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Low-frequency noise in *n*-GaN with high electron mobility

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We report on the results of measurements of low frequency noise in *n*-type gallium nitride (GaN) grown on sapphire with 300 K electron mobility of 790 $cm^2/V\,s$. The noise spectra have the form of $1/f$ noise with a Hooge parameter α of approximately 5×10^{-2}. This value of α is two orders of magnitude smaller than that observed before in *n*-GaN. The obtained results show that the level of flicker noise in GaN, just like that in GaAs and Si, strongly depends on the structural perfection of the material (the amplitude of the $1/f$ noise is much smaller in material with high mobility). The effects of band-to-band illumination on the low-frequency noise show that $1/f$ noise in GaN might be caused by the occupancy fluctuations of the tail states near the band edges. This mechanism of the $1/f$ noise is similar to that in GaAs and Si. *© 1999 American Institute of Physics.* [S0021-8979(99)07521-0]

I. INTRODUCTION

Gallium nitride (GaN) has an excellent potential for high temperature, high frequency, and high power microwave applications. Blue and violet light emitting diodes based on GaN have been commercialized, and GaN-based lasers, UV visible-blind photodetectors, and piezoelectric sensors have also been demonstrated (see, for example, Refs. 1–3). The level of the low-frequency noise is one of the most important parameters, which determines whether the devices are suitable for microwave and optical communication systems. First estimates of the low-frequency noise level in *n*-GaN were made using visible-blind GaN *p-n* junction photodetectors.[4,5] The estimated α value was very high ($\alpha \approx 3$). This value is comparable with the values of α for such disordered materials as conducting polymers.[6] The results obtained for *n*-GaN resistors confirmed these data.[7,8]

One might suggest several possible reasons for such a large $1/f$-noise level. The level of the $1/f$ noise is much higher for a semiconductor material with imperfections (see, for example, Ref. 9). Among other factors, a high dislocation density strongly increases the level of $1/f$ noise in certain cases.[10,11] The measured dislocation density in GaN samples grown on sapphire is on the order of $10^9-10^{10}\,cm^{-2}$.[12] On the other hand, theory[9,13] predicts that the level of $1/f$ noise should be proportional to the density of the tail states near the band edges. (It is worth noting that the density of states in the band tails depends also on the structural perfection of the material).[14,15] The density of states in the conduction band tail in GaN is much higher than that for Si and GaAs (see, for example, Ref. 16).

Structural perfection of a semiconductor is often estimated based on the values of the low-field carrier mobility. For the samples used in Refs. 7 and 8, the electron mobility μ_n was approximately 60 $cm^2/V\,s$ and was practically temperature independent in the range between 77 and 400 K.

In this article, we report on the results of the measurements of the low-frequency noise in the samples grown on sapphire substrates with $\mu_n = 790\,cm^2/V\,s$ at 300 K, and with the temperature dependence $\mu_n(T)$ close to that predicted by theory.[17]

II. EXPERIMENTAL DETAILS

The 20-μm-thick sample was grown by hydride vapor phase epitaxy on sapphire. Sputtered ZnO was used as a buffer layer between the sapphire and GaN, but the ZnO was no longer present after completion of the growth.[18] Except for a highly defective interface region of a few thousand angstroms thickness, the sample was of very high quality, with a 300 K mobility of 790 $cm^2/V\,s$, and a carrier concentration of $1.28\times10^{17}\,cm^{-3}$. Fits to the temperature-dependent Hall data in the bulk region yielded donor and acceptor concentrations of 2.1×10^{17} and $5\times10^{16}\,cm^{-3}$, re-

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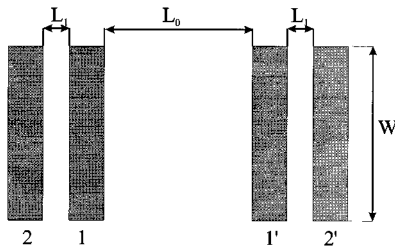

FIG. 1. Top view of the sample geometry. $L_0=1100$, $L_1=80$, $W=250\ \mu$m, the thickness of the film $t=20\ \mu$m.

spectively, and a donor activation energy of 16 meV. The interface region, on the other hand, was strongly degenerate, with a sheet carrier concentration of $8\times10^{14}\,\text{cm}^{-2}$ and an electron mobility of 55 cm^2/V s. Further information on the electrical properties can be found in Ref. 19. Ti (54 Å)–Al (1920 Å) contacts were deposited on the surface of the film and annealed at a temperature of 550 °C for 2 min. The contact resistance, R_c, has been estimated using a transmission line model measurement.[20]

Low-frequency noise was measured between contacts 1 and 2, and 1 and 1′ (see Fig. 1) in the dark and under band-to-band illumination. Current–voltage characteristics measured between the contacts were linear and symmetrical with an accuracy of approximately 1%.

Resistance R_{12} between contacts 1 and 2 was equal to 9.85 Ω; resistance R_{11}, between the contacts 1 and 1′ was equal to 30.2 Ω. The estimated contact resistance was approximately 1.9 Ω for both configurations.

