Low-frequency noise in GaN thin films deposited by rf-plasma assisted molecular-beam epitaxy

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We report detailed investigations of low-frequency excess noise in GaN thin-film cross-bridge structures deposited by rf-plasma assisted molecular-beam epitaxy on top of an intermediate-temperature buffer layer (ITBL) grown at 690 °C. The experimental data indicates strong dependence of the voltage noise power spectra on the thickness of the ITBL with an optimal thickness of 800 nm. A model has been presented to account for the observed noise, which stipulates that the phenomenon arises from the thermally activated trapping and detrapping of carriers. The process results in the correlated fluctuations in both the carrier number and the Coulombic scattering rate. Detailed computation shows that number fluctuation dominates in our samples. Our numerical evaluation indicates a reduction in the trap density by over an order of magnitude with the use of an ITBL in the growth of GaN thin films.
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I. INTRODUCTION

Gallium nitride and its alloys have many attractive physical properties that have made the material of choice for various optoelectronic and electronic applications. In the past several years, III-nitride based blue-green light emitters and ultraviolet (UV) detectors have been commercialized. The high electron saturation velocity, large breakdown field, high thermal conductivity, and superb mechanical stability are among the most important qualities that have made the III-nitrides excellent candidates for high-temperature and high-power electronic applications at high frequencies.[1–4] However, it has been well documented that the lack of a native substrate remains to be the main bottleneck for the development of III-nitride based technology. Sapphire substrates are commonly used for its relative low price and stability at high temperatures. Due to the large mismatch in the lattice constants between GaN and sapphire, GaN epilayers typically exhibit high defect concentration and poor crystallinity.[5] To improve the quality of GaN epitaxial layer on sapphire, the most common practice is to deposit the GaN epilayer on a low-temperature buffer layer (LTBL), which is typically grown at 500 °C of thickness about 40–50 nm. The role of the buffer layer has been studied extensively. It was found that the AlN or GaN LTBL serves to enhance two-dimensional growth and the density of nucleation for the epitaxial films.[6] This is because the interfacial energy for the AlN or GaN/buffer system is found to be significantly lower than the GaN/sapphire system.[7–9]

The use of the LTBL is highly effective in the improvement of GaN film quality deposited by the metalorganic chemical vapor deposition (MOCVD) technique. The effects of the LTBL have been less pronounced in molecular-beam epitaxy (MBE)-grown materials. To date, MOCVD-grown GaN films are superior to the (MBE) grown counterparts. Nevertheless, the MBE growth technique does have a number of advantages, particularly in the growth of the modulation-doped structure and solar-blind UV detectors.[10] It is therefore important to investigate the optimization of the growth parameters for improving the MBE-grown GaN film quality.

Low-frequency excess noise is an important figure-of-merit for optoelectronic devices. Not only does it represent the smallest signal the device is capable of handling, it is also a powerful technique for the characterization of defect states in the material. Recent studies of low-frequency excess noise in GaN thin films, deposited by electron cyclotron resonance-MBE technique, indicated the presence of deep levels at about 0.4 eV.[11] Experimental studies on thermally stimulated current in MOCVD-grown films indicated multiple deep levels at energy ranging from 0.11 to 0.62 eV. The concentration of the deep levels was estimated to be 10^{17} to 10^{18} cm^{-3}.[12] On the other hand, Kuksenkov *et al.*[13] reported low-frequency noise dominated by $1/f^{\gamma}$ fluctuations on samples prepared by MOCVD. They reported a Hooge parameter of approximately 3. Such a large Hooge parameter stipulates a highly defective material and the deep levels may be buried by traps that are broadly distributed in energy. Such traps are known to have caused low-frequency fluctuations with noise power spectral density of the form $1/f^{\gamma}$. The trap origin of flicker noise has been clearly demonstrated in the study of rapid thermal annealing of GaN thin films. The results show that annealing at about 800 °C leads to the significant reduction in the Hooge parameter from about 8.6×10^{-2} to about 1×10^{-2}.[14]

Recent work by the authors show the incorporation of an intermediate-temperature buffer layer (ITBL) results in substantial improvements in both the optical and electronic properties.[15] A high room-temperature electron mobility of 430 $cm^2\,V^{-1}\,s^{-1}$ has been reached. Furthermore, deep-

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levels-related yellow emission that is four orders of magnitude below the main photoluminescence (PL) peak has been obtained at 15 K. It is important to characterize how the ITBL affects the defect concentration in GaN films since crystalline defects are known to have substantial effects on the operation of optoelectronic and electronic devices.[16,17] In the following sections, we will present detailed experimental results on low-frequency noise for the characterization of deep levels in GaN thin films deposited on sapphire substrates by rf-plasma assisted MBE with the use of ITBLs.

