Origin of conductivity and low-frequency noise in reverse-biased GaN *p-n* junction

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We study the origins of conductivity and low-frequency noise in GaN *p-n* junctions under reverse bias. Carrier hopping through defect states in the space charge region is identified as the main mechanism responsible for low bias conductivity. Threading dislocations appear the most likely source of such defect states. At higher bias hopping is supplemented with Poole–Frenkel emission. A relatively high level of $1/f$-like noise is observed in the diode current. The bias and temperature dependencies of the noise current are investigated. © *1998 American Institute of Physics.* [S0003-6951(98)03811-X]

Gallium nitride (GaN) and its alloys offer a host of interesting applications in optoelectronics and high power electronics.[1] The technological interest has resulted in the development of crystal growth procedures capable of preparing high quality layers, heterostructures, and *p-n* junctions,[2] making it possible to study fundamental properties of electrical conduction in GaN.

The reverse-biased *p-n* junction of GaN presents an almost ideal vehicle for studies of defect-related conductivity at high electric fields. The depletion layer of such a *p-n* junction resembles an intrinsic semiconductor in that the Fermi level is at midgap. In addition, the built-in electric field in an abrupt junction can be as high as 10^5 V/cm, even at equilibrium, and can be easily increased with externally applied bias. On the other hand, the density of defects in epitaxial GaN, at least at present, is relatively high, with the dislocation density of 10^8–10^{10} cm^{-2}.

The structure used in our experiments was grown on sapphire by metal organic chemical vapor deposition (MOCVD), with the original purpose of fabricating solar-blind ultraviolet photodetectors.[3] It consisted of a thin AlN buffer layer, followed by 0.8 μm thick *n*-GaN ($n\sim 10^{18}$ cm^{-3}) and 2.2-μm-thick Mg-doped *p*-GaN layers. Reactive ion etching was used to define individual mesa diodes prior to ohmic contact deposition.

Reverse bias current–voltage ($I-V$) characteristics of GaN diodes were measured in the temperature range of 290–570 K. Figure 1 presents five curves taken on a 200×200 μm^2 device. All of the current–voltage ($I-V$) curves showed exponential increase in the dark current with the bias voltage. The currents also increased with temperature, and, for a given value of the reverse bias, the increase was approximately exponential.

The noise characteristics of the GaN diodes were measured in the frequency range of 1 Hz to 100 kHz using a low noise current preamplifier and a fast Fourier transform (FFT) spectrum analyzer. The bias was varied from -5 to -30 V, and the sample temperature from 298 to 523 K. The equipment was calibrated by measuring the room temperature noise current of a conventional 600 Ω resistor. The noise floor of the apparatus, determined by the noise parameters of the preamplifier, was $\sim 10^{-25}$ A^2/Hz. At elevated temperatures or high values of the reverse bias, where the current of the diode increased above $\sim$1 nA, the appearance of $1/f$ noise was observed. The results for a bias of -10 V and different temperatures are presented in Fig. 2. All of the measured noise spectra satisfy the usual relationship.

$$S_n = s_o \frac{I_d^2}{f^\gamma}, \tag{1}$$

where S_n is the spectral density of the noise current, I_d is the dark current, f is the frequency, and s_o and γ are fitting parameters. The value of γ was found to vary from 1.0 to 1.1. The values of s_o are plotted in Fig. 3 as a function of bias and temperature. The s_o decreased slightly with increasing bias and rapidly with increasing temperature. The data

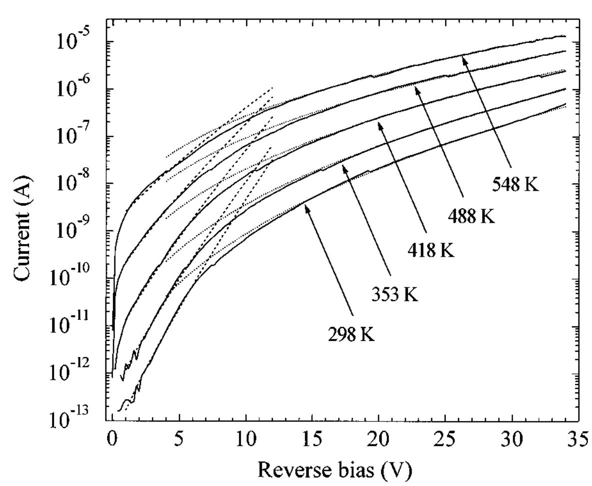

FIG. 1. Reverse bias branch of current–voltage characteristics for 200×200 μm photodiode at five different temperatures. Fitting results are shown by dashed lines for the low-bias data and by dotted lines for high-bias data.

