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Phonon–plasmon coupled modes in GaN

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Abstract

The phonon lifetime in GaN is known to exhibit a dependence on electron density. Recent noise measurements have also shown the lifetime to be temperature dependent. The source of these dependences is the coupling of the phonon and plasmon populations through the dielectric function. The effect of this anharmonicity is illustrated by comparing the frequency and wavevector dependent coupled-mode momentum relaxation rate with the phonon momentum relaxation rate obtained by Callen. A simple model that includes the anharmonic interaction and phonon migration yields phonon lifetimes depending on both electron density and temperature.

1. Introduction

The thermal performance of GaN devices is known to be poor, due in part to the lack of suitable substrate material. An undesirable side-effect to excessive device self-heating is the possibility of generating a significant population of non-equilibrium phonons known as hot phonons. This arises because the scattering rate between electrons and phonons is an order of magnitude shorter than the lifetime of the phonons. Such a population has a detrimental effect on device performance manifesting as a drop in mobility. The crucial parameter here being the A1(LO) phonon lifetime. It has been shown recently [1] that an anharmonic coupling between plasmons and phonons can result in a phonon lifetime that is density dependent. In addition a further apparent reduction in phonon lifetime can occur due to the migration of phonons from the channel of an heterojunction field-effect transistor (HFET). Experimental evidence has been mounting which shows that this is indeed the case. Tsen *et al* [2] find a phonon lifetime of 2.5 ps in bulk GaN this reduces to 0.35 ps at 2×10^{19} cm^{-3} using Raman techniques which probe phonon wavevectors at $q = 0$. Matulionis' group have employed noise techniques to measure phonon lifetimes in gateless HFETs measuring 1 and 0.4 ps at densities of 3×10^{18} and 1×10^{19} cm^{-3}, respectively [3, 4]. Matulionis *et al* [5] have also inferred the hot phonon temperature from their measurements; recently they have observed that the phonon lifetime is also temperature dependent. Pomeroy *et al* [6] have utilized Raman thermography technique to establish the presence of a hot phonon population and to measure its temperature directly.

2. Method

The wavevector, q and frequency, ω dependent dielectric function is given by

$$\mathrm{Im}\left(-\frac{1}{\varepsilon(\omega,q)}\right) = \frac{\mathrm{Im}\,\varepsilon(\omega,q)}{[\mathrm{Re}\,\varepsilon(\omega,q)]^2 + [\mathrm{Im}\,\varepsilon(\omega,q)]^2}. \quad (1)$$

The dielectric function can be written in a convenient form by making use of the two pole Padé approximant [7]. Whence the real and imaginary components of the total dielectric function are

$$\mathrm{Re}\left(\frac{\varepsilon(\omega,q)}{\varepsilon_\infty}\right) = \left(\frac{q_\mathrm{D}}{q}\right)^2 \frac{1}{2a}\left[\frac{S_+\{2+(\pi-2)^2S_+^2\}}{d_+} - \frac{S_-\{2+(\pi-2)^2S_-^2\}}{d_-}\right] + \frac{\omega^2-\omega_\mathrm{LO}^2}{\omega^2-\omega_\mathrm{TO}^2}$$

$$\mathrm{Im}\left(\frac{\varepsilon(\omega,q)}{\varepsilon_\infty}\right) = \pi^{1/2}\left(\frac{q_\mathrm{D}}{q}\right)^2 \frac{1}{2a}\left[\frac{1}{d_-} - \frac{1}{d_+}\right]$$

with

$$S_\pm = y \pm a/2, \qquad y = \left(\frac{m*}{2k_\mathrm{B}T}\right)^{1/2}\frac{\omega}{q},$$

$$a = \left(\frac{\hbar^2q^2}{2m^*k_\mathrm{B}T}\right)^{1/2} \quad d_\pm = 1 + (4-\pi)S_\pm^2 + (\pi-2)^2S_\pm^4. \quad (2)$$

The reciprocal screening length is obtained from $q_\mathrm{D}^2 = \frac{e^2N}{\varepsilon_\infty k_\mathrm{B}T}$. N is the electron density, T is the electron temperature, k_B is Boltzmann's constant, ε_∞ is the high frequency dielectric constant taken as 5.35, m^* is the effective mass taken as 0.2 in units of the free electron mass, ω_LO and ω_TO are the longitudinal and transverse bare optical phonon frequencies.

