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Importance of two-phonon processes in Hot Electron Energy Loss Rate of GaN/AlGaN Quantum Well

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Abstract:
The energy loss rate of hot electrons has been studied in GaN/AlGaN quantum well structures with emphasis on the role of two-phonon processes. Expression for the electron energy loss rate due to electron- two-zone edge transverse acoustic (2TA) phonon and longitudinal optical phonon interaction is derived without any assumptions. Non-equilibrium distribution of phonons for the polar optical phonon scattering has also been included. A very good agreement is obtained between experimental data and calculation in GaN/AlGaN quantum well demonstrates the importance of electron-2TA phonon scattering processes and hot-phonon effect in power loss from hot electrons.

Key words: electron-phonon interaction, electron energy loss rate, hot phonon effect, 2TA phonons.

1. Introduction:

Understanding of scattering of hot electrons in low-dimensional semiconductors has been of considerable interest over the last three to four decades due to their paramount importance in semiconductor physics and electronics and in device applications [1-6]. Hot electron-phonon interaction in Low dimensional semiconductor structures (LDSSs) explore the use of these structures as acoustical devices as high frequency ultrasonic generators and high frequency radiation modulators will enhances the field of device applications. The interaction of electrons with phonons plays an important role in determining the behavior of electrons under high electric field. One of such is electron energy loss rates (ELR) which provide better understanding of electron-phonon interaction than conventional mobility studies. Most of the experimental observations and theoretical analysis of ELR studies have been focused on GaAs, GaInAs, InSb and GaSb systems because of the favorable energy gap and well developed crystal growth techniques. Group III nitride materials are very suitable for applications in high power, high frequency and high temperature electronics [7]. Most devices are designed to operate under high electric field. At a high electric field, the electrons equilibrate at a much higher temperature than the lattice temperature. The determination of the temperature of electrons under electric field heating conditions in the steady sate provides useful information about electron-phonon interactions involved in the energy relaxation process. Till recently, very little work appears in literature concerning the study of ELR in widely band gap III nitride semiconductor such as GaN/AlGaN when 2D electron gas is confined in other semiconductors. GaN has vast applications in optoelectronic and electronic device technologies. GaN has recognized as very promising material for the visible ultraviolet range. Light Emitting Diodes (LEDs) and Laser Diodes (LDs) have been developed and show potential applications [8-9].

Temperature dependent 2D electron energy relaxation in GaN/AlGaN heterostructure has been studied experimentally by Shubnikov-de Hass (SdH) and Hall Effect techniques [XX] and compared theoretically [10]. For electron temperature below 14K, it was found that energy relaxation of electrons is due to acoustic phonons by unscreened piezoelectric interaction. But quantum lifetime values suggesting the remote impurity scattering is the dominant scattering mechanism [11]. Hot phonon life time in n-type channel GaN is measured and suggesting the presence of non-equilibrium of hot phonons in the low field regime at temperature close to ambient [8,12] and concluded the hot phonon life time of 3-4 ps. Ridley et al [13] proposed the accumulation of non-equilibrium phonons or hot phonons is responsible for lowering the drift velocity. The electron temperature relaxation tie reduces from 5ps to 0.4 ps at low electric field in 2D GaN by developing electron temperature method [14]. Balkan et al [15] observed energy and momentum relaxation of 2D GaN/AlGaN from mobility comparison method and are

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compared with existing theoretical model but noticed not good agreement between experimental and theory. This disagreement might be the failure of one of the assumption made in mobility comparison method and also about the accuracy of electron temperature model for the non-equilibrium phonons and hence of the accuracy of mobility comparison method. In this article we incorporated the non-equilibrium distribution of phonons in ELR due to electro-LO phonon interaction to compare the experimental data.

The aim of this work is to show, the importance of incorporating electron-two-phonon scattering mechanism in the energy loss rate studies in 2D GaN/AlGaN quantum well. In bulk and 2D semiconductor heterostructure, it is established that the effect due to two-phonon interaction are observable and have significant influence on the transport properties. To explain the energy loss data in GaN/AlGaN quantum well of Balkan et al [15], calculations are presented by taking into account this additional scattering mechanism.

