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Archives of Applied Science Research, 2014, 6 (3):70-73
(http://scholarsresearchlibrary.com/archive.html)

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ISSN 0975-508X
CODEN (USA) AASRC9

Current-voltage characteristics of GaN MOSFET: A monte-carlo simulation

[1]S. Chakraborty, [2]A. Biswas, [3]A Ghosal, [4]S. Majumder and [5]A. K. Bhattacharjee

[1]Kanksa Academy of Technology & Management, Panagarh, Dist.-Burdwan, West Bengal, India
[2]Dept of ECE, Hooghly Engineering and Technology College,
Vivekananda Road, Pipulpati Post, Hooghly, Kolkata, India
[4]Surface Robotics Lab, CSIR-CMERI, M. G. Avenue, Durgapur, West Bengal
[4]Dept. of ECE, National Institute of Technology, Durgapur

ABSTRACT

We have theoretically investigated drain current versus drain voltage characteristics for GaN MOSFET at 300K using one-particle Monte-Carlo method. The Boltzmann transport equation is solved incorporating deformation potential acoustic phonon, polar optical phonon, impurity and intervalley phonon scatterings. The variation of drain current with drain voltage exhibits a negative differential resistance (NDR) effect at 300K. The current-voltage curves show the NDR effect at low electric fields for the lattice temperatures considered.

Keywords: Monte-Carlo Simulation, Polar Optical Phonon Scattering, Negative Differential Resistance(NDR).

INTRODUCTION

GaN being a wide band-gap material has a high breakdown field and a high electron mobility, which make it suitable for optoelectronic devices like blue light-emitting diodes, photodiodes and other high frequency devices [1-2]. 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. This cannot be accomplished by the drift diffusion models [3]. The transferred-electron (TE) effect at high electric fields due to inter-valley scattering gives rise to a negative differential resistance (NDR) in GaN [4]. The diode oscillators based on the NDR mechanism in GaN have self-oscillating frequencies in the terahertz (THz) frequency range depending on the diode submicron dimensions [6].

2. Theoretical Model :

We have used the Monte-Carlo method to study the motion of one electron in momentum space encountering a large number of lattice scattering processes. The procedure used for following the motion of an electron requires random numbers to represent the time which the electron drifts before being scattered, and to represent the final state after the scattering event [5]. The probability distribution of these random numbers is correlated with the electric field strength and transition probabilities of the various scattering processes. A uniformly distributed random number r_1 between 0 and 1 is generated to calculate the time t for which the electron drifts freely in the applied field before being scattered. The random number r_1 is expressed as [5] :

$$r_1 = 1 - \exp[-\int_0^t \lambda[k(t')dt']] \quad (1)$$

where k (t') =k_0 +eE t' / ħ , k_0 is the wave vector at t = 0 at the beginning of the flight, E is the applied electric field and λ (k) is the total transition rate from the state k due to all the scattering mechanisms. The type of scattering is determined by a second random number r_2 uniformly distributed between 0 and 1 and satisfying the inequality

$$r_2 < \sum^m \frac{\lambda_q(k)}{\Gamma} \quad (2)$$

for all m. The value of Γ is chosen greater than the maximum value of λ (k). Two more random numbers r_3 and r_4 are required to determine the final state after the scattering. The drift velocity of the electron is calculated from the following expression

$$v = \frac{\sum E_f - E_i}{[\hbar \sum (k_{zf} - k_{zi})]} \quad (3)$$

where k_{zf} and k_{zi} are the initial and final values of the wave vector for a particular flight, E_f and E_i are the final and initial energies of the electron, and Σ represents the summation over all electron free flights. The authors have taken 15,000 collisions in order to obtain convergent results.

. The scattering rate for polar mode scattering in parabolic band approximation is given in accordance with [5] as

$$\lambda_{po}(k) = \frac{e^2 m^{*1/2} \omega_0}{4\sqrt{2}\pi\hbar \in_0} \left(\frac{1}{k_\infty} - \frac{1}{k_0} \right) E^{\frac{1}{2}} \times F_0(E, E') H \begin{cases} N_0 (absorption) \\ (N_0 + 1)(emission) \end{cases} \quad (4)$$

where $$E' = \begin{cases} E + \hbar\omega_0 (absorption) \\ E - \hbar\omega_0 (emission) \end{cases} \quad (5)$$

$$F_0(E, E') = \ln \left| \frac{E^{\frac{1}{2}} + E'^{\frac{1}{2}}}{E^{\frac{1}{2}} - E'^{\frac{1}{2}}} \right| \quad (6)$$

