Squeezed Electrons in GaN Quantum Wells

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ABSTRACT

We present an analytic theory of hot-electron transport in a GaN quantum well containing a large-enough electron concentration for strong electron-electron scattering to establish a drifted distribution. Novel behaviour includes the squeezed electron distribution and absolute cooling of the electron gas in a strong electric field when the electron temperature *decreases* with increase of the electric field. The current-voltage characteristics have the regions which obey the s-type dependence.

Keywords: Quantum well, hot electrons, electron temperature, GaN, squeezed electron distribution.

1 INTRODUCTION

In bulk material, or in zinc-blende quantum wells, strong electron-electron scattering can allow an electron temperature to be established at high electric fields, but a drifted distribution is commonly inhibited by the presence of impurity scattering and other scattering mechanisms which tend to control the electron momentum relaxation. This is because in order to obtain the necessary high electron density one has to use the highly doped materials. In this case the high electron density comes together with the high ionized impurities density and both the electron-electron and the electron-impurity scattering rates will have the same order of the magnitude. As a result of this the electron-electron scattering alone is unable to dominate the electron momentum relaxation The situation is different in the case of wurtzite GaN structures in which a large quasi-2D concentration of electrons can be established via spontaneous and piezoelectric polarization in the barrier layer without impurities being involved. As we show, it is possible for a drifted distribution to be established, and this leads to novel transport properties, including absolute cooling and a squeezing of the distribution in the direction of drift as the electrons encounter the strong phonon emission barrier when the average kinetic energy approaches the optical-phonon energy $\hbar\omega_o = 92.8$ meV. The effecs are strongest at low temperatures.

2 THE MODEL AND THE EQUATIONS

In order to describe the essential features as simply as possible, we consider a deep, square quantum well of GaN with AlN barrier, containing a 2D electron gas in a ground state with the quantization energy W_o, and limit the scattering mechanisms to electron-electron (e-e), polar optical (PO) phonon, piezoelectric acoustic (PA) and deformation acoustic (DA) potentials. In real structures it would be necessary to include scattering by background impurities, charged dislocations and interface roughness, but in principle, each one of these can be eliminated, whereas the scattering mechanisms we consider cannot be eliminated, although inclusion of these mechanisms in our theory has no principal difficulties. It is useful to appreciate the magnitude of each of these scattering rates. The most rapid is that for PO phonon emission (~10^{14} s^{-1}) when the electron energy is above the PO phonon energy; below the PO phonon energy, however, the rate is determined by PO phonon absorption which becomes weak towards low lattice temperatures $k_oT_o << \hbar\omega_o$. PA phonon scattering is always significant in wurtzite GaN, at T_o=50 K the rate is about 5×10^{12} s^{-1} for energies about k_oT_o, decreasing with increasing energy. DA phonon scattering is significantly weaker, the corresponding rate being about 10^{12} s^{-1}. The e-e scattering rate depends on electron density. In general, three different regimes of the electron kinetics are possible [1] which corresponds to different strength of the e-e interaction. Here we consider the case of high electron density when the e-e scattering controls both the energy and the momentum relaxation. At an energy equal to the PO phonon energy (the worst case in the range we consider) the rate in a gas of density 10^{11} cm^{-2} is about 4×10^{12} s^{-1}. In the range of the electron energies 0-100 meV it is easy for the e-e scattering to dominate both energy and momentum rates of randomization at densities 10^{12} cm^{-2} and above. Such densities are easy obtained in AlGaN/GaN structures [2, 3]. Here we will ignore the electron screening effects as well as the electron gas degeneracy and will assume the drifted Maxwellian distribution function over the electron wavevectors $\vec{k}$ $F_o(\vec{k}) = A_o \exp\left[-\hbar^2(\vec{k}-\vec{\kappa})^2 / 2m^*k_oT_e\right]$. The distribution is defined by two parameters: the drift wavevector $\vec{\kappa}$ and the electron temperature T_e (m^* is the electron effective mass and A_o is the normalization constant). In the presence of the external electric field F the electron system gains from the electric field both the momentum and the energy. It is important to point out that since the e-e scattering is the fastest scattering mechanism in the system, the energy and the momentum gained from the electric field by each individual electron will be first distributed within the whole electron gas without substantial loss to the other scatterers. At some point the

