IOSR Journal of Engineering (IOSRJEN) **www.iosrjen.org**
ISSN (e): 2250-3021, ISSN (p): 2278-8719
Vol. 08, Issue 6 (June. 2018), ||V (V) || PP 18-25

Investigating Ballistic Transport In Nano-Dimensional InAlAs/InGaAs HEMT At Cryogenic Temperature

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Abstract : This paper investigates the effects of ballistic mobility on carrier transport in a 100 nm $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ HEMT at cryogenic temperature. Simulation has been carried out using Genius Visual TCAD employing drift-diffusion model at 100 K temperature. Analytically obtained temperature dependent mobility is incorporated in the physical model of the simulator to investigate the ballistic transport effects in a nano-dimensional HEMT. Using this novel simulation model, temperature dependence of critical device functional parameters such as Fermi energy and Schottky barrier height has been obtained. Current characteristics obtained both at 300K and 100 K are compared with the experimental results to validate the results.

Keywords – cryogenic temperature, heterostructure, high electron mobility transistor, simulation.

Date of Submission: 12-06-2018 Date of acceptance: 16-06-2018

I. INTRODUCTION

Technological advances in high-performance systems has led to device dimensions reaching a level where further scaling down leads to hot electron effects, leakage currents etc, thus deteriorating the device performance. As we scale down the device size, the characteristics length scale of the device becomes comparable with the carrier mean free path making it possible for the carrier to go ballistic [1]. The ballistic carriers in an ultra-small device are expected to travel through the channel without experiencing any random scattering from lattice defects, impurities, and phonons. This has lead to new carrier transport models for nano-dimentional devices which involve understanding conduction at nanoscales and formulating new simulation techniques [2].

Cryoelectronics or low temperature electronics (LTE) is an old research field that has been used for studying physical and material properties of devices at low temperatures [3]. The concept of cryoelectronics was first proposed in the year 1979 by Pearson and Bardeen [4]. Ever since, there has been continuous progress in this field. Many researchers have reported measurement of drift and carrier mobility of the semiconductor devices at low temperature [5-6]. Also, LTE operations are required for many future NASA space missions where it is desirable to have cheaper, lighter and smaller spacecraft [7]. A semiconductor device capable of operating at cryogenic temperatures are required to tolerate the intense environmental conditions of deep space and help reducing the heating units, thus reducing cost. LTE also have potential use in medical diagnostic, cryogenic instrumentation and superconductivity magnetic energy storage [7]. In particular, certain semiconductor devices shows some promising improvement with temperature decreasing down to liquid nitrogen temperature (-196 ^{o}C) resulting in higher speed by increased carrier mobility and saturation velocity [8-9]. Operating semiconductors at low temperatures, shed more light on the transport behavior. At deep cryogenic temperatures, novel quantum-transport based phenomena may arise. *Bordallo et. al* demonstrated electrical performance of Tunnel-FETs, characterized down to 10K where they found increase in voltage gain and reduction of the transconductance due to the increase of the energy bandgap [10].

Motivation for LTE has risen further from the well-known drawbacks of technology scaling [11]. At low temperature, many parameters of semiconductors get modified like band gap increases and optical properties and carriers transport are improved. Increase in performance, speed and reliability are the key features that have attracted attention towards the high mobility semiconductor devices. [12-14].

The device operation at low temperature has the benefit of removal of self-heating capability of device with large number of devices on a single chip [15]. In HEMT modeling, there are various temperature dependent parameters such as energy band gap, carrier mobility, threshold voltage, schottky barrier height, sheet carrier

concentration etc. Thus, these parameters need to be modeled in accordance with the operating temperature [16]. In order to illustrate the possible carrier transport enhancement at cryogenic temperature, the physical models must take into account influence of different scattering mechanism such as optical phonons, acoustic phonons, impurity and alloy scattering on carrier mobility. Low field carrier mobility is controlled by optical phonon absorption, acoustic phonons and alloy scattering, while other scattering mechanisms such as optical phonon emission and intervalley scattering are also involved in carrier transport inside active devices [17]. Carrier mobility is enhanced at low temperature due to a strong reduction of acoustic phonon scattering. Impurity scattering still plays a vital role on carrier transport in low field regime, for impurity doping above 10^{14} cm$\cdot^{3}$ at deep cryogenic temperature. [18-19].