2. Two-phonon process in bulk and 2D semiconductor structures:

In bulk semiconductors there exist in literature, a strong experimental evidences supported by theoretical analysis for the two-phonon processes [16]. Sandercock [17] was the first to suggest the importance of two-phonon processes from the study of I-V characteristics of high purity InSb and pointed out that two-phonon processes can explain the missing energy loss rate. A fair good agreement is obtained between experimental and theoretical energy loss rate in n-InSb in the electron temperature range 10-20K by considering 2TA phonons with one adjustable parameter-the 2TA scattering rate [18]. Similar good results have been obtained in bulk GaAs and GaSb in the intermediate temperature range [19-21].

In 2D semiconductors, for GaAs/GaAlAs quantum wells, in comparison between experimental data and theoretical observation, it was found that below 20K the dominant source of energy relaxation is by acoustic phonon emission and above 40K the LO phonons dominates the energy loss process. Electron-2TA phonon interaction has significant influence on the energy loss rate in the intermediate temperature range 20-40K [22]. In GaInAs/AlInAs heterojunctions, the ELR by 2TA phonons is significant in the intermediate temperature range 20-40K , also theoretical calculations for ELR have been studied for GaSb and InSb quantum wells by considering 2TA phonons [23]. Without incorporating 2TA phonons, no good agreement is obtained for ELR between experimental and theoretical data over the wide temperature range.

It is demonstrated that, investigation of Gruneisen parameters and the phonon spectra in GaN indicating low-frequency phonon vibration modes correspond to change of thermal expansion. Below 5THz, the significant weighted negative values of more Gruneisen parameters, caused by the weakening of mixing mode constituted with two-transverse acoustic (2TA) modes [24]. Second order transverse acoustic (2TA) phonon mode at 300cm^{-1} was observed on Si substrate from Raman spectra of CdSe quantum dots [25]. In Zinc nanowires, some overtones due to 2TA phonon peaks are observed at high temperature due to larger wave vector from Raman scattering study [26].

3. Electron Energy Loss rate in Quantum Wells:

3.1. Two-phonon process:

In the one-phonon process, the momentum and energy conservation requirement prevents the more energetic acoustic phonons from scattering electrons. However, in two-phonon process the additional phonon adds an extra degree of freedom and allows the acoustic phonon having energies greater than those permitted in one-phonon transitions to participate in the scattering of electrons. If and q and q' are the phonon wave vector in the short wavelength regions such that $Q = q + q'$ is quite small so as to lie in the long wavelength region, then the two-phonon process can be treated formally as one-phonon process. The effective two-phonon interaction Hamiltonian for bulk semiconductor was mentioned detail in [22]. The contribution to the electron ELR in quantum well and heterojunction system for the two-phonon process can be calculated by employing the bulk description of phonons. Further, it will be assumed that the electrons are quasi-2D, with the electron wave function given by

$$\Psi_k(r) = \frac{1}{\sqrt{A}} e^{ik*r}\, \Phi(z) \qquad (1)$$

where A is the area in the plane of the layer, k and r are the usual two-dimensional vectors. Here only the first subband is assumed to be occupied.

It is convenient to calculate average energy loss per electron by calculating the energy gained by phonons from the electrons and dividing by the number of electrons (N_e) participate

$$\langle P\rangle = -\frac{1}{N_e}\sum_{k,q,q'}\hbar(w_q + w_{q'})\frac{2\pi}{\hbar}\{(N_q+1)(N_{q'}+1)f(E_{k'})[1-f(E_k)] - N_qN_{q'}f(E_k)[1-f(E_{k'})]\}|M(q,q')|^2|F(q_z,q_z')|^2\delta(E_{k'}-E_k-\hbar(w_q+w_{q'}))$$