balance will be established between the whole electron gas and the thermal bath. As a result the electron gas will acquire the drifted (macroscopic) momentum $\hbar\vec{\kappa}$. The average kinetic energy of the gas, which is described by the electron temperature T_e, will also change. Usually both these parameters increase when the electric field increases. Here we want to point out that this is not the case any more if a strong inelastic scattering mechanism is present. In the case considered such a mechanism is mediated by the interaction with the PO phonons. Due to large magnitude of the PO phonon energy in GaN, the majority of the electrons will interact with the PO phonons only at relatively high electric field (~1 kV/cm). Until these fields will be reached the electron gas will interact mainly with the PA and DA phonons. This interaction is quasielastic [4] and it does not prevent both $\hbar\vec{\kappa}$ and T_e to grow when F increases. At higher electric fields, when the interaction with the PO phonons dominates over the PA and DA phonon interaction, the electron gas looses its energy by large portions ($\sim \hbar\omega_o$). This effectively hinders the further growth of the electron temperature. Due to the large coupling constant in GaN the optical phonon energy level acts as a "hard wall" for the electrons, which prevent the electrons from penetrating to the higher energy. In general the above parameters $\vec{\kappa}$ and T_e are found from the system of two balance equations which describe the momentum and the energy conservation:

$$\frac{eF}{\hbar}=\kappa\left[\frac{1}{\tau_{da}}+\frac{\sqrt{\pi}}{\tau_{pa}}\frac{k_oT_o}{\sqrt{2m^*s_T^2k_oT_e}}\Psi_1(\kappa)+\frac{\pi}{\tau_{po}}(N_o+1)P(w_o)\left(e^{-\frac{\hbar\omega_o}{k_oT_o}}+\Psi_2(\kappa)e^{-\frac{\hbar\omega_o+\varepsilon_\kappa}{k_oT_e}}\right)\right], \quad (1)$$

$$\frac{e\hbar}{m^*}\kappa F=\frac{4m^*s_L^2W_o}{3k_oT_o}\left(\frac{1}{\tau_{da}}+\frac{9}{10}\frac{1}{\tau_{pa}}\sqrt{\frac{2(s_Tk_oT_o)^2}{m^*s_L^4W_o}}\right)\times\left(1-\frac{T_o}{T_e}e^{-\frac{\varepsilon_\kappa}{k_oT_e}}\right)+\frac{\pi}{\tau_{po}}\hbar\omega_o(N_o+1)P(w_o)\times\left(\Psi_3(\kappa)e^{-\frac{\hbar\omega_o+\varepsilon_\kappa}{k_oT_e}}-e^{-\frac{\hbar\omega_o}{k_oT_o}}\right). \quad (2)$$

Here $\tau_{da}=\sqrt{2m^*\lambda_a^2/9W_o}$ is the DA phonon scattering time for the 2D electrons in a ground state of the square quantum well, $\lambda_a=\pi\hbar^4\rho s_L^2/m^{*2}E_a^2k_oT_o$ is the electron mean free path in a bulk material due to DA phonon scattering [5], ρ is the material density, E_a is the DA potential constant, s_λ is the longitudinal (λ=L) or transverse (λ=T) acoustic velocity, $\tau_{pa}=2\pi\rho\hbar^2s_T/m^*e^2h_{14}^2$ is the characteristic scattering time for the bulk material due to PA phonons, h_{14} is the piezoelectric constant, $\tau_{po}=2\alpha_F\omega_o$ is the PO phonon scattering time, α_F is the Fröhlich coupling constant, $N_o=\left[\exp(\hbar\omega_o/k_oT_o)-1\right]^{-1}$ is the PO phonon distribution function, $\varepsilon_\kappa=\hbar^2\kappa^2/2m^*$ is the electron drift energy. The function $\Psi_i(\kappa)$ is defined as

$$\Psi_i(\kappa)=4/\pi\int_0^1 f_i(u)\sqrt{1-u^2}\,du,\ \text{where}\ f_1(u)=\exp\left(-\frac{\varepsilon_\kappa u^2}{k_oT_e}\right),$$