II. EXPERIMENT AND RESULTS

Gallium nitride thin films were deposited on sapphire (0001) substrates. The substrate was first cleaned using a standard cleaning procedure. It was then outgassed at 800 °C, which was followed by a nitridation process within the growth chamber at 500 °C. A conventional LTBL, of thickness about 40 nm, was grown at 500 °C. An ITBL was then deposited on top of the conventional buffer layer at 690 °C. Samples B, C, and D were fabricated with ITBL thickness of 400 nm, 800 nm, and 1.2 μm, respectively. On top of the ITBL, a GaN epitaxial layer of thickness 1.8 μm was deposited at 740 °C for each of the samples. Sample A, which has a 2.6 μm thick GaN epitaxial layer and no ITBL, was used as the control device. The thickness of sample A is chosen such that it matches with the total thickness of the ITBL and GaN epitaxial in sample C. Thus, the improvement in the film quality for sample C can be shown to arise from the utilization of the ITBL instead of simply due to the increase in the total film thickness alone.

Cross-bridge devices, of dimension 110 μm$\times$40 μm, were fabricated by wet etching using molten KOH to facilitate four-probe measurement of low-frequency excess noise at a wide range of temperatures. Typical values for room-temperature resistance measured across the samples is of the order 10 kΩ. Ohmic contacts were accomplished by sputter deposition of Ti/Al bilayers. All the samples were slightly doped with Si. Hall effect measurement on the cross-bridge structures were conducted to estimate the carrier concentration. For sample C, there are two conductive layers—the ITBL and the epitaxial layer. The carrier concentration of the epitaxial layer is estimated using a simple two-layer model as described in a recent publication which indicates that the carrier concentration for all the different samples are roughly 3×10^{17} cm^{-3}.[18]

Low-frequency excess noise was examined from room temperature to 77 K with the devices under current biased at a fixed voltage of 0.5 V. The devices were placed inside an exchange gas cryostat and the device temperature was controlled by a Lakeshore 91C temperature controller with a silicon diode sensor. An all-passive resistor inductor and capacitor (RLC) filter was used to filter the Lakeshore 91C current supplied to the heater to eliminate extraneous noise from the power line. The temperature controller is capable of stabilizing the device temperature to within 15 mK. The fluctuating voltage across the device was amplified by a PAR 113 low-noise preamplifier. The system was placed inside a shielded room. The amplified noise was then coupled to an HP3561A dynamic signal analyzer for the measurement of voltage noise power spectra.[19–20] Experimental results indicate that the low-frequency excess noise in our samples are at least 2–3 orders of magnitude above the thermal noise level.

Typical room-temperature voltage noise power spectra, $S_V(f)$, is shown in Fig. 1. The experimental data shows that at the low-frequency regime, $S_V(f)$ is found to consist of flicker noise superimposed with a Lorentzian bump. The inset of Fig. 1 clearly indicates typical dependence of the voltage noise power spectra on the voltage bias of the device. The data clearly indicates a quadratic dependence of $S_V(f)$ on the biasing voltage. This eliminates the possibility that the noise may be affected by the measurement equipment or other extraneous noise. The room-temperature Hooge parameters evaluated from the experimental data are 3.03×10^{-1}, 1.82×10^{-1}, 7.34×10^{-2}, and 2.19×10^{-1} for samples A, B, C, and D, respectively. We observe that there is a systematic reduction in the Hooge parameter with the minimum value obtained for sample C. It is interesting to note that although a lower Hooge parameter can be accomplished by rapid thermal annealing of GaN thin films grown without ITBL,[14] the electron mobility of the films remains to be quite low at about 150 cm^2 V^{-1} s^{-1}. In addition, the yellow emission of the films, although significantly reduced subsequent to rapid thermal annealing, remains to be relatively high. It is desirable to investigate growth techniques that lead to the improvements in all different aspects of optoelectronic properties.