(2)

with $f(E_k)$ and N_q respectively representing the Fermi distribution with T_e and Bose distribution with T_L. $|F(q_z,q_z')|^2$ is the overlap integral. The electron-two-phonon matrix element restricting to transverse acoustic branch of phonons is given by

$$|M(q,q')|^2 = \left(\frac{\hbar D p_{\Sigma}^{1/2}}{2\rho\Omega a^2(w_q w_{q'})^{1/2}}\right) \quad (3)$$

By evaluating equation (2) using equation (3) the average electron ELR yields,

$$\langle P\rangle_{2TA} = \frac{m^{*2}D_{\Sigma}^2 p_{\Sigma}}{N_s\pi^2\hbar\rho^2 a^7}\left(\frac{T_e}{\theta_{TA}}\right)\left[\exp\left(\frac{\theta_{TA}}{T_L}\right)-1\right]^{-2}\frac{\left[exp\left\{2\theta_{TA}\left(\frac{1}{T_L}-\frac{1}{T_e}\right)\right\}-1\right]}{\left[1-exp\left(-\frac{2\theta_{TA}}{L}\right)\right]}\left[ln(1+exp\{\eta\}) - ln\left(1+exp\left\{\eta-\frac{2\theta_{TA}}{T_e}\right\}\right)\right]\int_{-\infty}^{\infty}|F(q_Z)|^2 dq_Z$$

(4)

where $\eta = \frac{E_f}{k_B T_e}$, $\theta_{TA} = \left(\frac{\hbar w_{\Sigma}}{k_B}\right)$, $\hbar w_{\Sigma}$ is 2TA phonon energy, a is lattice constant, and N_s is the carrier concentration. E_f is the Fermi energy which is given by $E_f = k_B T_e ln\left[exp\left(\frac{E_F}{k_B T_e}\right)-1\right]$ with $E_F = \frac{\pi\hbar^2 N_s}{m^*}$. The overlap integral for quantum well is $|F(q_z)|^2 = \left[\frac{sin\left(\frac{Lq_z}{2}\right)}{\left(\frac{Lq_z}{2}\right)}\frac{1}{1-\left(\frac{Lq_z}{2\pi}\right)^2}\right]^2$.

3.2. One-phonon process:

In literature there exist theoretical calculations of power loss per electron via LO phonon emission at higher electron temperature with and without hot phonon effect [2-4, 27]. By assuming the phonon modes to be the same as those of bulk semiconductors, one calculate the expression for energy loss rate per electron due to LO phonon scattering including hot phonon effect, can be expressed as [22]

$$\langle P\rangle_{LO} = \frac{(\hbar w_o)^2 m^* k_F e^2}{N_s\pi^2\hbar^3\varepsilon'}\int_0^{\infty}\int_0^{\infty} q^{-2}\,F(w_o,q_z)\,\gamma(\eta_-,\eta_+)\,dq_{||}dq_z \quad (5)$$

where $\gamma(\eta_-,\eta_+) = \int_0^{\infty}\frac{1}{\sqrt{X}}f(X+\eta_-^2)[1-f(X+\eta_+^2)]\,dX$ (6)

with $f(X+\eta_{\pm}^2) = [exp\{\xi(X+\eta_{\pm}^2-\mu)\}+1]^{-1}$; $\eta_{\pm}^2 = \left(\frac{q_{||}}{2k_F} \pm \frac{m^* w_q}{\hbar k_F q_{||}}\right)^2$; $\xi = \frac{E_F}{k_B T_e}$; $\mu = \frac{E_f}{E_F}$

and $F(w_o,q_z) = |F(q_z)|^2\left[N_q^{HP}\left(exp\left\{-\frac{\hbar w_o}{k_B T_e}\right\}-1\right)+\left(exp\left\{-\frac{\hbar w_o}{k_B T_e}\right\}\right)\right]$ (7)

