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Quantum $1/f$ noise in epitaxial lateral overgrown GaN: piezoelectric effect

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Abstract
Low-frequency noise has been investigated for epitaxial lateral overgrown (ELO) gallium nitride (ELO-GaN). The noise parameter α evaluated was about 2. The coherent piezoelectric quantum $1/f$ noise theory was applied to model the experimentally obtained α and excellent correlation was achieved. The high value of α indicates the significant contribution of the piezoelectric interaction and of the transversal acoustic phonon scattering mechanism.

1. Introduction

Studying noise in semiconductors is important for understanding the physical processes that govern the transport of carriers [1]. The most common type of noise encountered in semiconductors is flicker or $1/f$ noise [2]. Flicker noise always manifests itself as fluctuations in sample resistance and hence it is commonly known as resistance fluctuations [3]. In view of the experimental deviation of the values of the Hooge's parameter α_H, a universal $1/f$ noise theory, using the quantum mechanical approach, was formalized in an attempt to explain the inconsistency of α_H [4, 5]. The universality of the theory lies in the fact that any infraquanta with infrared divergent coupling to the current carriers will contribute $1/f$ noise proportional to the coupling constant. Therefore, it is now well accepted that resistance fluctuations are very much dependent on the particular system under investigation, although they are universal [2, 6].

In heterostructure systems with sufficiently thin layers, the lattice mismatch is accommodated by internal strains as well as the formation of misfit dislocations. In the first case, the internal strains induce polarization fields, which alter the carrier concentration in the immediate vicinity of the heterostructure layer by changing the local electric field and conduction band profile [7]. As wurtzite gallium nitride (GaN) is a ferroelectric material, sizable carrier densities can be induced through the action of the piezoelectric field at strained layer interfaces. In the second case, the misfit dislocation density is about 10^6 cm^{-2} for a typical epitaxial lateral overgrown (ELO) GaN and 10^8–10^{10} cm^{-2} for a typical Si-doped n$^+$-GaN:Si layer on sapphire (Al_2O_3) substrate [8]. Due to this high dislocation density, the transport property of GaN based materials has been attributed to dislocation scattering, which limits the carrier mobility [9, 10].

Scattering mechanisms associated with misfit dislocations in semiconductors are generally distinguished as being caused either by dislocation cores or by the long-range strain fields. In the core region, the modification in the number of first neighbours and the strong lattice distortion may result in the apparition of extrinsic levels, localized along the dislocation line [11]. Any ionization of these levels transforms dislocations into charged lines. Outside the core region, long-range strain fields may displace the ions from their ideal lattice sites and the resulting effect is usually described by means of the deformation potential. Yet, deformation potential effects are generally negligible in comparison with core effects. However, piezoelectric effect caused by moving dislocations long-range strain field may also contribute to the scattering mechanism in GaN. This scattering mechanism appears to be very efficient and may become the prominent effect, even when the core effects are present [11].

In piezoelectric crystals besides the long-range elastic field, dislocations possess long-range electric and polarization fields. For a wurtzite-structure crystal, the dislocation-induced electric field $\boldsymbol{E}$ can be evaluated from div $\varepsilon_0 \boldsymbol{E} = -$div $\boldsymbol{N}$ [12], where ε_0 is the dielectric constant and $N_i = e_{ikl}\varepsilon_{kl}$ is the polarization due to the electric field of the dislocation. Here e_{ikl} is the piezoelectric constant and ε_{kl} the strain tensor. In this type of crystals, there are two kinds of screw-type dislocation, and each yields $\boldsymbol{E} = 0$. For the screw lying along the a-axis $\boldsymbol{N} \equiv 0$, whereas for that lying along the c-axis $\boldsymbol{N} \neq 0$ but div $\boldsymbol{N} \equiv 0$. In the case where $\boldsymbol{E} \equiv 0$ and the displacement field $\boldsymbol{D} = \varepsilon_0 \boldsymbol{E} + \boldsymbol{N} \neq 0$, this situation is characteristic of ferroelectrics. The important implication here is that screw dislocations do not possess any piezoelectric scattering mechanism. They would just scatter the free carriers by means of their core effect.

