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MONTE-CARLO STUDY OF HOT ELECTRON TRANSPORT IN BULK GaN

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ABSTRACT

Velocity-field characteristics and power dissipation of bulk wurtzite GaN at high electric field have been investigated and comparison has been made between the theoretical data and the simulated results obtained by using the Monte Carlo method. We have considered the electron density of $10^{18}cm^{-3}$ and have incorporated deformation potential acoustic phonon scattering, polar optical phonon scattering, ionized impurity scattering and intervalley phonon scattering. A NDR effect is observed only in the velocity-field characteristics of electrons at 300K but this effect is not found in case of hole transport.

Index Terms: Polar Optic Phonon (POP) Scattering, LO phonon, Reciprocal noise temperature, Dissipated power

I. INTRODUCTION

In recent years, a significant progress of wide band gap semiconductor technology promotes GaN as a perspective candidate in the fabrication of nanometer field effective transistors (FET). Also the material has high breakdown electric field strength and high electron mobility which makes it an attractive material for power transistor [1]. A comparison of the figure-of-merits between GaN and GaAs materials shows that a higher critical field (2MV/cm vs. 0.4MV/cm) can supply higher output power density, a higher electron saturation drift velocity ($2x10^7$cm/sec vs. $1x10^7$cm/sec) can yield ultra fast transition time therefore higher frequency and a higher thermal conductivity (1.3W/cmK vs. 0.5W/cmK) can occur from higher operating temperature for GaN based devices [2, 3]. The transferred electron (TE) effect at high electric fields due to interval scattering gives rise to a negative differential resistance (NDR) in GaN [4]. The main power dissipation mechanism in GaN at high electric field is due to the emission of Longitudinal Optical (LO) phonons by hot electrons. As a result, a large part of the supplied electric power is transferred to the LO-phonon sub-system and the latter is displaced from equilibrium. 'Hot phonons' thus result as a consequence of hot electron effect [5]. The accumulated hot phonons cause different effects e.g. introduce additional friction, reduce the electron drift velocity and electron energy dissipation [6]. The hot-phonon effects manifest themselves at a high density of electrons in channels subjected to high electric fields [7]. Measuring microwave noise of hot electron is a convenient way for experimental investigation of hot electron effect in voltage-biased channels [8]. The noise technique has provided with the hot phonon lifetime [8] in an excellent agreement with the value obtained from time-resolved experiment on the inter-sub-band absorption assisted by LO phonons [9]. For GaN-based channels, the lifetime is measured at different electron temperatures [6, 10], lattice temperatures [10, 11] and electron densities [12].

In the present communication the authors have made a comparative study between the obtained results [13] and those obtained with the help of Monte Carlo Simulation [7] in respect of the following parameters: relation between electric field and drift velocity, noise, transport mechanism, power dissipation in GaN channels. Monte Carlo methods have been widely used to study carrier transport in GaN because they provide a nearly exact solution of the Boltzmann transport equation by treating accurately the hot electron effects in GaN [14].

II. ANALYTICAL MODEL

The ensemble Monte Carlo method is used to solve the Boltzmann equation for electrons together with the equation for phonons treated in the relaxation-time approximation. The effect of non equilibrium longitudinal optical phonons on hot-electron energy distribution, mean energy, drift velocity and power dissipation is considered for bulk GaN subjected to electric fields in a range up to 100 kV cm^{-1}. We have

theoretically investigated the velocity-field characteristics in bulk wurtzite GaN by solving the Boltzmann transport

equation using the Monte Carlo method. Lattice scattering mechanisms included in the simulation are deformation potential acoustic phonon, piezoelectric, polar optical phonon, ionized impurity and intervalley phonon scatterings.

We have considered the effective mass for electrons in bulk wurtzite GaN as $0.21m_0$, where m_0 is the rest mass of electron. The band gap energy is taken as 3.39eV and interband (L-M) energy separation as 2.1eV [14]. The effective mass for holes has been taken from the reference [14] is $1.8m_0$ and the spin-off parameter as 0.2eV. The other parameters used in our calculations have been given below in Table 1.

Table 1: Material parameters of wurtzite GaN

Parameters	Values
a. Density (g/cm^3)	6.15
b. Acoustic deformation potential (eV)	8.3
c. Static dielectric constant	8.9
d. High frequency dielectric constant	5.35
e. Polar optical phonon energy (meV)	92
f. Inter-valley phonon energy (meV)	92
g. Inter-valley deformation potential (10^9eV/cm)	1
h. Hole acoustic deformation potential (eV)	19.6
i. Hole inter-valley phonon energy (meV)	92
j. Hole inter-valley deformation potential (10^9eV/cm)	1.5

The life time of hot phonon can be determined from experimental dependency of dissipated power on noise temperature. The dissipated power per electron under steady state $P_d = VI/N_e = P_s$ (1), where P_s is supplied power, I is current, V is voltage and N_e is the electron number in the channel.