$f_2(u)=\mathrm{ch}\left(2u\sqrt{\varepsilon_\kappa\hbar\omega_o}/k_oT_e\right)$, $f_3(u)=f_2(u)/2(1-u^2)$. The function $P(w_o)$ describes the overlap integral and is given by $P(w_o)=\frac{w_o}{4\pi}\left[\frac{2}{w_o^2}+\frac{1}{1+w_o^2}-\pi^{-1}\frac{1-e^{-2\pi w_o}}{w_o^3(1+w_o^2)}\right]$, where $w_o=\sqrt{\hbar\omega_o/W_o}$.

3 RESULTS AND DISCUSSION

The above equations have been solved numerically using the following parameters for the electrons in a square GaN/AlN quantum well (the well width was 70 Å with the ground state energy W_o=38 meV): $m^*=0.21m_o$, E_a=10.1eV, $h_{14}=4.24\times10^7$ V/cm, ρ=6.1 g/cm^3, $s_L=4.57\times10^5$ cm/s, $s_T=2.68\times10^5$ cm/s, α_F=0.45, $\omega_o=1.41\times10^{14}$ s^{-1}. The solution of the equations gives κ and T_e as a function of F.

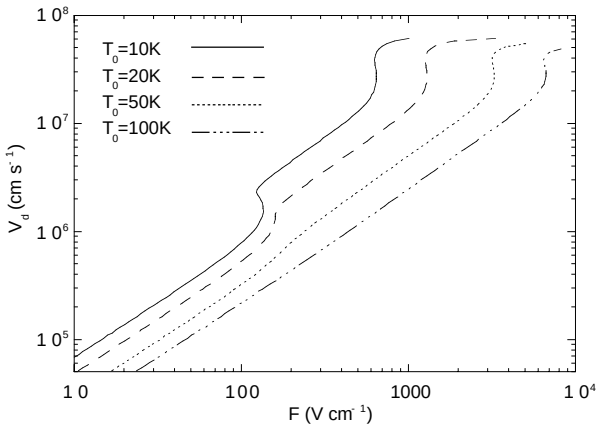

Figure 1: Variation of the electron drift velocity v_d with electric field F for different lattice temperatures T_o.

First we calculate the electric field dependence of the drift velocity $v_d=\hbar\kappa/m^*$ of 2D electrons which is shown in Figure 1 for different lattice temperatures T_o. The most interesting feature of this dependence are the regions which obey an s-type dependence. These regions exist only at low temperatures (T_o~10-20 K) and they disappear when T_o increases. This behaviour is a result of a complicated T_e-

dependent competition between PA and DA phonon scattering [1]. At higher lattice temperatures the DA scattering dominates over the PA scattering and the s-type regions disappear. Another interesting feature is a saturation of v_d at high electric field (~1-10 kV/cm). This effect is completely due to the e-e and PO phonon scattering. The PO phonon scattering effectively limits any further increase of the drift electron momentum since every time that an electron emits the optical phonon it loses almost all the energy and the momentum.

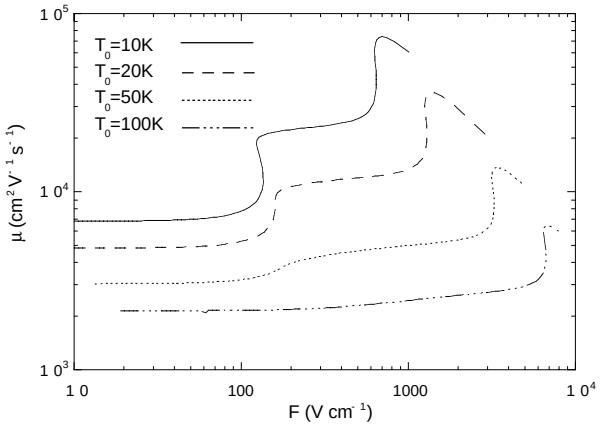

Figure 2: Variation of the electron mobility $\mu_d = v_d / F$ with electric field F for different lattice temperatures T_o.