The factor H is unity for absorption and is equal to the Heavyside unit function H (E- ħω_o) for emission. The angle β between the initial state **k** and the final state **k′** has been obtained from the angular probability distribution P_A(β) given in [5]:

$$\cos\beta = \frac{[(1+f) - (1+2f)^r]}{f} \quad (7)$$

where $$f = 2(E, E')^{\frac{1}{2}} (E^{\frac{1}{2}} - E'^{\frac{1}{2}})^{-2} \quad (8)$$

and r is the random number uniformly distributed between 0 and 1.We have included in our calculations the expressions for deformation potential acoustic phonon scattering, ionized impurity scattering and inter valley scattering as given in [5].

We have calculated the drain current (I_d) at the different values of the drain voltage (V_d) from the velocity and field values obtained from the Monte Carlo simulation.

RESULTS AND DISCUSSION

We have considered the effective mass for electrons in bulk wurtzite GaN as $0.21m_0$, where m_0 is the rest mass of the electron. The band gap energy is taken as 3.39eV and inter-band (L-M) energy separation as 2.1 eV [1]. The other parameters used in our computations have been given in Table 1.

Table 1 : Material parameters of wurtzite GaN.

Material Parameter	Value
Density (g/cm3)	6.15
Acoustic deformation potential (eV)	8.3
Static dielectric constant	8.9
High frequency dielectric constant	5.35
Polar optical phonon energy (meV)	92
Inter-valley phonon energy (meV)	92
Inter-valley deformation potential(109 eV/cm)	1

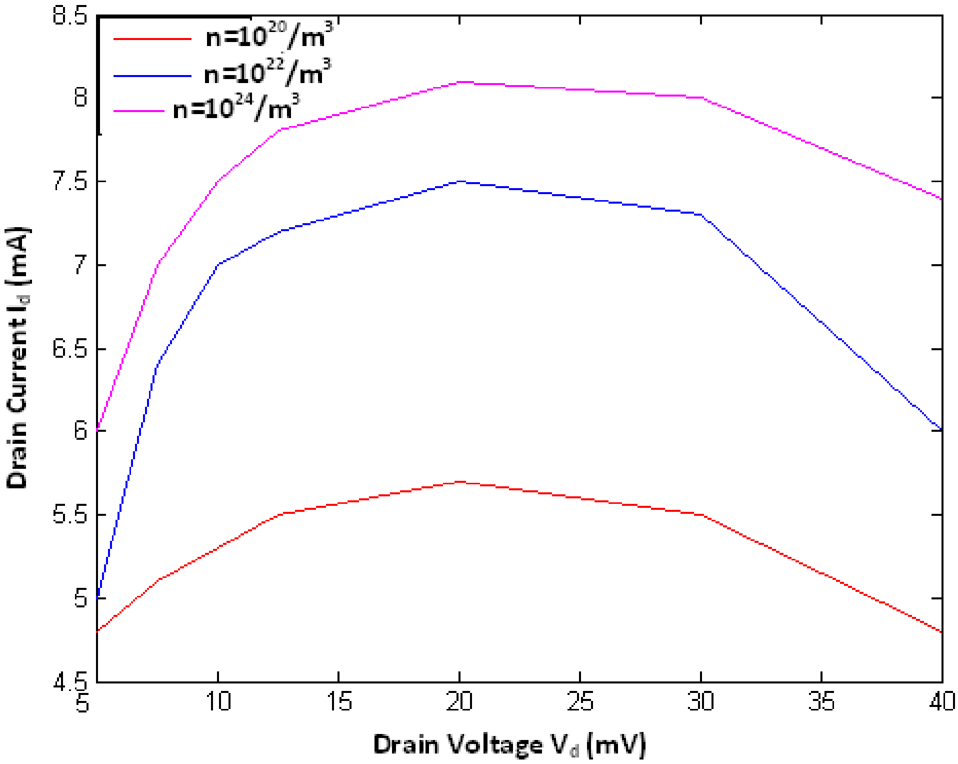

Figure 1. Variation of drain current (I_d) with drain voltage (V_d)of GaN MOSFET for various electron concentrations

CONCLUSION

The curves in the Figure 1 show a NDR effect with the velocity peaks more prominent at lower carrier concentrations. This may be attributed to the fact that scattering effects like impurity scattering is less effective at lower carrier concentration. The NDR effect as obtained by the authors will pave the path for design of high frequency electronic oscillators of submicron dimensions.

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