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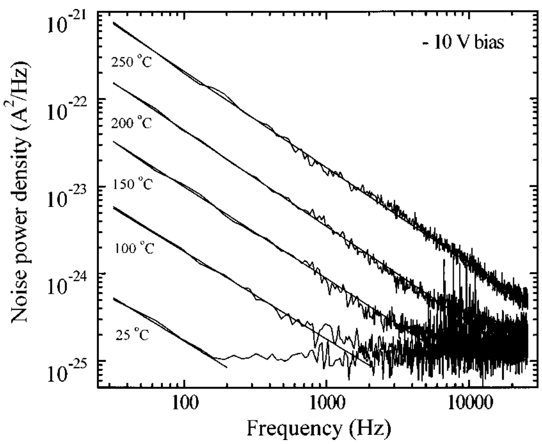

FIG. 2. Measured dark current noise spectra and corresponding fits at five different temperatures.

points for reverse bias of −5 V and temperatures below 450 K are absent in Fig. 3, because at these conditions the diode noise spectra were below the noise floor of our apparatus.

The exponential dependence of current on both the voltage and temperature is difficult to explain with conventional models of reverse-bias conductivity.[4] Measurements on devices with different sizes showed that the current scaled with the device area, rather than the perimeter of the active region, thus ruling out any significant contribution of leakage currents at the device mesa sidewalls. Due to the large band gap of GaN, and the extremely low thermal excitation rate, diffusion currents in the neutral region and generation-recombination (g-r) currents in the depletion region should be negligibly small. Even though the room temperature current for low reverse bias was less than 1 pA, that is still 10^6 times higher than the saturation current of $\sim 2\times 10^{-18}$ A expected from thermal excitation of carriers alone. Impact ionization in our diodes was observed only at a bias of ~ -42 V and this process is not, therefore, expected to contribute significantly to the measured $I-V$ characteristics. Finally, direct band-to-band or trap assisted tunneling current has exponential voltage dependence, but should be only weakly dependent on temperature.

We show that the conductivity of GaN diodes can be

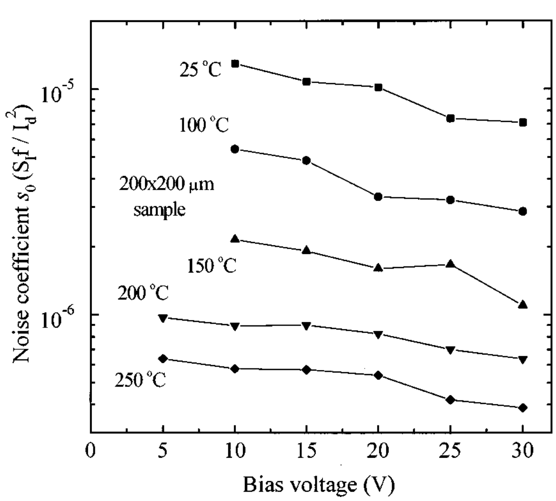

FIG. 3. Bias and temperature dependence of the proportionality coefficient between dark current and noise power.

modeled by assuming that the current is due to hopping of charged carriers via localized defect-related states (traps) in the depletion region. Hopping was studied extensively in amorphous semiconductors, where it was found to be the dominant mechanism of current flow, especially at low temperatures. Hill[5] and Pollak and Riess[6] concluded that for moderate electric fields the current-field dependence is described by

$$j=j(0)\exp\left(C\frac{eFa}{2kT}\left(\frac{T_0}{T}\right)^{1/4}\right), \tag{2}$$

where j is the current density, T_0 is a characteristic temperature parameter, T is the temperature, k is the Boltzman constant, F is the electric field, e is the electron charge, C is a constant of the order of unity, and a is the localization radius of the electron wave function. At very low fields hopping conductivity $\sigma(F)=j(F)/F$ is expected to follow Mott's law for variable-range hopping:[7]

$$\sigma(0)\propto \exp\left(-\left(\frac{T_0}{T}\right)^{\frac{1}{4}}\right), \tag{3}$$

where T_0 is the same parameter as in Eq. (2).