At low-temperatures, the Lorentzian bumps become much more prominent, indicative of the domination of the low-frequency noise by generation-recombination ($G-R$) processes. Typical results on the product of $S_V(f)$ and f as a function of frequency are shown in Fig. 2. In this case, $1/f$ noise will appear as a horizontal line, whereas a peak will be clearly identified in a Lorentzian bump. Figure 2 clearly demonstrates the shift in the cutoff frequency in response to the variation in temperature. Previous study of $G-R$ noise has shown that[21]

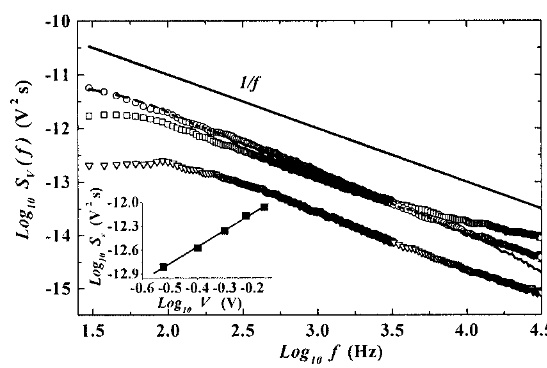

FIG. 1. Room-temperature voltage noise power spectral density of GaN thin films on various thicknesses of ITBLs: sample A (— - —); sample B (□); sample C (▽); and sample D (○). The solid line is $1/f$ spectrum for visual comparison. The inset shows the bias dependence of S_V for sample B (■) at 316 Hz.

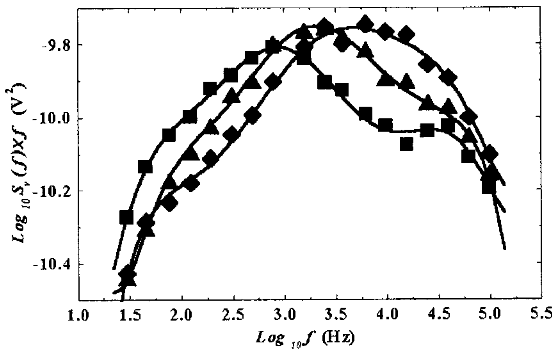

FIG. 2. Typical experimental results on $S_V(f)\times f$ for sample B at 96.4 K (■), 101.6 K (▲) and 108.3 K (♦).

$$S_V(f)=4N_T\Omega(\Delta I_0)^2R^2f_T(1-f_T)\frac{\tau}{1+4\pi^2f^2\tau^2},$$

$$=S_0\frac{\tau}{1+4\pi^2f^2\tau^2}, \tag{1}$$

where N_T is the trap density, R is the device resistance, ΔI_0 is the current fluctuation due to the capture of a single carrier, Ω is the total volume of the device, and τ is the fluctuation time constant. Experimentally, one obtains the values of τ from the reciprocal of the frequency of the Lorentzian bump. The Arrhenius plots of τ for samples A, B, C, and D are given in Fig. 3. The results show that the activation energy for the traps responsible for the observed $G-R$ noise is around 114 to 119 meV. The variation in the activation energies is well within experimental scatter. It is, therefore, reasonable to believe that the $G-R$ noise measured from different samples originate from traps of the same physical nature. From Eq. (1), the temperature dependence of S_0 is dominated by the Fermi Dirac factor, which peaks at the temperature where the Fermi energy, E_F, crosses the energy level of the trap.[22,23] Figure 4 exhibits $\log_{10}(S_0)$ plotted against $1/T$ for the different samples. From the data, we observe a systematic reduction of S_0 as a function of the ITBL thickness. The minimum value for S_0 is obtained for an ITBL thickness of 800 nm. Upon further increase in the ITBL thickness, a rebound in S_0 is observed.

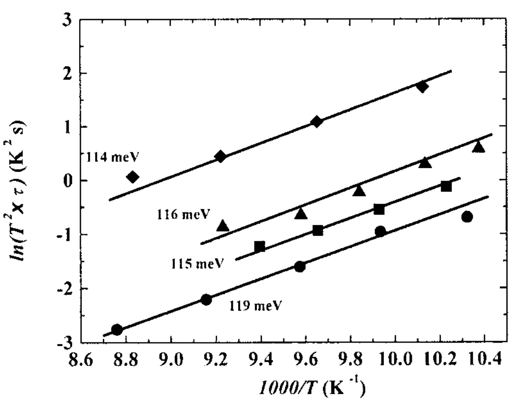

FIG. 3. Arrhenius plots of the fluctuation time constant, τ, for sample A (♦), sample B (▲), sample C (●), and sample D (■).

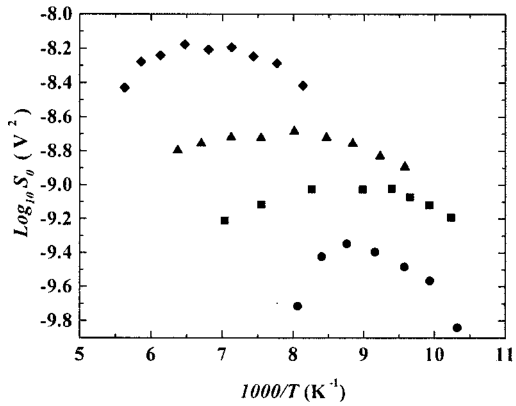

FIG. 4. Low frequency $G-R$ noise magnitude $\log_{10}(S_0)$ is plotted as a function of $1000/T$: for sample A (♦), sample B (▲), sample C (●), and sample D (■).