In the present work, authors have modeled and simulated the impact of cryogenic temperature on functional and material parameter of 100 nm $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ HEMT using Genius Visual TCAD device simulator. InAlAs-InGaAs-InP HEMTs is a high gain low noise device that offers minimum noise figures of 0.8 and 1.2 dB with gains of 8.9 and 7.2 dB at 60 and 94 GHz, respectively [20]. A complete investigation of device functional parameter at 100 K has been done using Genius VTCAD device simulator which incorporates the drift-diffusion model to simulate the electrical and thermal behaviors of semiconductor devices. Temperature dependent I/V characteristics of the device has been simulated by modifying the various physical and material models used by the Genius Visual TCAD device simulator [21].

The device structure and the simulation model for low temperature device physics are described in Section II. The simulation results thus obtained are reported and discussed in Section III. Finally the conclusion is presented in Section IV.

II. DEVICE STRUCTURE AND MODEL

HEMT (high electron mobility transistor) is based on a heterojunction that consists of two semiconductor materials of different band gaps (wide bandgap and narrow band gap). The principle is based on the idea that only the wide band gap material (InAlAs) is doped and the free electrons moves from the donor states to the undoped layer (InGaAs), confined along the hetero-interface. One can separate the free carriers from their parent impurities by employing modulation doping technique [22]. Being spatially separated from donors, the electrons are not subjected to ionized impurity scattering and thus can exhibit very high mobility in the formed two dimesnional electron gas (2-DEG).The schematic of the device structure is shown in Fig.1 and simulated device structure of selectively doped InAlAs/InGaAs heterostructure is shown in Fig.2.

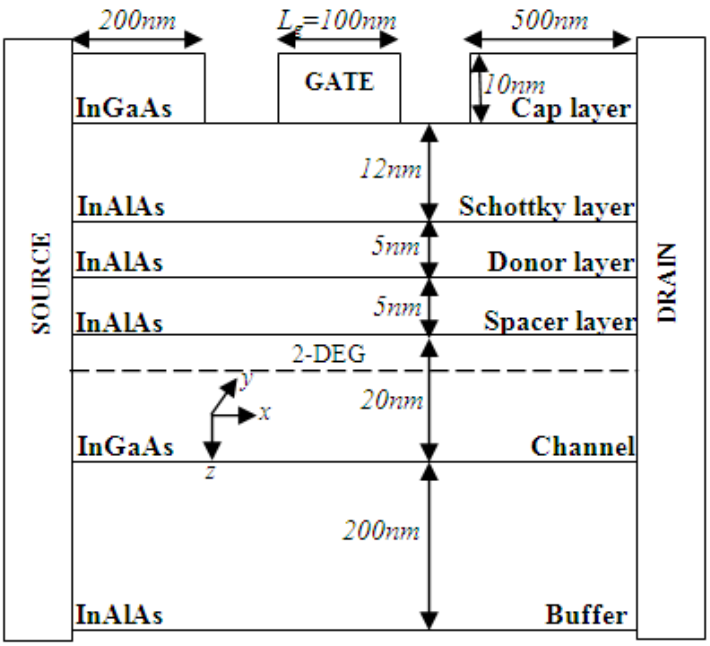

Figure 1. Schematic of 100 nm InAlAs/InGaAs Single Gate HEMT

The significance of the various layers shown in the above structure is as follows:

- Cap layer- Minimizes the Source and Drain contact resistances.
- Schottky layer- Provides a schottky gate contact.
- Donor layer- Source of electrons.

- Spacer layer- increase the spatial separation of ionized donor impurities and the free electrons in the 2-DEG thus minimizing the impurity scattering and enhancing the electron mobility.
- Channel- active conduction layer of the device.
- Buffer layer- Grown on substrate layer to isolate defects and create smooth surface to grow active layer.