We use Eq. (2) to fit the experimental $I-V$ data for reverse biases ranging from −1 to −6 V. For this bias range, the total current through the p-n junction is equal to the saturation current originating in the depletion region and its density is given by Eq. (2). The depletion region width $w\sim 0.4$ μm was obtained from capacitance–voltage ($C-V$) characteristics. The average electric field at a given reverse bias V was then found from $F=(V+V_i)/w$, where V_i is the built-in junction voltage (estimated at ∼1 V), and substituted into Eq. (2). Assuming a localization radius $a=10$ Å,[6] the best fit to the experimental data at all temperatures, shown in Fig. 1 by dashed lines, is obtained for $C=0.4$, a median value between $C=0.8$ obtained by Hill[5] and $C=0.17$ obtained by Pollak and Riess.[6]

The value of T_0, extracted from the temperature dependence of the extrapolated zero-field current $j(0)$, is $T_0=1.16\times 10^{10}$ K. The density of states, per unit energy, taking part in the hopping conduction is then estimated as $N\approx 18/(kT_0a^3)$.[5] We obtain $N\sim 1.8\times 10^{16}$ cm^{-3} eV^{-1}. The T_0 estimated here is approximately three orders of magnitude higher than the $T_0\sim 10^7$ typical of amorphous semiconductors.[5] The corresponding value of N is three orders of magnitude lower, which explains the extremely strong temperature dependence of the reverse-bias current in our diodes. Dangling bonds at dislocation boundaries[8] appear the most likely source of localized states taking part in hopping conduction.

Equation (2) is expected to be valid only for fields $F \ll 2kT/ea \approx 5\times 10^5$ V/cm at room temperature. It is evident from Fig. 1 that the slope of measured $I-V$ characteristics changes noticeably for reverse bias voltages higher than ∼7 V, which corresponds to the electric field of $\sim 2.2\times 10^5$ V/cm. We believe that at higher bias the diode conductivity behavior can be explained by a combination of hopping and the Poole–Frenkel effect, or field-assisted thermal ionization of carriers from traps in the depletion region. The field dependence of the current density for Poole–Frenkel conduction is given by[9]

$$j=j_0\ \exp\left(\frac{\beta_{\mathrm{PF}}\ F^{1/2}}{kT}\right),\quad \beta_{\mathrm{PF}}=\left(\frac{e^3}{\pi\epsilon\epsilon_0}\right)^{1/2},\tag{4}$$

where j_0 is the low-field current density, β_{PF} is the Poole–Frenkel constant, ϵ_0 is the vacuum permittivity, and ε is the high-frequency dielectric constant of the material. For GaN, taking $\varepsilon(\infty)=5.35$, we calculate $\beta_{\mathrm{PF}}=3.3\times10^{-4}$ eV $\mathrm{V}^{-1/2}$ $\mathrm{cm}^{1/2}$.

The dotted lines in Fig. 1, calculated according to Eq. (4), demonstrate an excellent agreement with the experimental high bias data. At all temperatures, the best fit is obtained for $\beta_{\mathrm{PF}}=4.5\times10^{-4}$ eV $\mathrm{V}^{-1/2}$ $\mathrm{cm}^{1/2}$, about 1.4 times the theoretical value. It is interesting to note that for high bias, Eq. (2) predicts currents much higher than those observed experimentally. This can be explained by assuming that the width of the energy band of localized states near the Fermi level is limited to a certain value ΔE. The enhancement of hopping conduction with electric field will saturate when the energy acquired by a charge carrier moving against the field eFR, where R is the length of the jump, becomes comparable to Δ. Any further conductivity increase is due to the Poole–Frenkel emission. At room temperature, for $F=2.2\times10^5$ V/cm, we estimate $\Delta E\approx0.1$ eV. This width is typical of dislocation-related energy bands.[8] Consequently, we obtain $N'=N\Delta E\sim2\times10^{15}$ cm^{-3} for the spatial density of hopping conduction centers.

Hopping conductivity results in $1/f$ noise. Two models of such noise, the number fluctuation theory[10] and the ''mobility'' fluctuation theory,[11] have been proposed. The ''mobility'' fluctuation theory predicts a very weak temperature dependence of the low-frequency hopping noise and it does not appear applicable in our case. The number fluctuation theory results in the frequency dependence of the noise spectral density given by a well-known Hooge formula

$$S_n=\alpha\frac{I_d^2}{f\bar{N}},\tag{5}$$

where $\bar{N}$ is the average number of electrons taking part in the conduction process and the predicted value of the Hooge parameter α is of the order for unity. In the number fluctuation model, both the bias and temperature dependence of the parameter s_0 in Eq. (1) can be explained by the change in the number of hopping electrons $\bar{N}$. With increasing bias, $\bar{N}$ goes up due to increasing width of the depletion layer, and with temperature, due to decreasing length of a typical jump. More detailed quantitative analysis of the obtained noise data will be presented elsewhere.[12]

In summary, we have studied the origins of dark conductivity and low-frequency noise in reverse biased GaN p-n junctions. Hopping via defect-related states in the depletion region is found to be the dominant current mechanism. The density of localized states in the forbidden gap is estimated at 2×10^{15} cm^{-3} and these states are thought to be related to dislocations. The observed noise is of the $1/f$ character.

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