In the presence of a high density of electrons, bare phonon modes become coupled phonon–plasmon modes [1].

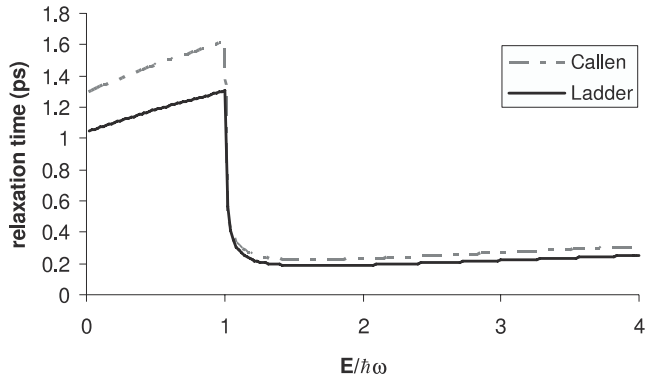

Figure 1. Callen momentum relaxation time compared to that obtained by the ladder method with $T = 300$ K.

The total spontaneous emission rate is given by

$$W(q,\omega) = \frac{2\pi}{\hbar}\int \frac{2\mathrm{d}^3k}{(2\pi)^3}\frac{e^2}{q^2}f(E_k) \times \left\{\frac{\hbar}{\pi}\,\mathrm{Im}\left(-\frac{1}{\varepsilon(\omega,q)}\right)\delta(E_{\mathbf{k}+\mathbf{q}} - E_{\mathbf{k}} + \hbar\omega)\right\} \tag{3}$$

where $f(E_k)$ is the electron distribution function which is assumed to be the Maxwell–Boltzmann factor associated with a non-degenerate gas. The assumption of non-degeneracy is consonant with conditions in practice, where high fields and high electron temperatures are the norm.

The momentum relaxation rate is given by

$$W_m(k) = \frac{2\pi}{\hbar}\int \frac{2d^3q}{(2\pi)^3}\frac{e^2}{q^2}\int \mathrm{d}(\hbar\omega)[1+n(q,\omega)] \times \left(\frac{q^2}{2k^2} + \frac{\hbar\omega}{2E_k}\right) \times \left\{\frac{\hbar}{\pi}\,\mathrm{Im}\left(-\frac{1}{\varepsilon(\omega,q)}\right)\delta(E_{\mathbf{k}+\mathbf{q}} - E_{\mathbf{k}} + \hbar\omega)\right\}. \tag{4}$$

3. Discussion

The momentum relaxation rate given above is the out scattering rate, to obtain the exact rate one should apply the ladder method to the Boltzmann equation [8]. However, given the complexity of equation (4) this method would be extremely computationally intensive. Therefore equation (4) is calculated by numerical integration for a range of temperatures and densities. These momentum relaxation rates are compared with those given by Callen [9]. At high energies the Callen result is not too different from that obtained by the ladder method, figure 1. A comparison with the Callen relaxation rate should therefore be sufficient to highlight the consequences of the dynamic screening. Coupled-mode momentum relaxation rates as a function of energy are shown in figure 2 for electron densities of 1×10^{18} and 1×10^{19} cm^{-3} with an electron temperature of 3000 K. At modest electron densities, 1×10^{18} cm^{-3} there is no discernable difference in the two rates. At higher densities $\sim 1 \times 10^{19}$ cm^{-3} there is a clear difference between the rates; the phonon absorption makes a greater contribution in the coupled-mode case. The same trend is

