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Energy Relaxation Rate of Hot Electrons in N-Type GaN Epilayers using Heat Pulse Techniques

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Abstract

We have measured the energy relaxation rate of hot electrons in MBE grown bulk GaN epilayers on GaAs and sapphire substrates over the electron temperature range 1 - 130 K. The measurements were made using heat pulse techniques. For layers grown on GaAs substrates the results show that the carriers reside in the substrate, probably as in a GaAs/AlGaAs heterojunction. For layers grown on sapphire substrates we obtain a $P \propto T_e^4$ dependence for the relaxation rate in the low temperature limit, consistent with piezoelectric coupling in the so-called 'dirty' regime, changing to a linear dependence in the high temperature, equipartition, regime.

1. Introduction

To date semiconductor devices have made relatively little impact in the field of high power microwave electronics. Gallium arsenide, despite offering the possibility of high gain at microwave frequencies, has not been able to deliver the power per device, and reliability, easily achieved with vacuum valve technology, though at much greater cost. The situation may change however since recent theoretical predictions that gallium nitride based devices could give more than an order of magnitude greater power output than a similar GaAs device, with considerably greater thermal stability. Recent advances in growth, particularly MOCVD but also MBE, have lead to the availability of rapidly improving material and some intense research activity. It is envisaged that GaN devices will run at high temperatures, possibly even orange heat, without GaAs's attendant problems. At these elevated temperatures the device characteristics will be strongly influenced by the processes of hot carrier energy and momentum relaxation due to phonon emission. A knowledge of these processes at this early stage in device development could be extremely helpful, particularly once the fabrication difficulties peculiar to GaN have

been overcome. We present a study of the hot electron energy relaxation rate made on n-type bulk GaN films grown by MBE on GaAs, and, the more commercially interesting, sapphire substrates, over a wide range of temperatures. The measurements have been made using a novel pulse technique in which the carriers are electrically pulse heated above the surrounding lattice temperature. The carriers subsequently relax by emission of phonons, which can be observed using time-of-flight techniques.

In previous work [1] on the two dimensional electron gas formed at a GaAs/AlGaAs heterojunction using the same method, we have shown that above a carrier temperature T_e of 50 K, the dominant energy relaxation mechanism changes from acoustic ($P \propto T_e^3$) to optical ($P \propto \exp[-E_{LO}/k_B T_e]$) phonon emission. A summary of the relevant physical parameters for GaN are shown in Table 1, together with those of GaAs for comparison. Important points to note are the relatively high values of piezoelectric coupling constant, e_{14}, electron effective mass, m_e, longitudinal optic (LO) phonon energy, E_{LO}, and bandgap, E_g, in GaN.

Table 1. Physical parameters for GaN and GaAs.

		GaN	GaAs
Ξ_d	eV	9.8	12
e_{14}	Cm^{-2}	0.375-0.6	0.15
E_g	eV	3.5	1.42
E_{LO}	meV	92	36.6
m_e^*		$0.2m_e$	$0.067m_e$
v_{la}	ms^{-1}	8000	5200
v_{ta}	ms^{-1}	5000	3200

High values of e_{14} and m_e act to increase the electron-acoustic phonon coupling strength while a high value for E_{LO} will push the acoustic-optic change-over to higher carrier temperatures than in GaAs. GaN's large bandgap contributes to its thermal stability.

2. Experimental Details

Table 2 shows the layer parameters for the two devices/wafers used. The electrical characteristics were determined from Hall measurements on adjacent pieces of material cut from the same wafers. As mesa formation in GaN requires reactive ion etching (RIE) it was decided to define the active device area using a Corbino disk geometry.

Table 2. Wafer/device parameters for the two samples.

Substrate	t μm	Device area m^3	Doping n-type (Si) m^{-3}	μ©4.2K $\mathrm{cm}^2V^{-1}S^{-1}$	N_H©4.2K m^{-3}
GaAs (111) SI	0.9	1.6x10^{-7}	~6x10^{24}	20	2.0x10^{24}
Sapphire c-axis	0.5	2.0x10^{-7}	~3x10^{24}	95	2.3x10^{24}

