still incompletely understood [9–11]. The PPC is expected to degrade the performance of ultraviolet and X-ray detectors and field-effect transistors. The role of deep levels in the PPC behavior is not clear. In a previous paper we reported the observation of two metastable deep levels in Mg-doped GaN and showed that they are partially responsible for the PPC [12]. In order to obtain complementary information on these levels we used electronic noise analysis to determine the thermal capture and emission energies of the traps. In the light of these results we propose a configuration-coordinate diagram similar to that of DX-centers in AlGaAs to explain the metastability of the observed defects.

We investigated the noise properties of epitaxial GaN:Mg thin films grown by metalorganic chemical vapor deposition (MOCVD) on *c*-plane sapphire substrates. The thickness of the GaN film is about 1 μm. The Mg concentration is $2–5\times10^{19}$ cm^{-3}. We annealed the as-grown samples under N_2-flow at 800°C for 20 minutes. Hall effect measurements performed on the samples yield a free hole concentration of $p = 1\times10^{17}$ cm^{-3} and a hole mobility of $\mu_p = 10$ cm^2 V^{-1} s^{-1}. Ohmic contacts were fabricated by evaporating Au/Ni onto the samples followed by annealing at 800°C for 30 minutes.

3. Results and discussion

The two deep centers reported in previous work [12] were labeled T1 and T2 and determined to have optical ionization energies 1.1 and 1.9 eV, respectively. We attributed both centres to Mg and demonstrated that both of them are metastable and responsible for a part of the PPC observed in the samples. As increased structural inhomogeneity implies an increase in crystal defects and interfaces, it is reasonable to expect an increase in the magnitude of $1/f$ noise under such conditions. The noise spectrum, for frequencies in the range of 1 to 30 Hz and temperatures between 250

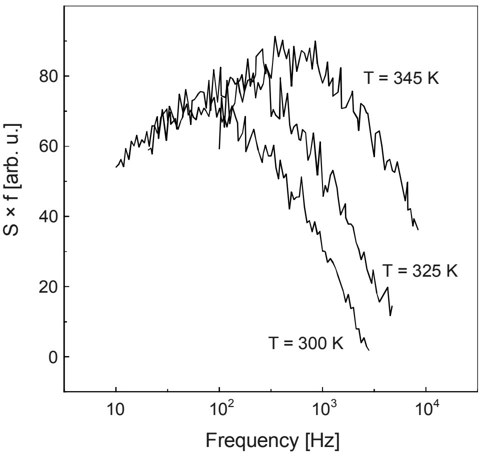

Fig. 1. Noise power density spectra at different temperatures.

and 400 K, is strongly correlated to the microstructure [13]. Using the assumptions in [14] the Hooge parameter was calculated using the volume between the voltage contacts. Values of $\alpha = 10–100$ were obtained for our samples. In homogeneous materials the Hooge parameter is usually much lower [13]. Hence, the high values measured in our samples suggest the presence of a large level of structural imperfections. The noise value and frequency dependence of the noise may be changed considerably by appropriate annealing. It therefore appears that annealing at higher temperatures for longer time increases the Hooge parameter.

Figure 1 shows the noise power spectral density normalized to the $1/f$ noise at 300 K. Before the normalization the spectra exhibit a clear $1/f$ noise at low frequencies. As shown, the experimental data agree with a g-r noise source. Instead of focusing our studies on the noise-versus-frequency spectra we find it more convenient to investigate the changes in the noise as a function of temperature for a given frequency. Figure 2 shows representative examples of the noise power versus temperature at 10 and 100 Hz. Curves *a* and *b* were measured in the dark whereas curve *c* was measured for a frequency of 10 Hz after illumination of the sample at 1.5 eV for 10 minutes. Each point of the curves has been constructed by averaging 100 acquired noise-versus -frequency spectra. The $1/f$ noise was quite significant and therefore it was convenient to multiply the noise signal by the frequency f. In this case, the $1/f$ noise appears as a constant background. The curves in Fig. 1 are dominated by a single broad peak. In our data analysis we decided to determine the peak temperature, the peak temperature, from the peak amplitude of the noise curve. We repeated the measurements at several frequencies and observed that the peak temperature is frequency-dependant. Further, we illuminated the sample using a 1.5 eV photon energy light before measurement and noticed that the noise spectrum does not exhibit a significant maximum any longer. The activation energy determined from the slope $T^2\tau_p$ as a function of $1000/T$ is $E_1 = 45\pm4$ meV. Given the explanation above this activation energy should be taken for the smaller of the capture and emission energies of the corresponding center. The slope of T^2/f_p^2S *vs*. $1000/T$ gives a value of $E_2 = 0.42\pm0.02$ eV which we note is much