The existence of the s-type regions and the saturation of the drift velocity is evident also from the electric field dependence of the electron mobility $\mu=v_d/F$, which is shown in Figure 2. Usually the drift velocity saturation takes place in the streaming regime [5], when the electron moves ballistically in the momentum space until it reaches the optical phonon energy, emits the optical phonon and repeat the ballistic motion again. But in our case the streaming regime does not take place because the necessary acceleration time $\tau_F = \sqrt{2m^*\hbar\omega_o}\,/eF$ is much longer (~5×10^{-12} s^{-1}) than the e-e scattering time.

The electric field dependence of the total mean electron energy <E> is shown in Figure 3. The total mean energy of the electron is a sum of the mean kinetic energy $<E_k>=k_oT_e$ and the drift energy ε_κ: $<E>= k_oT_e + \varepsilon_\kappa$. Again we see that at low T_o the electric field dependence of <E> has more complicated character than at higher T_o. At low T_o the PA phonon scattering is very strong in GaN and it suppresses increase of <E>. When F increases the electrons penetrates into the higher energy region where the PA scattering is weak. This results in a steep increase of <E> when F increases. At higher T_o the intensity of the PA scattering is small in comparison with the DA scattering and the region of steep increase of <E> disappears. Note that this region corresponds to the same range of F where the drift velocity obeys the s-type dependence as was shown in Figures 1, 2.

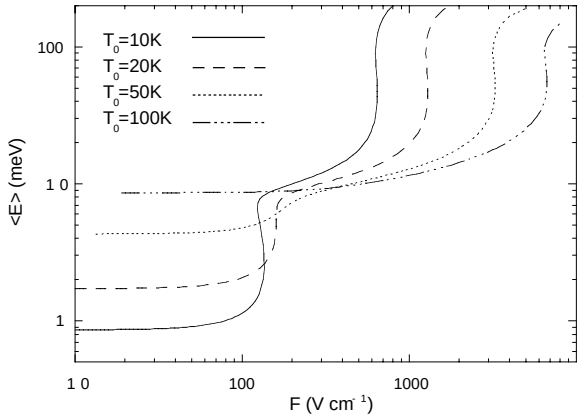

Figure 3: Variation of the total mean electron energy <E> with electric field F for different lattice temperatures T_o.

Increase in the total energy <E> does not mean that the electron temperature T_e increases as well when F increases. Figure 4 shows variation of the electron temperature T_e with the drift energy ε_κ for different lattice temperatures T_o. As we see this dependence is a non-monotonous function which has a region where the electron temperature decreases. This region corresponds to the electron cooling effect because the electron temperature T_e decreases with increase of the electric field. It is even possible to obtain at high electric field an electron temperature T_e which is smaller than the lattice temperature T_o – the absolute cooling effect. Of course, the total energy of the electron gas increases, as it should be, due to increase of the drift energy ε_κ. The physical reason of the electron gas cooling is the intensive emission of the optical phonons when the total energy of the majority of the electrons is close to the PO phonon energy $\hbar\omega_o$.

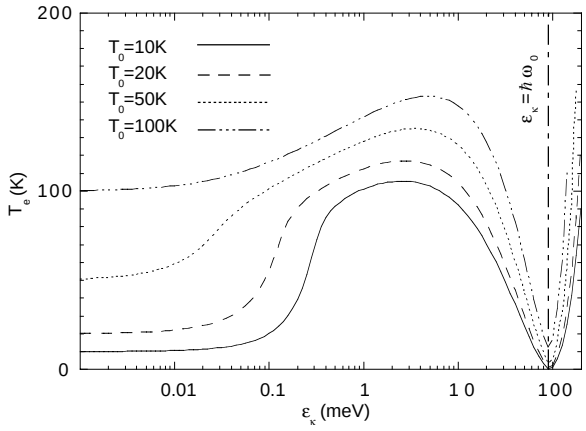

Figure 4: Variation of the electron temperature T_e with the drift energy ε_κ for different lattice temperatures T_o.