The ohmic contacts were formed by thermally evaporating aluminium and annealing in a dry nitrogen atmosphere for about 20 minutes. Directly opposite the device was

fabricated a thin-film superconducting aluminium bolometer. With the sample held in a liquid helium cryostat at the bolometer transition temperature, the device was briefly excited with 20 ns voltage pulses of amplitude 0.1 - 30 V. The carriers are heated above the surrounding lattice temperature and relax by emission of phonons which ballistically traverse the substrate to the bolometer. Here they produce a small rise in temperature and hence resistance, which is detected as a voltage signal with a small bias current applied. Many such signals are averaged together with a high speed digitising system to give phonon time-of-flight traces, Figure 1. The power absorbed during a pulse and device resistance are deduced by noting the forward and reflected pulse amplitudes in the 50 Ω feeder cable. DC Hall measurements were made of the layer carrier concentration and mobility as a function of temperature between 1 and 300 K. By comparing the device resistance during a pulse with the Hall calibration data it was possible to deduce the carrier temperature [1].

3. Results and Discussion

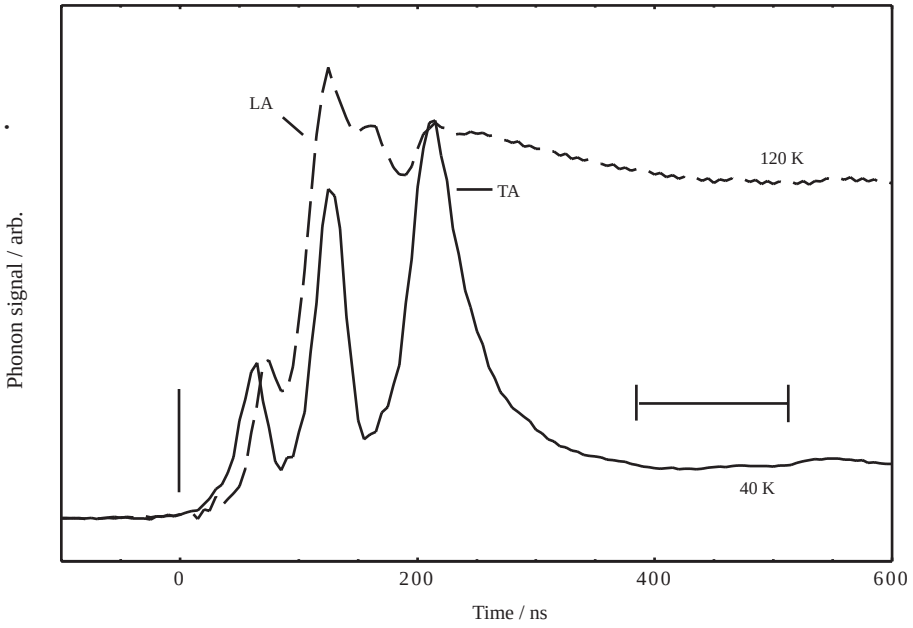

Figure 1. Phonon time of flight traces for the GaAs sample.

3.1 GaN on GaAs:

Figure 1 shows phonon time-of-flight traces taken at 120 K and 40 K. The initial peak occurring at 50 ns is due to direct electrical pickup of the excitation pulse. From the times of flight we can associate the two indicated peaks with the arrival of ballistic longitudinal

(LA) and transverse (TA) acoustic phonons. In the high power trace the TA mode signal has developed a long tail previously noted in studies of the GaAs/AlGaAs heterojunction as characteristic of optical phonon emission [1]. The strong LA mode signal is in contrast however, to the negligible LA emission observed from the GaAs/AlGaAs heterojunction [1], but consistent with measurements on bulk n-type GaAs layers [2], where deformation potential (DP) coupling to LA modes is the dominant energy loss process. Figure 2 shows the normalised LA and TA mode intensities (integrated over their leading edges) and tail intensity (integrated over the gate marked in Figure 1) as a function of carrier temperature. (The intensities have been normalised by dividing by the power and scaling to a maximum of one.) Below about 50 K the LA and TA mode signals are approximately constant, indicating that the detected signal scales linearly with power. The phonon peaks are sharp (Figure 1), characteristic of emission of low frequency modes and suggesting that coupling to acoustic phonons is the dominant energy relaxation process.