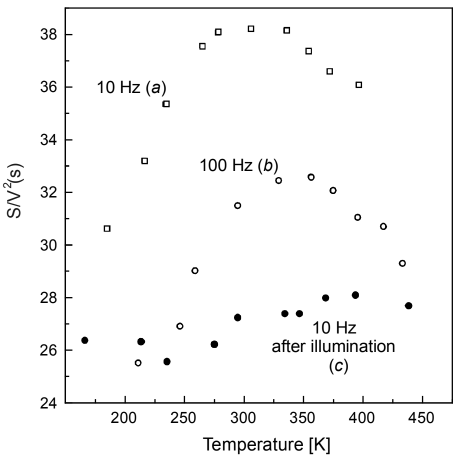

Fig. 2. Temperature dependence of noise power for 3 measuring frequencies.

larger than E_1. These energies must be associated with the capture and emission process of a deep center in the material. The fact that the noise signal is not observed when the sample has been primarily illuminated with a 1.5 eV photon energy light suggests that this center is correlated to the T1 defect. Indeed, the T1 defect has an optical ionization energy of 1.1 eV and is therefore photoionized with the 1.5 eV photon energy light. When the T1 center is in its metastable state after photoionization there should be less g-r recombination at its fundamental state and this explains why we do not observe any noise signal from the defect in this case. The T2 center is not photoionized with the 1.5 eV photon energy light and therefore is still able to exhibit a noise signal. However, since our noise signal disappears after illumination we deduce that T2 does not contribute in this signal. Hence the g-r noise signal observed here originates from T1 which allows us to determine the emission and capture energies of the trap. In addition, in our previous work we investigated the decay of the PPC from this center. The activation energy of the lifetime of the PPC from T1 which we estimated by investigating the PPC at various temperatures is quite close to E_1. Therefore we attribute E_1 and E_2 to the capture and emission barriers E_c and E_e, respectively. These results suggest a DX-like behavior for the metastable center T1. The value of the capture energy is similar to that measured for Si-related centers observed in AlGaN [15]. Taking into account the various energy values that we determined using photocapacitance and noise spectroscopy we can draw a simplified DX-like configuration coordinate diagram of the T1 center in GaN:Mg as shown in Fig. 3. The noise peak as a function of frequency becomes broader at temperatures above 350 K which suggests that there may be contributions from more than only one defect. This is possibly a contribution from the T2 defect.

In conclusion we have used noise spectroscopy to demonstrate the presence of two DX-like metastable defects in Mg-doped GaN that are partially responsible for the persistent photoconductivity usually observed in this material. We showed that the noise in GaN:Mg is significantly controlled by g-r from these metastable states. We have measured all the energies related of the DX-like center and proposed

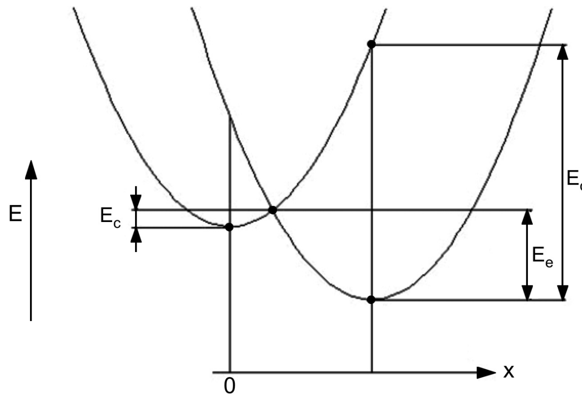

Fig. 3. Configuration coordinate diagram of the T1 center in GaN:Mg showing the energies that we determined in this work.

a configuration coordinate diagram that describes the metastability in our materials. Investigations of the 1/*f* noise suggests that the latter is mainly due to mobility fluctuations and that there is a large level of structural imperfections in the GaN materials.

4. Generation-recombination noise in GaAs:Si

The EL2 defect is one of the most investigated intrinsic centers in GaAs [16–18]. Reasons for this include its role in obtaining semi-insulating GaAs substrates and its effects on the device performance of GaAs-based integrated circuits from a practical aspect. Other metastable defects have also been observed in *n*-type GaAs, the formation of which has been found to strongly depend on heat treatment and growth conditions [19]. It is known that silicon doping of bulk GaAs is known to lead to the appearance of point defects and silicon segregation, which negatively influence the performance of devices [20]. The effect of Si-doping on the properties of EL2 is not clear. Below we describe an experimental investigation including noise spectroscopy of metastable defects related to EL2 in Si-doped GaAs.