For edge dislocations, the piezoelectric effect gives rise to different configurations of the electric fields. At positions where the dislocations intersect a crystal surface or interface, the difference in polarizations across the interface dislocations gives rise to an effective surface charge [13]. This piezoelectrically induced surface charge density creates electric fields in the material which induce free charges that screen the electric fields far from the surface. The piezoelectric effect of the dislocations leads to a modulation of the surface potential of the semiconductor and there is minimal piezoelectric scattering of electrons and holes due to the dislocations within the bulk of the material.

Since $1/f$ noise is caused mostly by surface effect, we will therefore focus our attention on edge dislocation induced piezoelectric effect as well as that from the internal strains. In this paper, we show that ELO-GaN demonstrates considerable piezoelectric effect by correlating the proposed coherent piezoelectric quantum $1/f$ noise theory with the experimentally obtained noise parameter α. ELO-GaN is an important material which is commonly employed as template for further growth of device quality GaN epilayers to reduce dislocations [14]. Knowledge of noise properties of this material, and the subsequent growth of GaN based layers such as n^+-GaN:Si, AlGaN and InGaN, is the key to the development of low-noise high-power and high-frequency electronic devices as well as the blue laser.

2. Experiment

The sample used in this study was an ELO-GaN [15]. Planar resistors in the form of bridge-shaped Hall-bar were used for noise evaluation. It approximates very well an infinitely long Hall-device, and with the use of relatively large contacts, this minimizes heating and noise [16]. The longitudinal noise can be measured from a pair of terminals parallel to the current direction and the transverse noise can be measured from a pair of terminals vertical to the current direction [17]. In our case, only longitudinal noise was measured. Contacts containing Ti/Al layers were used as they display the lowest contact resistivity to n-type GaN [18, 19]. Linear current–voltage (I–V) characteristic was observed and the contact resistance R_C measured was approximately 50 Ω. The carrier concentration n, mobility μ and resistivity ρ were measured with temperature variation from 100 to 550 K. Voltage (S_V) noise spectral density was measured for the temperature variation from 130 to 550 K.

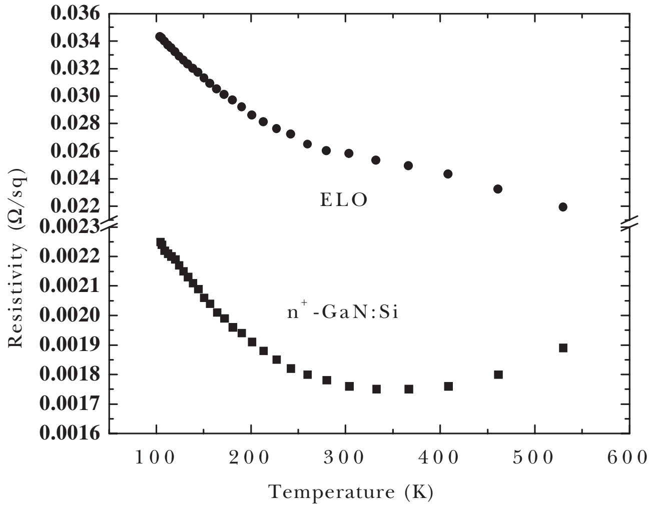

Figure 1. Temperature-dependent resistivity of ELO-GaN. The n^+-GaN:Si is included for comparison.