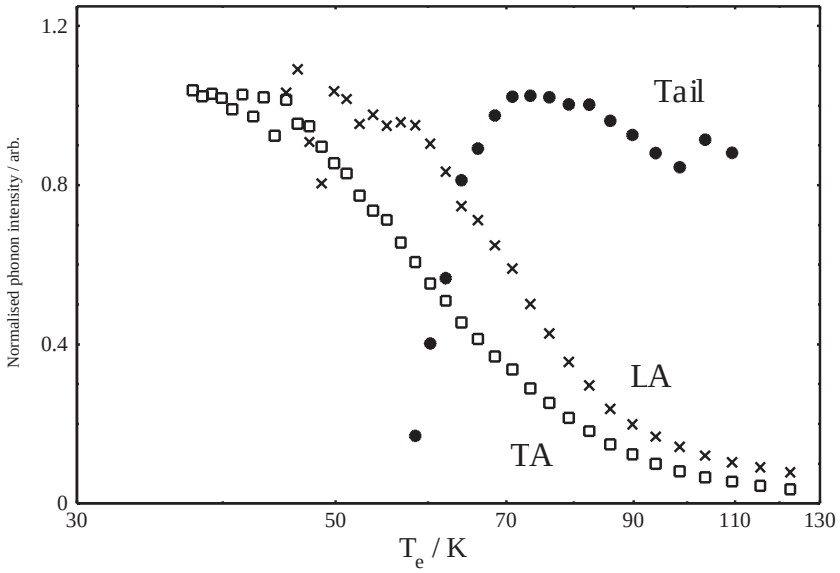

Figure 2. Normalised LA, TA and tail intensities as a function of power.

Above this temperature the previously negligible tail intensity rises rapidly, eventually reaching a constant value, while the LA and TA signals fall. This is consistent with a changeover to optical phonon emission as the dominant energy relaxation process [1]. Longitudinal optical (LO) phonons decay rapidly via a series of steps to high frequency TA modes which propagate diffusely to the bolometer, producing the observed tail.

The emission rate into LO phonons can be written as;

$$P_e = \frac{\hbar\omega_{LO}}{\tau} \exp\left(\frac{\hbar\omega_{LO}}{k_B T_e}\right) \tag{1}$$

where τ and ω_{LO} are the LO scattering time and frequency respectively. Figure 3 shows the energy relaxation rate plotted as a function of inverse temperature, From the figure we obtain $\hbar\omega_{LO} = 34$ meV and $\tau = 5.5$ps. These are in excellent agreement

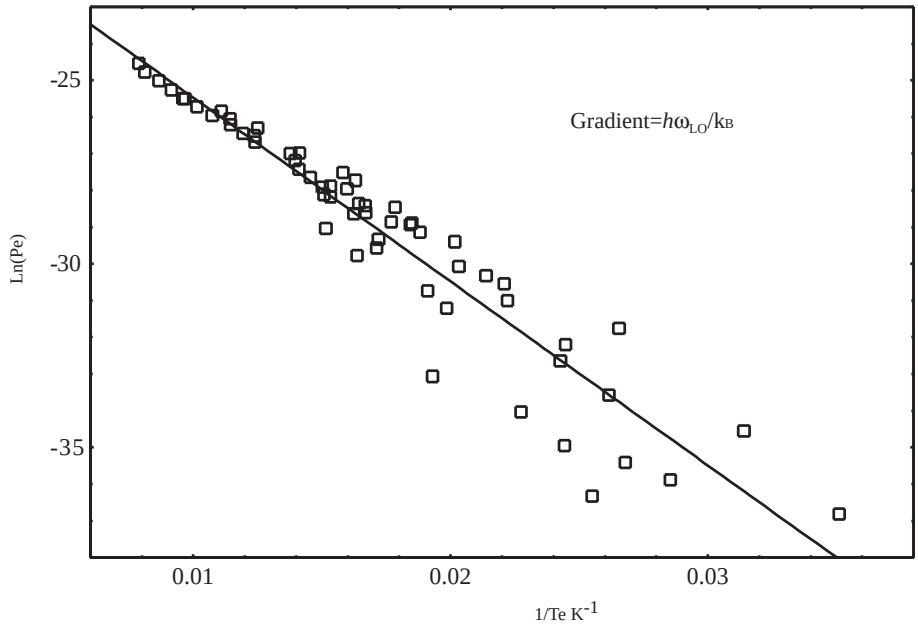

Figure 3. Electron energy relaxation rate..