III. RESULTS AND DISCUSSIONS

Figure 2 shows the frequency dependencies of the noise relative spectral density measured between the contacts 1 and 2. In the dark (curve 1), the noise is typical 1/*f* (flicker) noise.

The flicker noise level in different materials is frequently characterized by the dimensionless Hooge parameter, α[21]

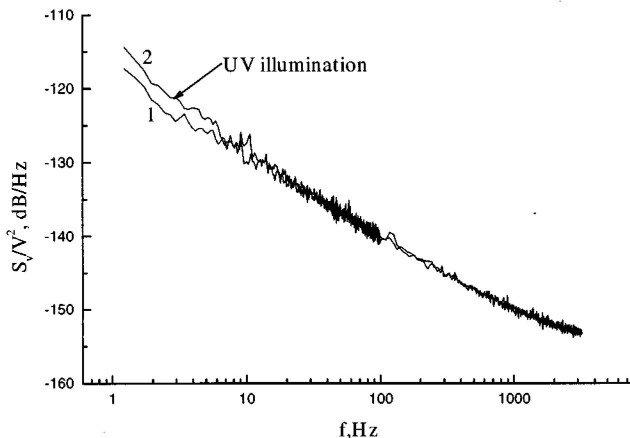

FIG. 2. Frequency dependencies of the current noise relative spectral density S_v/V^2 in the dark (curve 1) and under band-to-band illumination (curve 2) measured between contacts 1 and 2.

$$\alpha=\frac{S_V}{V_o^2}fN, \tag{1}$$

where $N=L_1\times W\times t\times n_0$ is the total number of the conduction electrons in the sample (determined for the homogeneous situation as the value of the carrier density times the sample volume), f is the frequency, $V_o=IR_{12}$ is the voltage drop between contacts. The value of α calculated accordingly for the data presented in Fig. 2 is equal to $\sim5\times10^{-2}$. This value is two orders of magnitude smaller than values of α in *n*-GaN reported earlier.[4,5,7,8] Nevertheless, even this relatively low value of α is overestimated for two reasons.

First, as usual for two-probe measurements, the contacts can give an essential contribution to the overall low-frequency noise.[22] Second, the obtained estimate is valid for a fully homogeneous current density distribution. However, in our case, the contacts penetrate into the GaN film not more than for a fraction of a micron. Estimated transfer length is $L_T=(6\text{-}8)\ \mu m$. Therefore, the current density j close to and under the contacts is substantially larger than the average current density across the sample. The noise spectral density S_V strongly depends on j: [21]

$$S_V=\frac{1}{\text{I}^2}\int\int\int\frac{\alpha\rho^2j^4}{nf}dv, \tag{2}$$

where $\rho=1/\sigma$ is the local resistivity, and n is the local electron concentration. The integral in Eq. (2) should be taken over the whole sample. However due to very strong dependence of S_V on j, the effective value of the total number of conduction electrons N in Eq. (1) (and, therefore, the value of α) should be less than the value of $N=L\times W\times t\times n_0$ used in the estimate for a homogeneous case. In fact, a relatively small region close to the contacts could make a dominant contribution to the 1/*f* noise.

Curve 2 in Fig. 2 presents the results under band-to-band illumination with an incandescent lamp. At a given illumination intensity, the photoconductivity $\sigma/\sigma_0\approx2\times10^{-2}$. The effect of the illumination is relatively weak. However the qualitative effect is quite similar to that for Si and GaAs.[9,23] The illumination has no effect at higher frequencies and increases the noise at relatively low frequencies.

Figure 3 shows the frequency dependencies of the noise relative spectral density measured between the contacts 1 and 1′. The curve measured in the dark (curve 1) has the form of 1/*f* noise (flicker) noise. Comparing curves 1 in Figs. 2 and 3 one can see that the difference in the level of the dark noise is rather small for these two very different electrode configurations. The noise measured between contacts 1 and 1′ should be considerably less than that between contacts 1 and 2. It is clear that the total number of the conduction electrons involved is substantially smaller for the case represented in Fig. 2 (contacts 1 and 2) compared to that shown in Fig. 3 (contacts 1 and 1′) provided the metal contacts penetrated the whole depth of the film.

A crude estimate for the expected noise level measured between contacts 1 and 1′ can be obtained using the results of Ref. 24. According to these results, if the distance between the contacts L_0 is much larger than the width of the

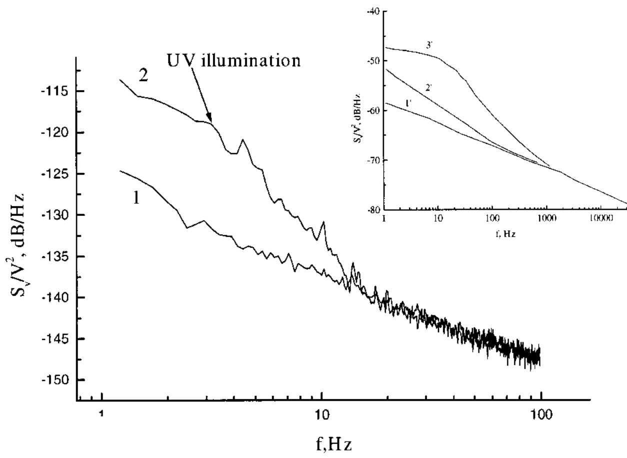

FIG. 3. Frequency dependencies of the current noise relative spectral density S_v/V^2 in the dark (curve 1) and under band-to-band illumination (curve 2) measured between contacts 1 and 1′. Inset shows the theoretical frequency dependencies of the noise spectral density under band-to-band illumination, which changes the occupancy of the tail levels responsible for the $1/f$ noise. 1′. $b=0$, 2′. $b=10^{-16}$. 3′. $b=10^{-15}$. Here b is a parameter which is approximately proportional to the illumination intensity (see Ref. 23).