The investigated samples were Si-doped bulk GaAs grown using the horizontal Bridgman method. Capacitance-voltage profiling was used to measure the net charge donor density and a value of $N_d - N_a = 2\times10^{16}$ cm^{-3} was determined. For electrical characterization ohmic and Schottky contacts were fabricated by evaporating Au/Ge and Au onto the back and the front face of the samples, respectively.

5. Results and discussion

In Figure 4 several noise power spectra at various temperatures are shown. Two Lorentzian peaks are observed, denoted P1 and P2. The emission and capture energy barriers for the two traps were calculated from the Arrhenius plots as described above.

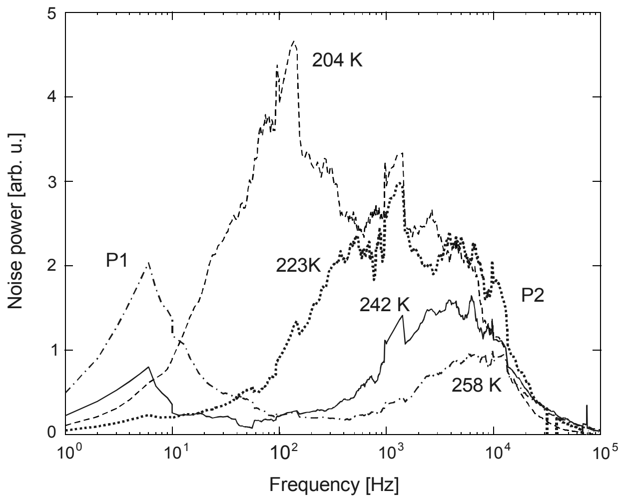

Fig. 4. Noise power density at different temperatures showing the g-r components of P1 and P2.

We found the values $E_c = 0.41$ eV and $E_e = 0.55$ eV for P1 and $E_c = 0.2$ eV and $E_e = 0.3$ eV for P2, where E_c and E_e are the capture and emission energy barriers, respectively. The distribution of the centers in the material was studied by varying the voltage applied to the Schottky diode. The results showed that P1 and P2 are located throughout the material and not confined to the metal-semiconductor interface. DLTS measurements reveal several peaks in the temperature range from 77 to 400 K. One of these defects has a thermal activation energy close of that of P1, that is $E_a = 0.65$ eV. In addition, DLTS depth analysis also shows that this defect is present throghout the material. We therefore believe that the DLTS signal corresponds to the center P1 observed in noise spectroscopy. No DLTS peak which might originate from P2 was observed. A reference sample which was not doped with Si, exhibits a clear DLTS peak corresponding to the well known EL2 with a thermal activation energy and an apparent capture cross-section in good agreement with those of EL2. However, no defect with same DLTS characteristics as P1 was observed in the reference sample. Figure 5 shows the time evolution of the photocurrent as a function of light intensity at 80 K. The sample was illuminated using a halogen lamp with appropriate filters for the photon energy of 1.24 eV. The curves in the figure correspond to various intensities of illumination. For low light intensities the photocurrent increases until it reaches a saturation value and no quenching is observed in any reasonable time interval. For higher light intensities the quenching of the photoconductivity is well defined. In this case, there is a sharp increase in the photocurrent during the first seconds of illumination followed by a slow decay. The same behavior in the photocurrent was observed for temperatures up to about 130 K. For higher temperatures, however, no quenching was observed no matter what light intensity was used. This quenching and subsequent recovery of the PC is quite similar to that of EL2 being widely reported [21]. Therefore, although our samples do not exhibit the typical DLTS signal

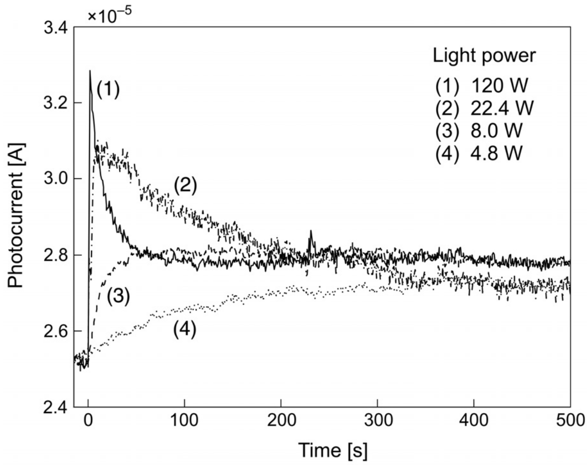

Fig. 5. Photocurrent versus time for various powers of the halogen lamp used to illuminate the sample.

from EL2 they contain a defect with similar properties as EL2, that is P1. We believe that the Si doping affects the traditional properties of EL2. The center P1 must be related to EL2, probably it is a complex defect involving EL2. It has been proposed that doping with Si creates defects involving the gallium vacancy [22]. The nature and characteristics of these defects depend strongly on the Si-doping level and doping conditions. From the present work, it is difficult to speculate on the microscopic nature of P1 and P2 and measurements are in progress.