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here N_q^{HP} is the non-equilibrium distribution function of phonons given by

$$N_q^{HP} = \left[\frac{N_q + \tau_p \alpha \left(exp\left\{-\frac{\hbar w_o}{k_B T_e}\right\}\right)}{1 + \tau_p \alpha \left(1 - exp\left\{-\frac{\hbar w_o}{k_B T_e}\right\}\right)}\right] \quad (8)$$

with τ_p be the optical phonon life time and α is given by

$$\alpha = \frac{2m^* k_F e^2 (\hbar w_o)}{\hbar^3 L \varepsilon' q_{||} q^2} |F(q_z)|^2 \gamma(\eta_-, \eta_+) \quad (9)$$

with $\varepsilon' = \left(\frac{1}{\varepsilon_\infty} - \frac{1}{\varepsilon_s}\right)^{-1}$ (10)

The total power loss per electron is obtained by adding contribution from 2TA and LO phonons (equations 4 and 5).

4. Results and Discussions:

Numerical calculations of power loss per electron as a function of electron temperature for one-phonon and zone edge 2TA-phonon processes have been performed for the GaN/AlGaN quantum well sample of Balkan et al [15]. The material parameters used in the calculations characteristic of GaN/AlGaN are m^* = 0.22m_0, a = 3.189 A^0, $(\hbar w_o)$ = 92meV, V_s = 2.16x10^3 m/s, ε_∞ = 5.35ε_0 and ε_s = 9.7ε_0.

In figure 1, the contribution to energy loss from LO phonons and 2TA phonons are shown along with experimental data of Balkan et al [15]. For this sample, N_s = 1.5x10^9 m^{-2} and well width L= 65 A^0 [15]. The solid line represents the total contribution from both LO and 2TA phonon processes.

For electron temperature greater than 150K, the power loss is dominated by LO phonon scattering. Hot phonon effects are expected to be important for 2D GaN/AlGaN similar to 2D GaAs quantum wells. From figure 1, it is seen from our calculations that the calculations without hot phonon effects (dash-dot line) do not account very well with the experimental data in the higher temperature region. The calculations show much higher power loss values than the experimental data. Similar deviation between experimental data and theoretical calculations is obtained by Balkan et al [15] and they expected this deviation is due to free carrier density were reduced by increasing field or there were hot phonons present in high fields. So we have included hot phonon effects in the calculations with a optical phonon life time of τ_p = 5 ps. This value is the same used by Balkan et al [15] and may be compared with the value mentioned in reference [27]. In literature it is found that the hot phonon effects will reduce the power loss rate. Even with the inclusion of hot phonon effect with hot phonon life time τ_p = 5 ps, our calculations are not in good agreement with experimental data for LO phonon scattering alone. Hot phonon life time varies in the range from 150 to 180 fs and depends on electron density, temperature and electric power supplied [28]. Also optical phonon life time has been found to decrease from 2.5ps at low density to 0.35ps at high density [29].