It is interesting to investigate behaviour of the electron distribution function with the increase of the electric field

F. This is shown in Figure 5 for two different lattice temperature T_o=10 K and T_o=100 K. The numbers near each curve are the values of the drift energy ε_κ. As the drift energy is a monotonous function of the electric field the higher drift energy corresponds to the higher electric field

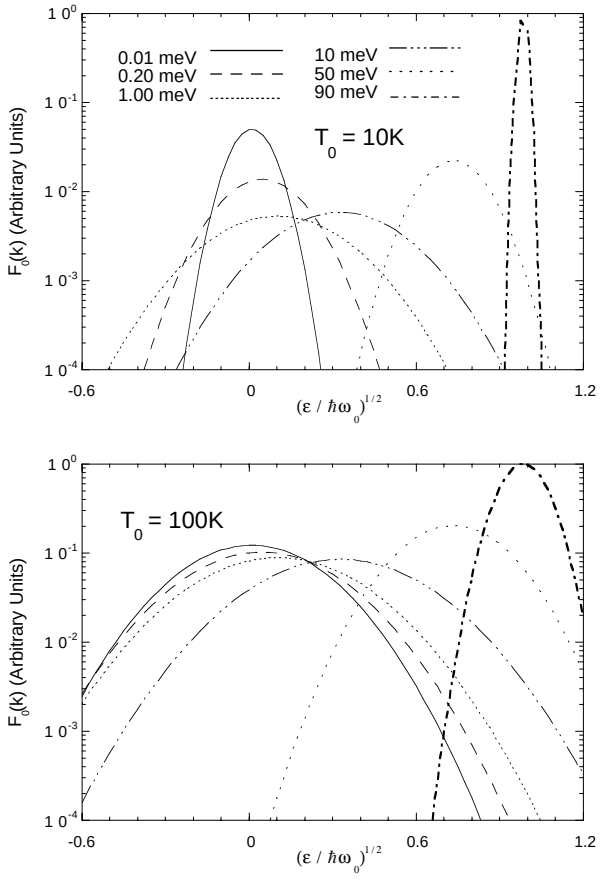

Figure 5: Squeezing of the distribution function $F_o(\vec{k})$ of hot electron gas for two different lattice temperatures T_o=10 K and T_o=100 K at different values of the drift electron energy ε_κ (numbers near each curve).

Figure 5 shows that at very small electric fields the electron distribution function is close to the Maxwellian equilibrium distribution function which is a maximum at zero kinetic energy. When the electric field increases the distribution becomes wider in the momentum space. This corresponds to an increase of the electron temperature T_e. At the same time the distribution function is no longer centered at zero energy but has shifted along the electric field, a shift that corresponds to the drift of the electron gas as a whole. This behaviour continues with increase of the electric field until the electrons start to penetrate to the optical phonon energy. Strong inelastic scattering prevents the electrons from any further increase of their kinetic energy energy. As a result the electron distribution becomes more narrow or squeezed. This corresponds to a decrease of the electron temperature. At the same time the centre of the distribution function continues its shift when the electric field increases, which means increase of the electron drift energy. The most interesting physical consequence of this behaviour is that the electron distribution function is inverted in the momentum space – a majority of the electrons populate the high-energy region. Another interesting consequence of the decrease of the electron temperature with increase of the electric field is that the non-equilibrium electron gas becomes "less randomised". This should give, for example, a decrease of the electron noise temperature.

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REFERENCES

[1] N.A. Zakhleniuk, B.K. Ridley, M. Babiker, and C.R. Bennett, Physica B 272, 309, 1999.

[2] R. Oberhuber, G. Zandler and P. Vogl, Appl. Phys. Lett. 73, 818, 1998.

[3] O. Ambacher, J. Smart, J.R. Shealey, N.G. Weimann, K. Chu, M. Murphy, W.J. Schaff, L.F. Eastman, R. Dimitrov, L. Wittmer, M. Stutzmann, W. Reiger and J. Hilsenbeck, J. Appl. Phys. 85, 3222, 1999.

[4] B.K. Ridley, "Quantum Processes in Semiconductors", 4th edition, Oxford Press, 1999.

[5] V.E. Gantmakher and Y.B. Levinson, "Carrier Scattering in Metals and Semiconductors", North-Holland, 1987.