3. Experimental results

As illustrated in figure 1, it is revealed that resistivity decreases as temperature increases (100–300 K) for both ELO-GaN and n^+-GaN:Si. This is attributed to the fact that ionized impurity scattering is dominating [20]. As temperature increases further (300–530 K), the resistivity also increases for n^+-GaN:Si. This is attributed to crystal defect scattering [20]. Since the presence of a lattice defect is always associated with an increase in the electrical resistivity and the fact that the dislocation density of ELO-GaN is significantly lower compared to n^+-GaN:Si, hence the resistivity of ELO-GaN decreases with increasing temperature. Figure 1 also reveals that the change in the measured resitivity for ELO-GaN at high temperature (300–500 K) is negative whereas for n^+-Ga:Si it is positive. The resistance change is expressed as [21]

$$\frac{\Delta R}{R} = \frac{\Delta\rho}{\rho} + 4\gamma\frac{1-2\nu}{1-\nu}s\,|\Delta\varepsilon| = \frac{\Delta\rho}{\rho} + s\beta\,|\Delta\varepsilon| \qquad (1)$$

where $\Delta\rho = \rho_D \Delta n_D$, Δn_D is the variation of dislocation density, ρ_D the dislocation resistivity, γ the Grüneisen's constant, ν the Poisson ratio, $\Delta\varepsilon$ the strain variation and $s = \pm 1$ depending on whether the stress is compressive ($s = +1$) or tensile ($s = -1$). The total resistivity ρ contains vacancies, interstitials and dislocations with respective densities n_v, n_I and n_D. It is usually expressed as $\rho = \rho_{ph} + \rho_v n_v + \rho_I n_I + \rho_D n_D$, where ρ_{ph} represents the phonon contribution. The term $s\beta|\Delta\varepsilon|$ incorporates the piezoelectric resistance changes. Since the thermal expansion coefficients of GaN and Al_2O_3 are respectively $\alpha_{GaN} = 5.45 \times 10^{-6}$ °C^{-1} and $\alpha_s = 7.5 \times 10^{-6}$ °C^{-1} [22], and $\alpha_{GaN} < \alpha_s$, heating from the unstressed state leads to tension, cooling to compression. For GaN material, $\gamma = 1.8$ [23], therefore, the term incorporating the piezoelectric resistance changes $s\beta|\Delta\varepsilon|$ in (1) is negative since s is negative (tension) at high temperature. From figure 1, we can infer that $s\beta|\Delta\varepsilon| > \Delta\rho/\rho$ for ELO-GaN in (1) and the reverse is true for n^+-GaN:Si. This leads us to conclude that dislocation rearrangement (and other defects) dominates in n^+-GaN:Si whereas piezoelectric effect dominates for ELO-GaN at high temperature.

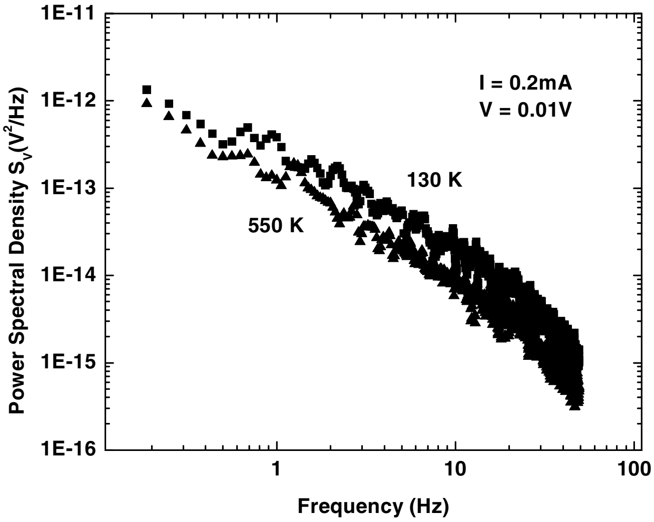

Figure 2. Power spectra densities of the voltage fluctuations S_V for ELO-GaN at 550 K. The S_V at 130 K is included for comparison.

In evaluating α, the operating voltage range was selected to be less than 0.05 V so that both the carrier concentration and the mobility of ELO-GaN do not fluctuate. Measurements taken at this voltage range ensure the invariance of S_V with the applied voltage V indicating a negligible contribution of contact noise to the overall noise levels. The S_V of ELO-GaN measured at 130 K and 550 K are shown in figure 2 for a constant biasing current of 0.2 mA. The spectra show $1/f$ behaviour below 50 Hz. The noise parameter can be estimated experimentally as $\alpha = S_V f N/V^2$.