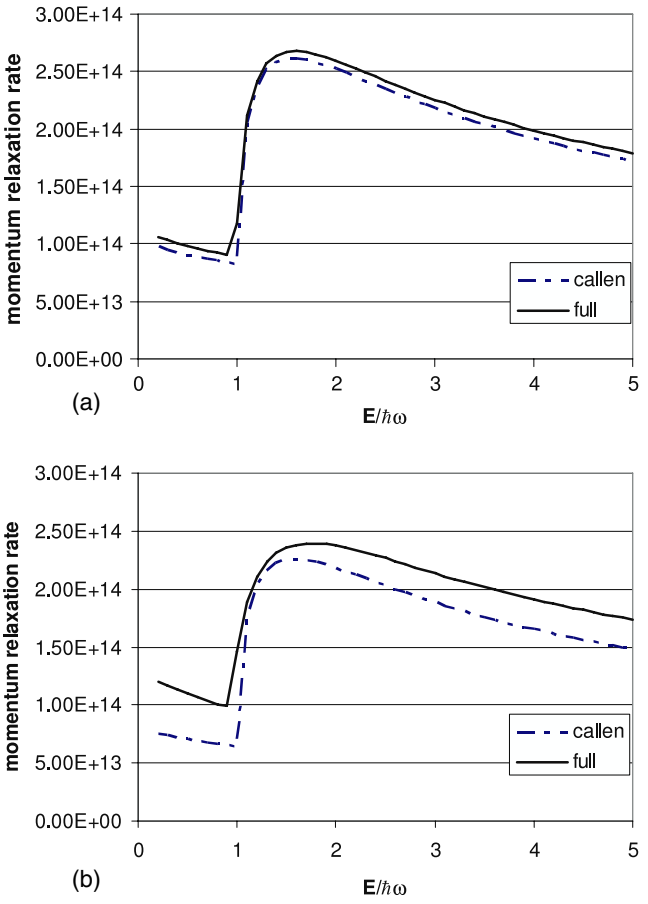

Figure 2. Coupled-mode and Callen momentum relaxation rates as a function of energy normalized to the bare phonon energy. Electron temperature of 3000 K and electron density (a) 1×10^{18} and (b) 1×10^{19} cm^{-3}.

evident at a lower electron temperature of 1500 K, figure 3. In addition the peak rate in this case has shifted towards higher energy. Both of these effects arise due to the character of the dielectric interaction changing with coupled-mode frequency and wavevector and electron temperature and density.

One consequence of the coupling through the dielectric response function is that the coupled modes have group velocities two or three orders of magnitude greater than those of the bare phonon modes. In the context of a heterostructure, phonon migration out of the channel is likely. A simple model that combines the anharmonic interaction and the migration of phonons out of the channel of an HFET has been used to describe anomalously low phonon lifetimes from noise experiments in gateless HFETs [1]. Previously a reduction in phonon lifetime with increasing electron density was found; here the same model, characterized by equation (5) is used to demonstrate excellent agreement with Matulionis' most recent results on AlInN/GaN heterostructures [5].

$$\frac{1}{\tau_{\mathrm{eff}}} \approx \frac{1}{\tau_{\mathrm{p}}(0)} + f\frac{v_{\mathrm{g}}}{L} \tag{5}$$

where v_{g} is the average group velocity of the coupled-mode, f is the fraction of inter-subband transitions taken $= 1/3$, the channel width, $L = 4$ nm and the bare phonon

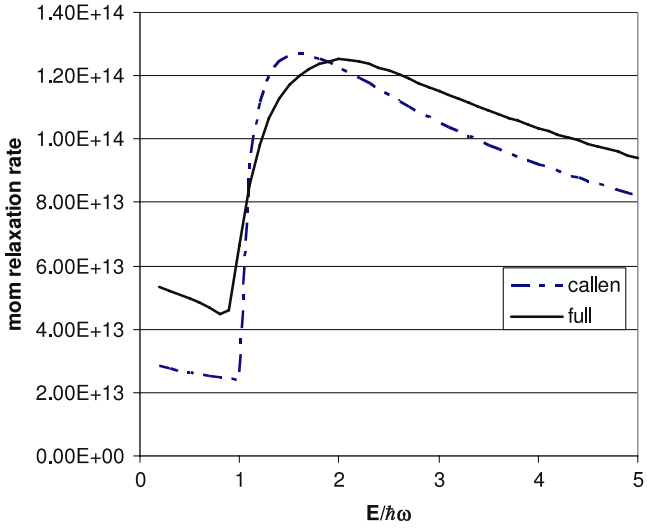

Figure 3. Coupled-mode and Callen momentum relaxation rates as a function of energy normalized to the bare phonon energy. Electron temperature of 1500 K and electron density 1×10^{19} cm^{-3}.