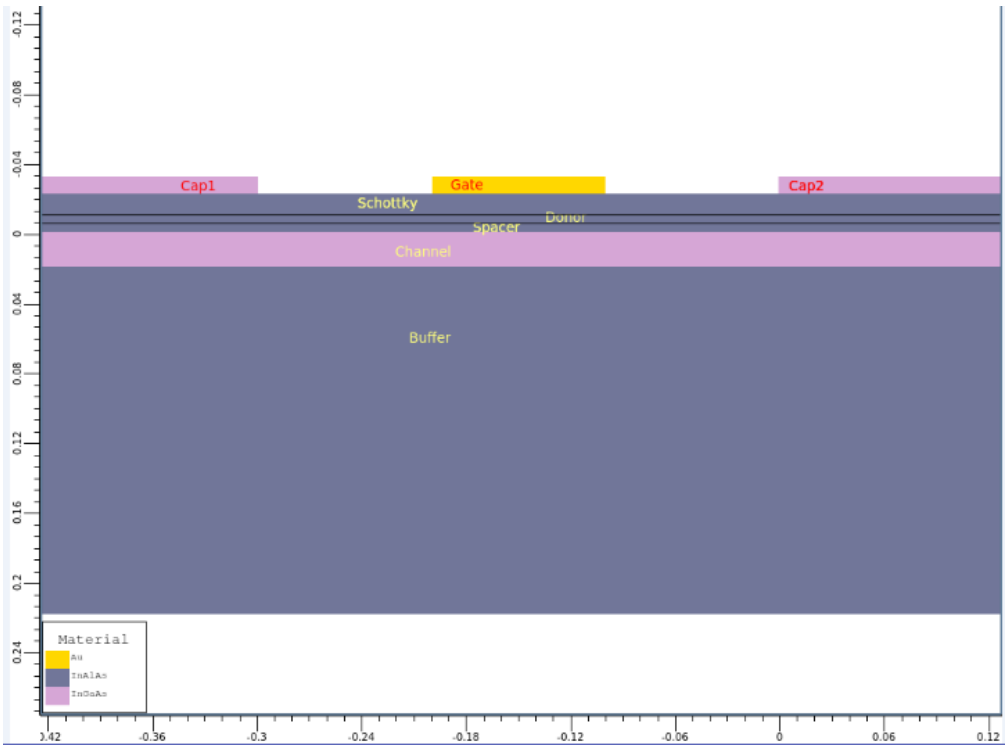

Figure 2. Simulated structure of 100 nm InAlAs/InGaAs Single Gate HEMT using TCAD

The conduction and valence band discontinuity at the InAlAs and InGaAs interface results in the creation of a triangular quantum well at the discontinuity. The electrons transferring from the doped layer into the undoped layer are then confined in this thin quantum well.

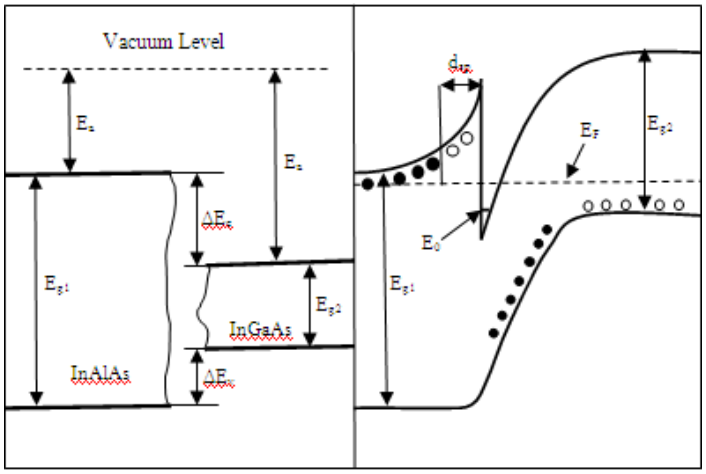

Figure 3. (a) Energy band diagram of selectively doped InAlAs/InGaAs heterostructure. (b) Quantum Well formation at the hetero-interface.

The motion of the electrons is restricted or quantized in a direction perpendicular to the heterointerface and thus the motion of the carriers becomes two dimensional and the resultant system is known as the two dimensional electron gas [2DEG] [23].

Energy band diagram of selectively doped InAlAs/InGaAs heterostructure is shown in Fig.3 (a) and also the quantum well formation is illustrated in Fig.3 (b). The ever decreasing dimensions of semiconductor based devices together with the increasing complexity of modern technology highlight the necessity of device

simulation. Genius Visual TCAD form Cogenda has been used for the two dimensional simulations in present work. This simulation tool is capable of simulating semiconductor devices down to sub-100 nm where short channel effect, non-equilibrium transport and quantum mechanics govern their operation. It incorporates advance physical models and numerical methods for simulating the device electrical behavior. The overall methodology of device simulation of 100 nm InAlAs/InGaAs SG-HEMT using Genius Visual TCAD is illustrated in Fig. 4. TCAD tools use the drift diffusion model which is being constantly improved in accordance to various operating properties [19]. The simple approximations used are [21]:

- All phonon-phonon and electron- phonon collisions are elastic.
- No change in Band-gap during collisions.
- Carrier temperature is the same as lattice temperature.
- The gradient of driving force is small.
- Carrier degeneration is neglected.