At 550 °C, the measured carrier concentration for ELO-GaN is 3.2×10^{16} cm^{-3} and carrier mobility is 132 cm^2 V^{-1} s^{-1}. The total carrier number within the $160 \times 5 \times 8$ μm^3 bridge-shaped Hall-bar is $N = 2.04 \times 10^8$. The noise parameter α was evaluated from figure 2 by taking the intercept point with the gradient fixed at -1. Since the intercept point is equivalent to $\alpha V^2/N$, with a measured voltage of 0.01 V, the noise parameter evaluated was $\alpha = 2$. This value is three orders higher than the classical theory of Hooge's $1/f$ noise value of roughly $\alpha_H = 2.3 \times 10^{-3}$. This is expected as GaN is a ferroelectric material. This material normally demonstrates lattice-dynamical quantum $1/f$ effect and can yield an α that is up to six orders of magnitude larger than α_H. The ferroelectricity manifests itself in ELO-GaN due to the strain-induced polarizations. At high temperature, the tensile strain is particularly large in ELO-GaN on Al_2O_3, and is much smaller in typical Si-doped n$^+$-GaN:Si on sapphire. Its decrease goes hand in hand with the creation of stress-relaxing arrays of dislocations.

4. Discussion

The coherent piezoelectric quantum $1/f$ noise theory [24] is given as $S_j(f)/j^2 = 4g_\lambda/\pi f\left[1-(\langle \boldsymbol{v}\rangle/v_s)^2\right]$, where $|\langle \boldsymbol{v}\rangle| = u$ is the drift velocity of the carriers, v_s the transversal acoustic sound velocity and m^* is the electron effective mass. The parameter g_λ is the electron–phonon coupling constant to the phonon mode λ and is defined as $g_\lambda = e^2 f_{TA}/\hbar\varepsilon_0 v_s$ [25]. Here ε_0 is the dielectric tensor and f_{TA} is the angular-averaged acoustic electromechanical coupling constant in the transverse mode [25]. In our evaluation, the angular dependent g_λ values for GaN material were within the range 3–8. For coherent lattice-dynamical quantum $1/f$ effect, the factor 4 is replaced with 2, because for the coherent field, the polarization direction is predetermined by the geometry of the stationary current distribution. Note that if we treat α as equivalent to $2g_\lambda/\pi\left[1-(\langle \boldsymbol{v}\rangle/v_s)^2\right]$, rearranging gives $(\langle \boldsymbol{v}\rangle)^2 = (v_s)^2[1-2g_\lambda/\alpha\pi]$. For this expression to be valid, the condition $\alpha > 2g_\lambda/\pi$ must be satisfied. With $g_\lambda = 3$–8, α must be greater than 1.9–5.1. Since our $\alpha = 2$, we can safely use this expression.

At low electric field the drift velocity u is proportional to the electric field strength E, i.e. $u = \mu E$ [26]. For our ELO-GaN, the measured mobility was $\mu = 132$ cm^2 V^{-1} s^{-1} at 550 K. With an applied voltage of 0.01 V, the electric field was $E = 0.625$ V cm^{-1}, this corresponds to $u = 82.5$ cm s^{-1}. Since u is very much smaller than v_s, the quantum $1/f$ coefficient α is simplified to $\alpha = 2g_\lambda/\pi$ which yields 2 for $g_\lambda = 3$. This result correlates well with our experimentally obtained α value, which is 2.

The slight non-uniformities present in any sample could slightly increase the theoretical value, above 2, if properly taken into account, as mentioned above. They could also down-correct the measured α to values below 2, because the assumed number of carriers in the expression $\alpha = S_V f N/V^2$ used by us to define the measured value may have been slightly larger than the effective number that remains when nonuniformities are taken into account.

In conclusion, the theoretically evaluated noise parameter α based on coherent piezoelectric quantum $1/f$ noise agrees with the experimentally obtained result for ELO-GaN. This result indicates that piezoelectric effect is indeed relevant both for the transport process in ELO-GaN and for its fluctuations.

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