III. DISCUSSION

From the experimental data, we observe that $G-R$ process constitutes an important component of low-frequency excess noise. The $G-R$ noise is found to be thermally activated with activation energies about 114 to 119 meV. This is indicative of the trap origin of the noise, whereby electrons are randomly captured and emitted by localized states through a thermally activated process and the activation energy corresponds to the difference between the Fermi level and the energy level of the trap. The physical nature of the traps, other than the activation energy, cannot be determined based on low-frequency noise measurement alone. In general, it is assumed that these traps arise from crystalline defects or impurities. It is not known if any of the traps responsible for the observed noise are associated with the dislocation defects, which are prevalently found in III-nitride thin films. It has been shown that traps that are distributed over a wide energy range will lead to a voltage noise power spectral density that is roughly inversely proportional to the frequency of the form $1/f^\gamma$, where γ approximately equals 1. However, in the case, where the trap concentrations at some discrete energy levels are substantially higher than the rest, one will observe Lorentzian bumps corresponding to those energy levels.[24,25] Thus, our experimental results clearly indicate that traps distributed over an broad energy range are seen in our samples. However, occasionally there are certain energy levels with significantly higher defect levels. This will give rise to $1/f^\gamma$ noise superimposed with Lorentzian bumps as seen in our experimental data.

It is noted that the trapping and detrapping process leads to a change in the charge state of the trap. This affects the local Fermi level and consequently results in the modulation of the local carrier concentration. In addition, this also results in the correlated fluctuation in the Coulombic scattering rate, thereby causing a fluctuation in the electron mobility. This phenomenon is described by the following mathematical expression

$$\delta v=\delta v_\mu+\delta v_n, \tag{2}$$

where δv_μ and δv_n are the voltage fluctuations arising from mobility fluctuations and number fluctuations, respectively.[26] The autocorrelation function for the fluctuating voltage is then given by

$$\begin{aligned}\langle \delta\nu(t)\,\delta\nu(t+t_0)\rangle &= \langle[\delta\nu_n(t)+\delta\nu_\mu(t)][\delta\nu_n(t+t_0)\\ &\quad +\delta\nu_\mu(t+t_0)]\rangle,\\ &= \langle \delta\nu_n(t)\,\delta\nu_n(t+t_0)\rangle + \langle \delta\nu_\mu(t)\,\delta\nu_\mu\\ &\quad \times(t+t_0)\rangle + \langle \delta\nu_n(t)\,\delta\nu_\mu(t+t_0)\rangle\\ &\quad + \langle \delta\nu_\mu(t)\,\delta\nu_n(t+t_0)\rangle, \end{aligned} \tag{3}$$

where t_0 is the time displacement. Wiener–Khintchine theorem stipulates that the Fourier transform of Eq. (3) gives the total voltage noise power spectral density, $S_V(f)$, due to trapping and detrapping processes in the device. The first term on the right-hand side of Eq. (3) arises from number fluctuations, the second term arises from mobility fluctuations due to the modulation of the Coulombic scattering rates, and the third and fourth terms arise from the cross-correlation between number and mobility fluctuations.[27]

We first derive the mobility fluctuation arising from the capture and emission of carriers by localized states using the Conwell–Weisskopf model, which states that the mobility due to Coulombic scattering by ionized states is given by[28]

$$\mu_T = \frac{64\sqrt{\pi}\epsilon_0^2\epsilon_s^2(2k_BT)^{3/2}}{N_T q^3 m^{*1/2}\ln[1+(12\pi\epsilon_0\epsilon_s k_B T/q^2N_T^{1/3})^2]}. \tag{4}$$

Here, the term N_T is the trap density that is responsible for the observed $G-R$ noise. Thus, Equation (4) corresponds to the mobility due to ionized trap scattering. We note that the logarithmic term in the denominator of Eq. (4) is only weakly dependent on temperature and practically unchanged by the fluctuations in N_T due to the trapping and detrapping process. Then μ_T can be approximated by $CT^{3/2}/N_T$, where C is the proportionality constant. The noise power spectral density for μ_T is related to noise power spectral density of the occupancy of N_T by the following expression

$$\begin{aligned} S_{\mu_T}(f) &= \left(\frac{\partial\mu_T}{\partial N_T}\right)^2 S_{N_T}(f),\\ &= \frac{C^2T^3}{N_T^4} S_{N_T}(f). \end{aligned} \tag{5}$$