In conclusion, we observed deep defects in bulk GaAs doped with silicon using noise spectroscopy. However, no evidence was found for the well known DLTS signal from EL2. These defects are present throughout the material and have a thermally activated capture. We show that the defect with an emission energy of 0.55 eV is metastable and we assign it to a complex center involving EL2 and another defect created by Si.

6. Generation-recombination noise in AlGaN/GaN heterosructures

Only a few investigations of localized deep centers in AlGaN have been reported so far despite the fact that AlGaN heterostructures have an excellent potential for applications in high-temperature/high-power/high-frequency electronics [23–25]. The impact of deep point defects is crucial in all applications of the material. Below, we report results from noise measurements on MOCVD-grown $Al_{0.3}Ga_{0.7}N$/GaN heterostructures and discuss the effect of point defects on the electronic characteristics of AlGaN related devices.

The $Al_{0.3}Ga_{0.7}N$ samples were nominally undoped and grown on GaN buffer layers on a sapphire substrate by the EMCORE Corporation using MOCVD. The thickness of the layers was about 1.6 μm. The free electron densities obtained by Hall measurements were 5.2×10^{17} cm^{-3} in the samples. Ohmic contacts were made by evaporation of Al and Schottky contacts by evaporating Au onto the layer. We present results from samples labeled S1, S2, and S3. Samples S2 and S3 were annealed at 500°C for 10 and 20 minutes, respectively. The dc and noise measurements were made over a temperature range from 77 to 300 K and frequency range from 10 Hz to 100 kHz.

7. Results and discussion

In Figure 6 a few typical noise spectra recorded at 77 K are shown. Similar curves of the noise were observed over the whole range of temperatures between 77 and 300 K. The $1/f$ component of the noise is clearly dominant at low frequencies in all the samples. The amplitude of the signal decreases with the increase of temperature until $T = 150$ K, where the noise amplitude starts to increase again. Figure 7 shows the variation of the $1/f$ noise amplitude for a given frequency ($f = 20$ Hz) with the forward current in the diode. From the log-log scale of Fig. 7 it is found that the noise is proportional to $I^{1.3}$ in S1, to $I^{1.1}$ in S2, and to $I^{1.9}$ in S3. A nonlinear type of variation such as that in S3 usually indicates the presence of a g-r component in the noise signal, probably related to deep defects. In addition, sample S3 exhibits the highest value of the noise density. This is believed to be related to the annealing which activates the defects in the sample. It is not always straightforward to reveal the g-r component from electrically active centers in the noise spectrum. Indeed, it is strongly sample dependent. In order to reveal this g-r component one has to multiply the spectra by the frequency f to eliminate the $1/f$ contribution. Figure 8 shows the Lorentzian signal obtained from sample S3 at low temperatures. No such a signal was observed in samples S1 and S2. It is a broad band that shifts in frequency when the temperature is changed. We attribute this signal to g-r noise originating from a deep defect. By

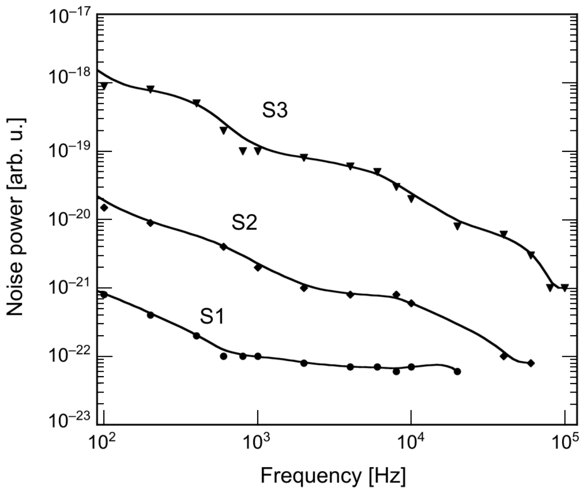

Fig. 6. Noise power density as a function of frequency at T = 77 K and forward current I = 100 μA.