contacts W ($L_0 \gg W$, see Fig. 1), the rectangular contacts can be approximated by circular contacts with the effective radius $r_{\mathrm{eff}}=W/4$. For such contacts (at $L_0 \gg W$) the integral (2) can be evaluated to yield

$$S_V=\frac{1}{I^2}\int\int\int\frac{\alpha\rho^2 j^4}{nf}dv$$
$$=\frac{\alpha\times t\times\sigma^2}{n_0\times f\times I^2}\int\int E^4 ds$$
$$=\frac{\alpha\times V_0^2}{16\pi^2\times t\times n_0\times f\times r_{\mathrm{eff}}^2\times\ln^2\left(\frac{2L_0}{r_{\mathrm{eff}}}\right)}, \quad (3)$$

where t is the thickness of the film, $r_{\mathrm{eff}}=W/4$ (see Fig. 1), and V_0 is the bias applied between the circular contacts. Hence,

$$\alpha=\frac{S_V}{V_0^2}\times f\times 16\pi^2\times n_0\times r_{\mathrm{eff}}^2\times t\times\ln^2\left(\frac{2L_0}{r_{\mathrm{eff}}}\right). \quad (4)$$

Comparing Eqs. (1) and (4) with $t=20\,\mu\mathrm{m}$, $r_{\mathrm{eff}}=60\,\mu\mathrm{m}$, and $L_0=1100\,\mu\mathrm{m}$, one can conclude that the flicker noise measured between contacts 1 and 1′ at the same frequency f should be ≈25 dB smaller. However, the measured difference in the noise levels is only ≈7 dB (compare curves 1 in Figs. 2 and 3).

Once again, these results demonstrate that relatively small regions close to the surface contacts disproportionally contribute to the noise, and the deduced value of $\alpha\approx 5\times 10^{-2}$ is only an upper bound for α.

Curve 2 in Fig. 3 represents the results under band-to-band illumination. At a given illumination intensity, the photoconductivity $\sigma/\sigma_0\approx 5\times 10^{-3}$. Despite the fact that this photoconductivity is less than that for the case represented in Fig. 2, the effect of the band-to-band illumination is much stronger. Qualitatively, the curves 2 in Figs. 2 and 3 are very similar: the illumination has no effect at the higher frequencies of analysis and increases the noise at relatively low frequencies.

Such an effect of band-to-band illumination on the $1/f$ noise was analyzed in detail for Si samples in Ref. 25 using the model of $1/f$ noise developed in Ref. 13 (see the inset in Fig. 3). Based on the multiphonon capture mechanism,[26] the model predicts that the capture time constant τ exponentially increases with the energy of the levels in the tail of density of states, E ($E=0$ at the conduction band boundary)

$$\tau(E)=\tau_0\times\exp(E/E_1). \quad (5)$$

Here E_1 is a characteristic energy of the capture cross-section reduction. (For Si, $E_1=5$ meV;[25] for GaAs, $E_1=10$ meV.)[9]

The holes generated as a result of band-to-band illumination are captured by the tail states. This process is accompanied by changes in the level occupancy and, hence, by changes in the noise generated by the tail levels of energy E. The probability of hole capture by the tail states is independent of energy E. However, the level occupancy under steady state conditions very strongly depends on E because the electron capture time τ for the empty levels exponentially depends on energy [see Eq. (5)].

Weak illumination has practically no effect on the level occupancy for the levels at low energy, E. Such levels are responsible for the $1/f$ noise at relatively high frequencies because the electron capture time for these levels is rather small.

The levels with large energies are practically fully emptied even at very low illumination intensities, since the electron capture time for these levels is exponentially large. Such ''deep'' levels are responsible for the noise at the very low frequencies. Therefore, one can expect that at very low frequencies the spectral density of noise is frequency independent (see curve 3 in the inset). Such an effect has been observed in Si and GaAs.[9]

At intermediate frequencies (i.e., for the levels with intermediate energies, E), the holes captured by the tail levels reduce the level occupancy, F ($F\approx 2/3$ for the maximum noise level-generated noise).

IV. CONCLUSIONS

The comparison of the observed effect of band-to-band illumination on the low-frequency noise (see Fig. 3) with the theory (see the inset) shows that the nature of the $1/f$ noise in GaN should be similar to that in GaAs and Si. The $1/f$ noise is caused by the fluctuations of the occupancy of the tail states near the band edges.

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