The fluctuation in μ_T causes a corresponding fluctuation in the overall electron mobility μ. From this, one obtains

$$\begin{aligned} S_\mu(f) &= \left(\frac{\mu^4}{\mu_T^4}\right) S_{\mu_T}(f),\\ &= 4\,\frac{\mu^4}{C^2T^3} N_T\Omega f_T(1-f_T)\,\frac{\tau}{1+4\pi^2f^2\tau^2}, \end{aligned} \tag{6}$$

where $S_\mu(f)$ is noise power spectral density of the electron mobility. Thus, the voltage noise power spectral density arising from mobility fluctuations is given by[29]

$$S_{V\mu}(f) = 4\,\frac{V^2\mu^2}{C^2T^3} N_T\Omega f_T(1-f_T)\,\frac{\tau}{1+4\pi^2f^2\tau^2}, \tag{7}$$

where V is the dc voltage bias applied to the device.

To determine $S_{Vn}(f)$, we assume that $\delta n = \delta N_T$, where n is the carrier density. From this the voltage noise power spectral density arising from number fluctuation is shown to be[30]

$$\begin{aligned} S_{Vn}(f) &= \frac{V^2}{N^2} S_{N_T}(f),\\ &= \frac{V^2}{N^2} 4N_T\Omega f_T(1-f_T)\,\frac{\tau}{1+4\pi^2f^2\tau^2}, \end{aligned} \tag{8}$$

where N is the number of carriers in the device. Detailed numerical evaluation of Eqs. (7) and (8) shows that $S_{Vn}(f)$ dominates over $S_{V\mu}(f)$ for our devices and as a result $S_V(f)\approx S_{Vn}(f)$.

It is important to note that sample A has two conduction layers deposited at two different temperatures. It is necessary to consider the noise source from each independent layer separately in order to obtain an accurate estimation of the noise in the epitaxial layer. In a recent publication, the authors have presented a two-layer model in which the noise source from the ITBL is parallel to that of the epitaxial layer. It is shown that the total noise voltage, $\overline{V_{\text{total}}^2}$, over the entire structure is given by

$$\overline{V_{\text{total}}^2} = \left(\frac{R_2}{R_1+R_2}\right)^2\overline{V_1^2} + \left(\frac{R_1}{R_1+R_2}\right)^2\overline{V_2^2} \tag{9}$$

where R_1, R_2, $\overline{V_1^2}$, and $\overline{V_2^2}$ are the resistance of the ITBL, the resistance of the epitaxial layer, the noise voltage of the ITBL and the noise voltage of the epitaxial layer, respectively. To obtain $\overline{V_1^2}$, a similar cross-bridge structure was fabricated on an ITBL alone to facilitate the direct measurement of $\overline{V_1^2}$. Substituting the results into Eq. (9), one can determine $\overline{V_2^2}$.

Based on this model, the trap densities for our samples are found to be $3.0\times10^{18}\ \text{cm}^{-3}$, $4.0\times10^{17}\ \text{cm}^{-3}$, $1.5\times10^{17}\ \text{cm}^{-3}$, and $3.5\times10^{17}\ \text{cm}^{-3}$ for samples A, B, C, and D, respectively. Our experimental results clearly show that the use of ITBL can effectively reduce defect density in MBE-grown GaN epitaxial layers. The optimal thickness for the ITBL is found to be around 800 nm. The trap density appears to experience a rebound when the ITBL thickness exceeds 800 nm. Lastly, it is important to note that recent experiment on mobility and PL measurements revealed the same dependencies of the electronic and optical properties of GaN films on the thickness of the ITBL.[15,31] Our experimental results clearly show that ITBL is an effective technique for the improvement of the GaN film quality.

IV. CONCLUSIONS

We have conducted detailed experiment on the characterization of low-frequency excess noise in rf-plasma MBE-grown GaN epitaxial layers on different thickness of intermediate-temperature buffer layers. The observed $G-R$ noise is found to be thermally activated with activation energies between 114 and 119 meV. The results are indicative of trap origin of the noise whereby the capture and emission of carriers result in the correlated fluctuations of the electron mobility and concentration. A model for the noise, based on first-principle calculation, is presented. Model evaluation shows that the noise is dominated by number fluctuations. Numerical computation of the trap density shows that the use of ITBL leads to over an order of magnitude reduction in the defect density with an optimal ITBL thickness of 800 nm.

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