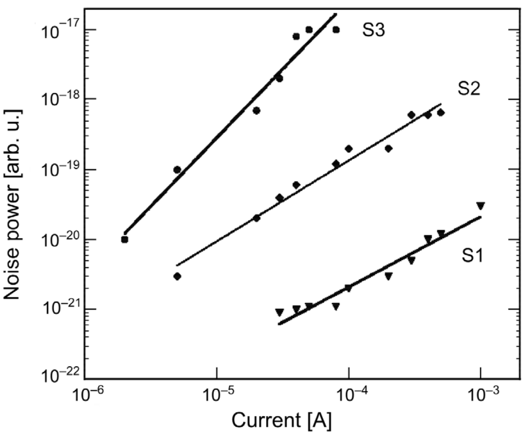

Fig. 7. Noise power density as a function of forward current at T = 77 K and frequency f = 20 Hz.

varying the voltage applied to the Au/AlGaN barrier we deduced that the g-r signal originates from the area in AlGaN close to the GaN layer. Indeed, when the reverse voltage is such that the edge of the depleted region between the metal and the AlGaN layer approaches the GaN layer the Lorentzian noise component disappears. We believe that the g-r noise is stronger when the corresponding center is located in the neutral part of the semiconductor and not in the depleted region. The reason for this is the lack of free electrons in the depleted region which eliminates the recombination.

Following the procedure described in [8] one can calculate the emission and capture energies of the center. However, since our Lorentzian components are quite broad it is difficult to determine the position of the peak. A rough estimate, however, gives the values $E_a \approx 0.8$ eV and $E_c \approx 0.26$ eV for the emission and capture barrier energies, respectively. The large capture barrier suggests a metastable nature for the defect. In addition, when the sample is subjected to illumination with a white light prior to measurement at low temperatures no Lorentzian g-r component is observed. This finding is an additional argument to the metastable nature of the defect. The center may be responsible for a part of the generally observed PPC in AlGaN. HIRSCH *et al.* [26] investigated the PPC decay time in GaN and attributed it to a distribution of defects with a mean value for the capture barrier of 0.2 eV. NOZAKI *et al.* [27] observed a collapse in the drain current from AlGaN/GaN MODFETs and attributed it to the presence of DX-like centers in the AlGaN layer. It is not clear, however, why we do not observe the same g-r noise signal in samples S1 and S2. Identical measurements as those performed on sample S3 were carried out on samples S1 and S2 and no Lorentzian noise signal was detected. Perhaps the g-r component was too weak to be observed in these samples. Hence, the deep defect is either absent or present with a lower density in S1 and S2 than in S3. One can deduce that the long annealing of S3 activates this center. Indeed, in a previous work [28] we reported efficient activation of defects by annealing AlGaN. Using the calculation model in [29] we estimated the capture cross-section of our center to $\sigma = 2\times10^{-16}$ cm^2

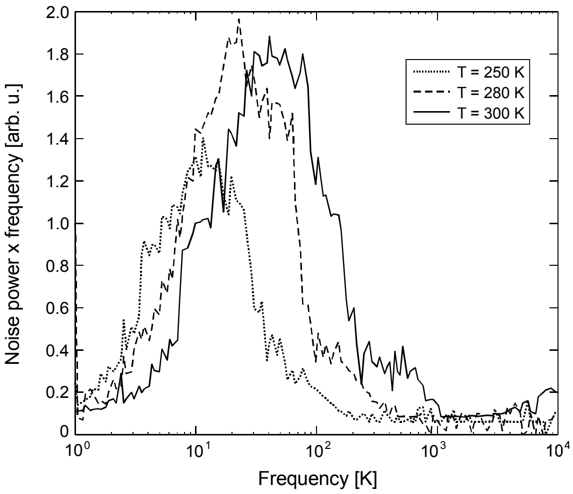

Fig. 8. Generation-recombination noise component obtained after multiplying the spectrum by the frequency *f* at various temperatures.

at 250 K. NGUYEN *et al.* [30] have also reported compression in the drain current in AlGaN. They reported slow decay transients in the drain current with time. These authors attributed the behavior to the loss of free electrons due to trapping by defects in the AlGaN layer. The low capture cross-section we measured for our center along with the high capture barrier is compatible with a slow relaxation in the drain current due to trapping. If the defect is present in the material in significant concentration it can induce slow relaxation behavior in the current due to slow trapping of electrons by the center. Further measurements using complementary characterization techniques are in progress to elucidate the nature of this trap.

In conclusion Au/AlGaN/GaN structures were characterized using noise spectroscopy. We observed a center located in the AlGaN side close to the GaN layer. The emission and capture barriers of this energy level were calculated. We show that the defect has a DX-like metastable nature and may be responsible for a part of the PPC in AlGaN. Also, the center is activated by annealing and therefore it may be a defect that migrates from the GaN layer into AlGaN.

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