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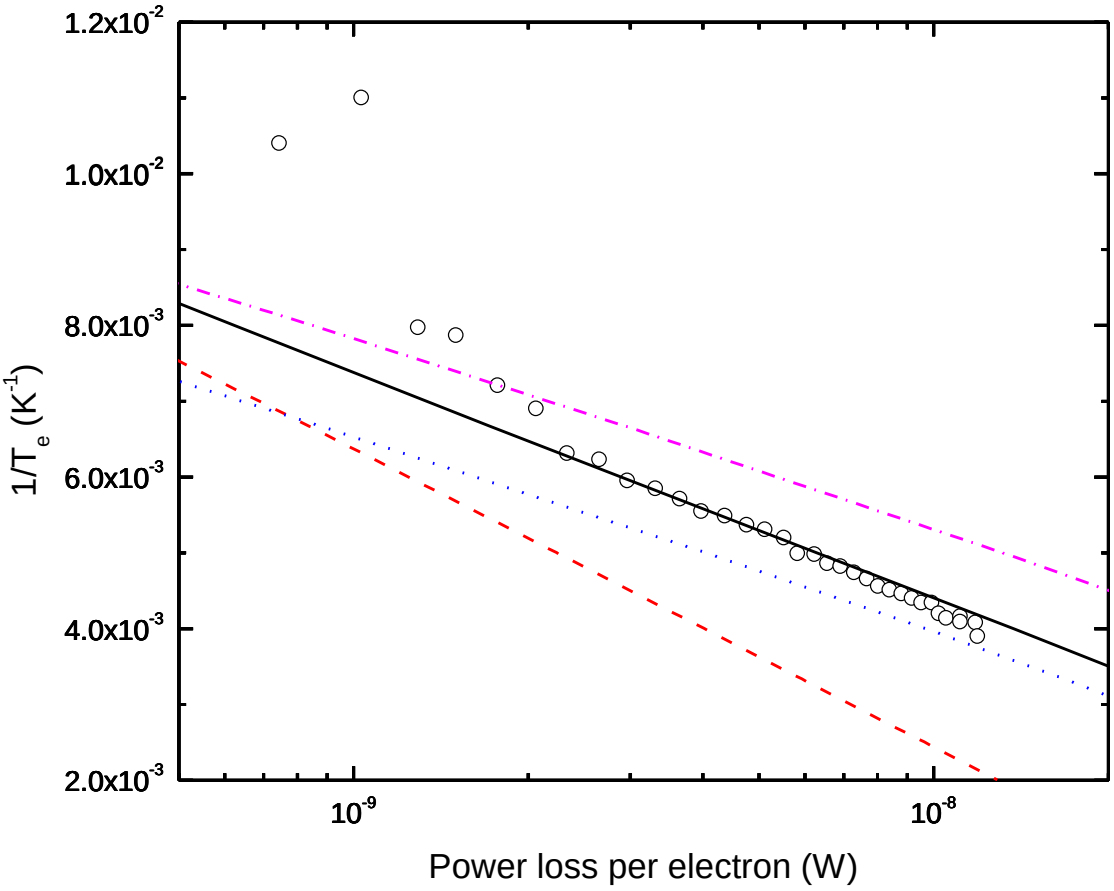

Figure 1.Inverse of electron temperature versus ELR for GaN/AlGaN sample of Balkan et al [15]. Dashed line (red) denotes contribution from 2TA phonons, dotted line (blue) denotes from LO phonons with hot phonon effect and solid line (black) represents for total contribution. Dash-dotted line (pink) corresponds to LO phonons without hot phonon effect.

In GaAs and GaInAs heterostructes, one-phonon acoustic (both deformation and piezoelectric scattering) and polar optical phonon scattering contributions are inadequate to account for the observed power loss in the intermediate temperature range (20 – 40K). An additional energy relaxation mechanism such as 2TA phonon scattering will dominate the power loss in the intermediate temperature range and hence obtained a good agreement over the entire temperature range [23]. So we tried to include this additional energy relaxation mechanism due to two-phonon scattering process in order to compare the experimental data of GaN/AlGaN quantum well. We have used in our calculations a value of 25meV as 2TA phonon energy for GaN which may be compared with 19.4 meV for GaAs. The two-phonon deformation potential constant D_{Ξ} was varied to obtain best fit with the experimental data. The value so used is D_{Ξ} = 4.0x10^3 eV, this value may also be compared with D_{Ξ} = 2.0x10^3 eV for GaAs and for fraction of the Brillouin zone p_{Ξ} a value 0.5. With inclusion of 2TA phonon scattering processes in addition to LO phonon scattering mechanism, we obtain a good agreement with the experimental data. Also from figure 1 that, we observe that power loss due to LO phonon process cross over 2TA phonon process at around 150K indicating that 2TA phonon scattering mechanism is dominant process below 150K. More experimental data is waiting for GaN/AlGaN to show importance of 2TA phonon scattering mechanism over a wide range of electron temperature.