The microwave noise temperature T_n nearly equals the electron temperature T_e and assuming all other noise sources are weak. Hence for dominant interaction of hot electrons with longitudinal optical (LO) phonons under the condition $T_n \cong T_e$, the dissipated power can be expressed as,

$$P_d=(\hbar\omega/\tau_{ph})\{[\exp(\hbar\omega/k_B T_n)-1]^{-1}-[\exp(\hbar\omega/k_B T_0)-1]^{-1}\} \quad (2)$$

where $\hbar\omega$ is the LO phonon energy, T_0 is the equilibrium temperature and k_B is the Boltzman constant. The fitting parameter τ_{ph} is the effective LO phonon life time.

III. RESULTS AND DISCUSSIONS

We have theoretically investigated velocity-field characteristics for both electrons and holes in bulk wurtzite GaN at 300K using Monte Carlo method. Electron velocity is calculated from the measured data on current, electron density and channel lengths, which is indicated Fig.1 by star marks. The velocity approaches the value of 2.8×10^5 m/s at electric field 300kV/cm. Hot phonons reduce the drift velocity as shown in Fig.1 by solid curves from simulation of [7]. The drift velocity for electrons reaches a peak of about 5.23×10^7 cm/s for an electric field of 100kV/cm and then

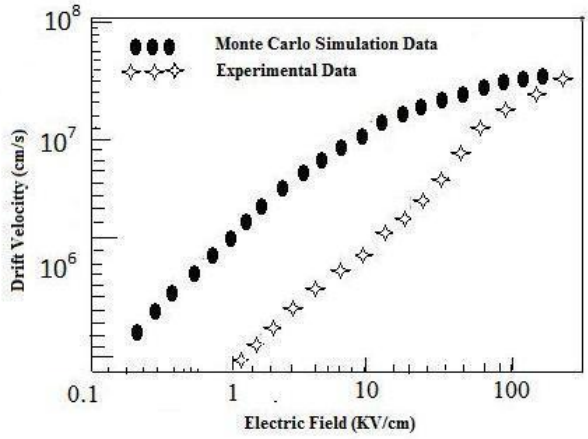

Fig.1: Drift Velocity–Electric Field graph for GaN at electron density 10^{18} cm^{-3}

decreases and attains almost a saturation value. Velocity peaks are more prominent for higher electric field values. A NDR effect is observed in the velocity-field characteristics, which is due to the interval transfer of electrons from the low effective mass high mobility central valley to the high effective mass low mobility higher satellite valley [15]. But his NDR effect is absent in the characteristics of holes. The simulated results for

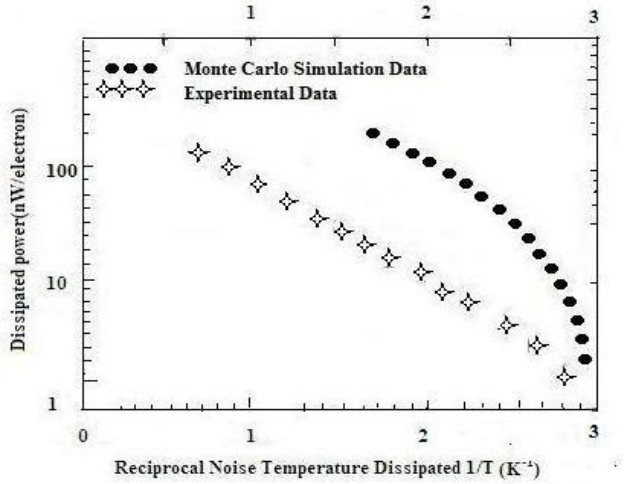

Fig.2: Dissipated power against Reciprocal noise temperature for GaN at electron density 10^{18} cm^{-3}

dissipated power per electron depend on the mean kinetic energy of the electrons as shown in Fig.2. The activation energy is close to the LO phonon energy [16, 17]. Also the simulation (Fig.2) shows a weaker hot phonon effect than the

experimental data. This contradicts with the conclusion obtained from the analysis of the electron drift velocity (Fig.1). The contradiction is reduced if LO-LO phonon collision (scattering) are taken into account. The hot phonon effect on electron drift velocity results from the non-equilibrium occupancy of the LO phonon modes allowed by energy and momentum conservation as shown in Fig.3.

IV. CONCLUSIONS

This paper deals with the development and application of Monte Carlo simulations to study electron transport in bulk GaN in the wurtzite crystal structure and the properties of field effect transistors made from the material. Monte Carlo simulation approach is used for a detailed comparative analysis of the transient electron transport that occurs within bulk zinc blende gallium arsenide and bulk wurtzite gallium