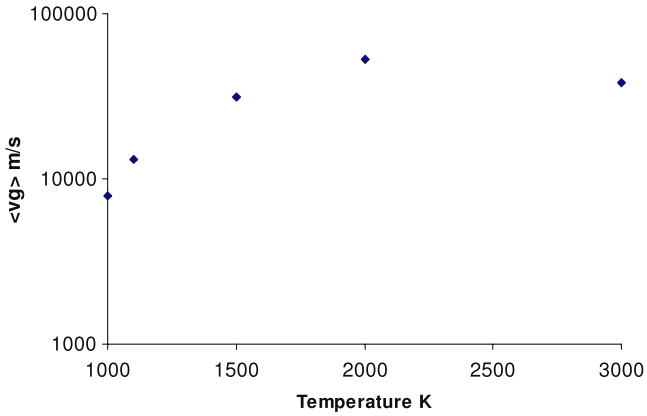

Figure 4. Average group velocity as a function of electron temperature for an electron density of 6×10^{18} cm^{-3}.

lifetime, $\tau_p(0) = 2.5$ ps. An average value of the group velocity can be obtained from $|d\omega/dq|$ weighted with the hot phonon distribution function. The weighting and averaging are done numerically, figure 4 shows the average group velocity obtained as a function of temperature for a fixed electron density. Equation (5) is calculated for each temperature considered and the result is shown in figure 5, the agreement with the experimental results is reasonable given the crudity of the model. The experimental results found no saturation in the relaxation time, while the theory does at the highest temperature considered. The electron density is kept fixed at 6×10^{18} cm^{-3}. In the experiment the sheet density is 1.2×10^{13} cm^{-2}, the density per unit volume is difficult to estimate particularly during device operation. The channel width is roughly 4 nm at equilibrium giving a density $\sim 10^{19}$ cm^{-3}. Given the rough nature of the model and the uncertainties in

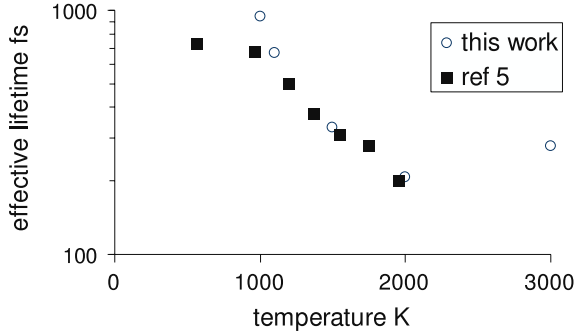

Figure 5. Effective lifetime as a function of hot electron temperature.

channel width and electron density during operation there is little to be gained from using a higher density in the theoretical calculation.

4. Conclusions

The effect of the anharmonic coupling of plasmons and phonons has been demonstrated by comparing the coupled-mode and phonon momentum relaxation rates. At a density of 1×10^{18} cm^{-3} there is little difference between the two rates. For a density of 1×10^{19} cm^{-3} the rates are different and also depend on electron temperature. A simple model combining the anharmonic interaction with the migration of phonons out of an HFET channel results in effective phonon lifetimes that decrease with increasing electron temperature. Rough agreement is obtained with noise measurement data from AlInN/GaN heterostructures showing the same trend.

Acknowledgment

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References

[1] Dyson A and Ridley B K 2008 *J. Appl. Phys.* **103** 114507
[2] Tsen K T, Kiang J K, Ferry D K and Morkoc H 2006 *Appl. Phys. Lett.* **89** 112111
[3] Aninkevicius V, Matulionis A and Matulioniene I 2005 *Semicond. Sci. Technol.* **20** 109
[4] Matulionis A, Liberis J, Matulioniene I, Ramonas M, Eastman L F, Shealy J R, Tilak V and Vertiatchikh A 2003 *Phys. Rev.* B **68** 035338
[5] Matulionis A, Liberis J, Sermuksnis E, Xie J, Leach J H, Wu M and Morkoc H 2008 *Semicond. Sci. Technol.* **23** 075048
[6] Pomeroy J W, Kuball M, Uren M J and Martin T 2008 *Phys. Status Solidi* b **245** 910–2
[7] Lowe D and Barker J R 1985 *J. Phys. C: Solid State Phys.* **18** 2507
[8] Delves R T 1959 *Proc. Phys. Soc. Lond.* **73** 572
[9] Callen H 1949 *Phys. Rev.* **76** 1394