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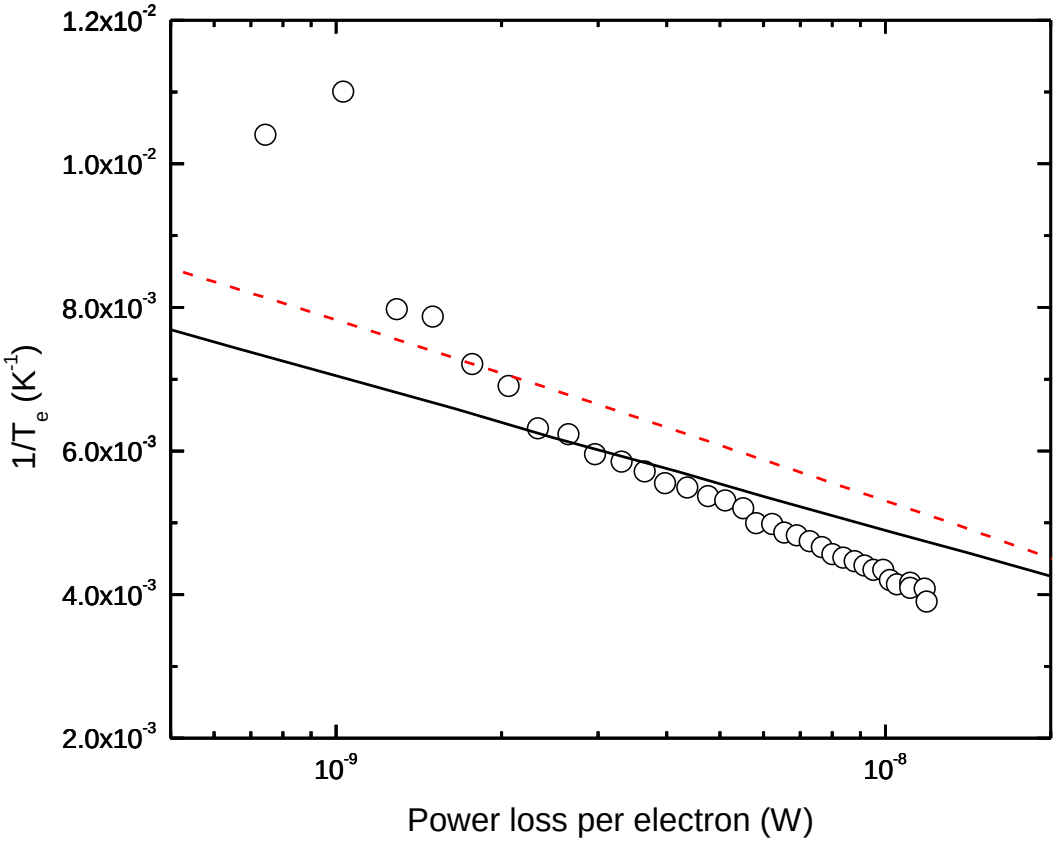

Figure 2. Comparison of theoretical ELR with experimental data of Balkan et al [XX]. Dashed line corresponds to LO phonons without hot phonon effect from our calculations and solid line denotes contribution from theory of Balkan et al [15].

Figure 2 shows comparison of our calculations of ELR for LO phonons without hot phonon effect with theoretical calculations (equation 6) of Balkan et al [15]. Both calculations show disagreement with experimental data. Balkan et al [15] concludes that disagreement is may be due to assumptions made in the simplified theory (equation 6 and 7).

Conclusions:

The electron-two-phonon interaction, which has been successful in explaining variety of experiments in bulk semiconductors and 2D semiconductor heterostructure (GaAs, GaSb and InSb) is also important in 2D GaN/AlGaN quantum well the intermediate temperature range. From a comparison of our calculations with the experimental data, we find that, LO phonon scattering mechanism alone cannot account for the observed energy loss rate and the contribution to energy loss from 2TA phonons is significant. More experimental data on power loss over a wide electron temperature range and different electron concentration in GaN/AlGaN heterostructure would be able to throw more light on 2TA phonon mechanism involved.

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