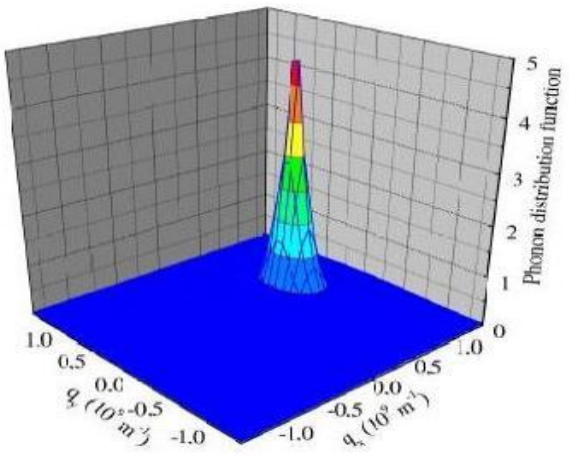

Fig.3: Hot phonon distribution function at 100kV/cm for GaN at electron density 10^{18} cm^{-3}

nitride. In our paper**,** the Monte Carlo study for velocity-field characteristics in bulk wurtzite GaN at high electric field reveals the fact that electrons reside in the upper valleys and in the high field regime electrons acquire enough energy to be scattered into the satellite conduction valleys. It is found that the peak drift velocity is most influenced by the optical phonon energy and the interval separation energies. This interval scattering of the electrons cause the NDR effect [15]. Furthermore, the theoretically simulated results as obtained by the authors agree quite satisfactorily with the available experimental data and with other theoretical works of GaN based MESFET structures.

References

[1] R.J.Trew, M.W.Shin and V.Gatto, "High power applications for GaN-based devices", Solid State Electronics, **41**, 1561-1567 (1997).

[2] E.R.Brown, "Megawatt solid-state electronics", Solid State Electron, **42**, 2119-2130 (1998).

[3] K.Shenai, R.S.Scott and B.J.Baliga, "Optimum Semiconductors for High-Power Electronics", IEEE Trans.Electron Devices, **36**, 1811-1823 (1989).

[4] J.T.Lu and J.C.Cao, "Terahertz generation and chaotic dynamics in GaN NDR diode", Semicond. Sci. Techno., **19**, 451-456 (2004).

[5] A.Matulionis, J.Liberis, I.Matulioniene, H.Y.Cha, L.F.Eastman, M.G.Spencer, "Hot-phonon temperature and lifetime in biased 4H-SiC" JAP, **96**, 6439-6444 (2004).

[6] A.Matulionis, "Hot phonons in GaN channels for HEMTs", Phys. Status Solidi A., **203**, 2313-2325 (2006).

[7] M.Ramonas, A.Matulionis, L.F.Eastman, "Monte Carlo evaluation of an analytical model for nonequilibrium phonon induced electron velocity saturation in GaN", Semicond.sci.techno., **22**, 875-879 (2007).

[8] A.Matulionis, J.Liberis, I.Matulioniene, M.Ramonas, L.F.Eastman, J.R.Shealy, V.Tilak, A.Vertiatchikh, "Hot-phonon temperature and lifetime in a biased $Al_xGa_{1-x}N$/GaN channel estimated from noise analysis", Phys. Rev.B, **68**, 035338-03533844 (2003)

[9] Z.Wang, K.Reimann, M.Woerner, T.Elsaesser, D.Hofsletter, J.Hwang, W.J.Schaff, L.F. Eastman, "Optical Phonon Sidebands of Electronic Intersubband Absorption in Strongly Polar Semiconductor Heterostructures", Phys. Rev. Lett., **94**, 037403-037406 (2005)

[10] M. Ramonas, A. Matulionis, J. Liberis, L. Eastman, X. Chen " Hot phonon effect on power dissipation in a biased AlxGa1-xN/AlN/GaN channel", Phys. Rev. B **71**, 075324 (2005).

[11] K.T.Tsen, D.K.Ferry, A.Botchkarev, B.Sverdlov, A.Salvader, H.Marcov, "Time-resolved Raman studies of the decay of the longitudinal optical phonons in wurtzite GaN", Appl.Phys.Lett., **72**, 2132-2134 (1998)

[12] K.T.Tsen, J.G.Kiang, D.K.Ferry, H.Marcov, "Subpicosecond time-resolved Raman studies of LO phonons in GaN: Dependence on photoexcited carrier density", Appl. Phys. Lett., **89**, 112111-11213 (2006).

[13] J.Liberis, M.Ramonas, O.Kiprijanovic, A.Matulionis, N.Goel, J.Simon, K.Wang, H.Xing, D.Jena, "Hot phonons in Si-doped GaN", Appl. Phys. Lett., **89**, 202117_1-202117_3 (2006).

[14] Shiyu Chen and Gang Wang, "High-field properties of carrier transport in bulk wurtzite GaN: Monte Carlo perspective", Appl. Phys., **103**, 023703-023708 (2008).

[15] K.Sarkar, Dr.A.Ghosal, "Monte-Carlo study of velocity overshoot and Terahertz generation in GaN", IJECT, **2**, 146-148 (2011).

[16] A.Matulionis, J.Liberis, L.F.Eastman, W.J.Schaff, J.R.Shealy, X.Chen and Y.J.Sun, "Electron Transport and Microwave Noise in MBE- and MOCVD-Grown AlGaN/AlN/GaN", ACTA Physica Polonica A, **107**, 361-364 (2005).

[17] Stephen K. O'Leary, Brian E. Foutz, Michael S. Shur, Lester F. Eastman, "Potential performance of indium-nitride-based devices", Appl. Phys. Lett., **88**, 152113-152115 (2006).