with the generally accepted values for GaAs of 36.6 meV and $\sim$ 1 ps. (In GaN, $h\omega_{LO}$ $\approx$90 meV [3].) We therefore conclude that the electrons are located in the GaAs and not in the GaN layer. The bandgaps of GaN and GaAs are 3.5 eV and 1.5 eV respectively. By analogy with the GaAs/AlGaAs heterojunction it seems reasonable to assume that a confining potential will exist at the interface with a potential barrier on the GaN side of order 1 eV (half the bandgap difference). If all of the carriers in the epilayer go to the interface, the two dimensional (2D) sheet concentration will be $\sim$ 2x10^{14} cm^{-2}. At such a high concentration many subbands will be occupied. With one subband occupied momentum conservation considerations lead to a suppression of DP coupled LA emission [4]. With many subbands occupied the restriction is lifted and the electron sheet acts as a thin bulk layer rather than a genuinely 2D layer. The occupation of a large number of subbands and the extremely low mobility (table 2) would also lead to a suppression of effects associated with quantum confinement. Magnetoresistance measurements showed no evidence of Schubnikov de Haas oscillations, just weak negative magnetoresistance at low field, characteristic of quenching of weak localisation.

3.2 GaN on Sapphire:

Figure 4 shows time-of-flight traces at three different carrier temperatures. Only one

peak is observed which we can associate with the arrival of ballistic TA phonons. There is no evidence of a characteristic optic emission tail developing even at the highest carrier temperature obtained in the experiment (130 K). This is in strong contrast to GaAs but consistent with the unusually high values of piezoelectric coupling constant ($\approx$0.5 Cm^{-2}) and LO phonon energy (92.0 meV) in GaN.

Figure 5 shows the energy relaxation rate in pW per electron as a function of temperature. Above 10 K we observe a linear dependence characteristic of the

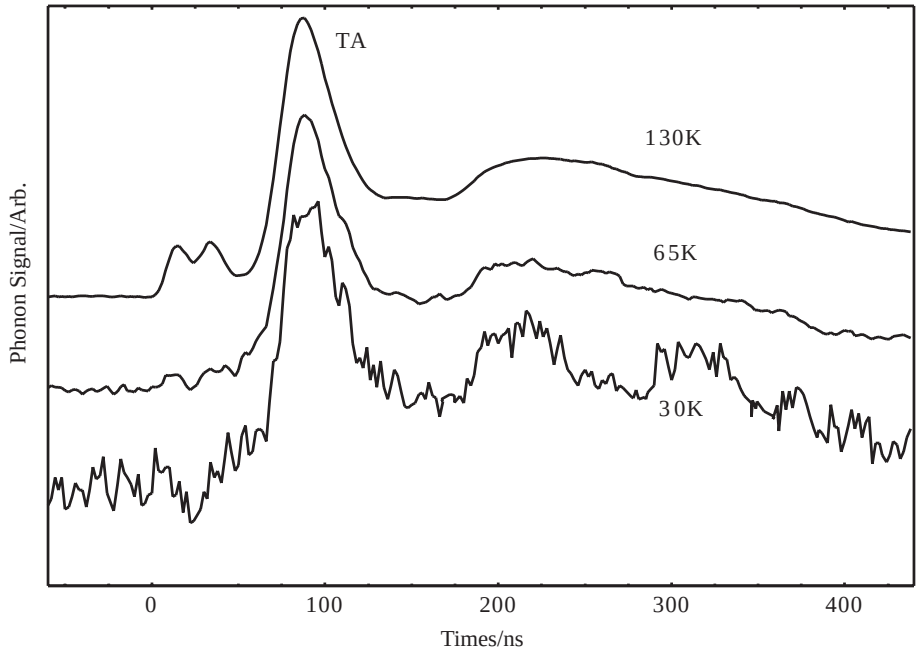

Figure 4. Time-of-flight traces for GaN on sapphire sample.

equipartition regime [5]. For piezoelectric coupling, the total power emitted into a single mode s, including static screening, is given by,

$$P \propto \int_0^{q_D} \omega_q^2 \frac{1}{1+q_0^2/q^2} \left[n_q(T_e) - n_q(T_1)\right] \frac{G(q)}{q} d\omega_q \tag{2}$$

where the n_q are the phonon occupation numbers at the electron, T_e and lattice, T_l temperatures, q_o is the Thomas-Fermi wavevector, and q_D is the Debye wavevector. Factor $G(q)$ results from energy and momentum conservation and is approximately proportional to q for $q < 2k_f$. For $q > 2k_f$, $G(q)$ falls rapidly to zero. At temperatures above 10 K the dominant thermal phonon wavevector, q_{th}, is greater than $2k_f$ and only phonons with $\hbar\omega_q < k_B T_e$ are emitted. Under these conditions the phonon occupation numbers can be approximated to,

$$n_q(T) \approx \frac{k_B T}{\hbar \omega_q}$$

resulting in a linear dependence of P on T_e as observed, independent of the coupling mechanism involved.

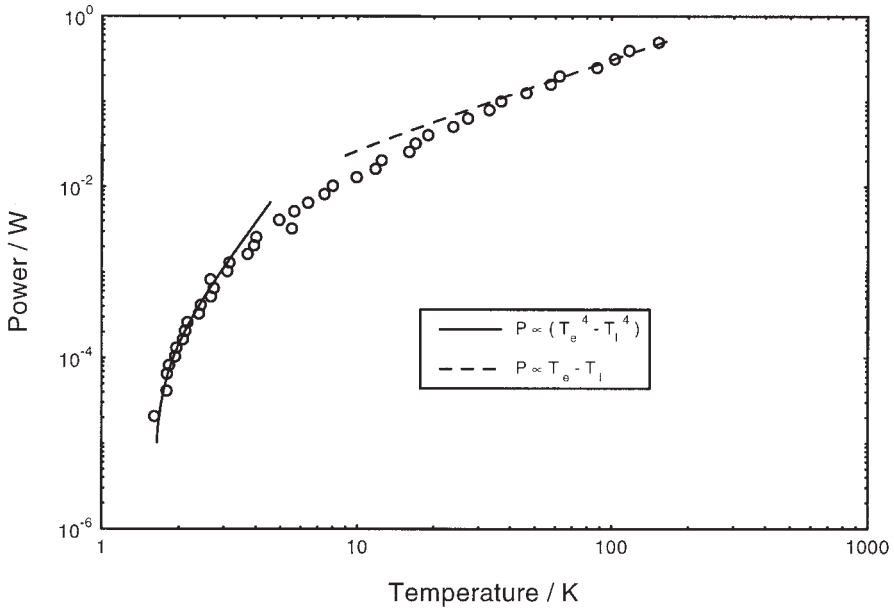

Figure 5. Electron energy relaxation rate.

Below 10 K, we observe $P \propto T_e^4$. It has been shown [6] that in the so-called 'dirty' limit ($q_{th} l_{elastic} < 1$, where $l_{elastic}$ is the electron elastic mean free path) such a dependence can be accounted for assuming piezoelectric coupling as the dominant energy relaxation mechanism. Frequent scattering of electrons by the disorder potential relaxes the momentum and energy conservation requirements. The rate of emission of a particular phonon mode becomes independent of its frequency and momentum, and the q dependence of G(q) is lost. In the clean limit equation (2) gives a T_e^5 dependence. In the dirty limit however, it can be seen by simple power counting that dependence becomes T_e^4. (Unscreened deformation potential coupling would also give the observed dependence. In our samples, $q_o \sim 1.6\text{x}10^9$ m^{-1}, or a characteristic temperature of about 25 K. Screening will be significant at temperatures below this and must be included.) The condition $q_{th} \ell_{elastic} \approx 1$ defines a temperature $T_d = \hbar v_s / k_B l_{elastic}$, where vs is the velocity of phonon mode s, below which the dirty limit arises. For our sample $T_d = 22$ K and so for all temperatures at which a non-linear temperature dependence would be expected we are in the dirty regime.

4. Conclusion

We have obtained the energy relaxation rate temperature dependence for n-type bulk GaN epilayers grown on GaAs and sapphire substrates. In the former case we observe features characteristic of a changeover to optic phonon emission at powers above 0.5 pW per electron. We deduce values of LO energy and scattering time consistent with those in GaAs, and conclude that the carriers are probably confined in the GaAs as in a GaAs/AlGaAs heterojunction. For the sapphire device we find that the relaxation rate shows a $P_e \propto T_e^4$ dependence at low temperatures, characteristic of piezoelectric coupling in the so-called 'dirty' limit. No evidence is observed for a transition to optical phonon emission even at the highest temperature of the experiment (130 K). This is in remarkable contrast to GaAs but consistent with the high values of piezoelectric coupling constant and LO phonon energy in GaN.

Acknowledgments

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