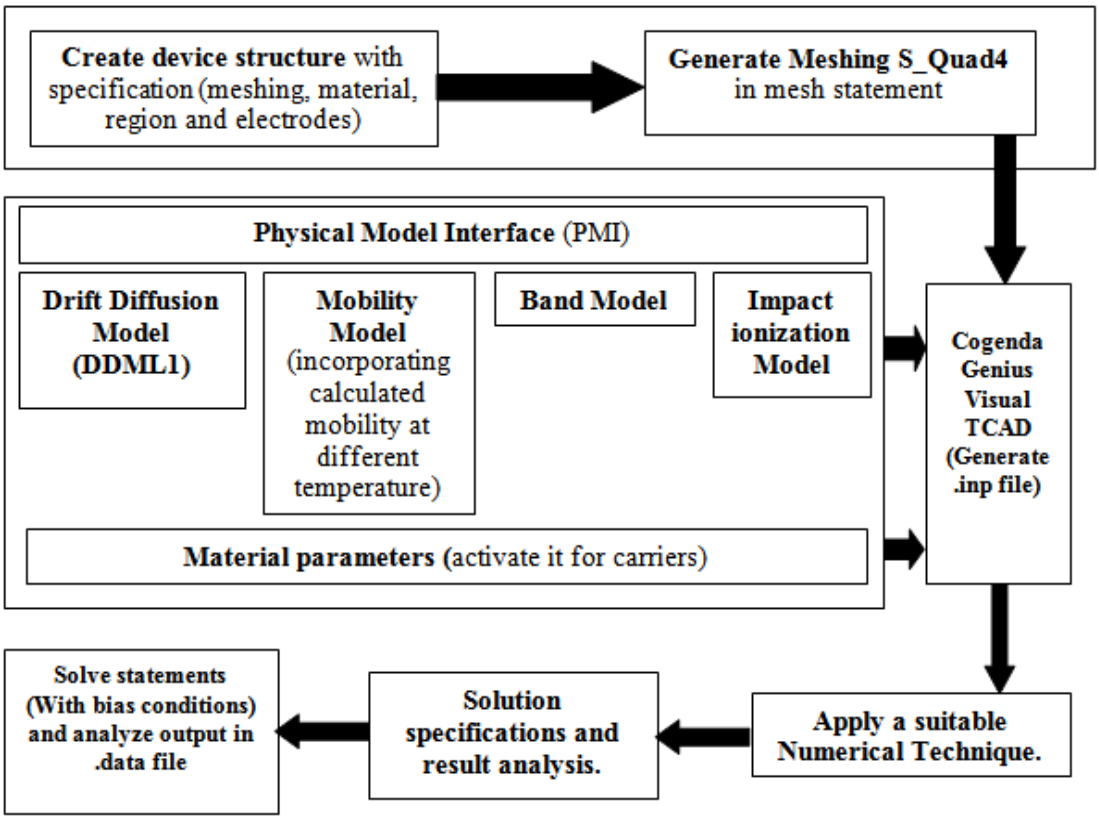

Figure 4. Flow chart of the device simulation in Genius Visual TCAD

Steps used for simulations are indicated in the Flow Chart in Fig. 4 and explained below:

i. The device structure is created using Genius Visual TCAD,
ii. Mesh is defined using*S_Quad4* in mesh statement. Since in InAlAs/InGaAs HEMT channel region is at the heterointerface therefore the mesh density should be tight around this heterointerface region where large variation in the charge carrier are observed. Also doping and mole statements should exist in the same input file so that device doping profile and mole distribution can be rebuilt on the new mesh.
iii. Necessary physical parameter defined for each material used in the device structure.
iv. Choose the appropriate Physical model. In Genius Visual TCAD simulator, the physical models of each material are loaded through the physical model interface (PMI). Physical model supported by genius namely (basic model, band model, impact model, mobility model and thermal model) are used to describe physical behavior of semiconductor device. Among mobility model, carrier temperature based mobility model was included in our device simulation in order to obtain some reliable prediction about the ballistic nature of the device at cryogenic temperature. Since at low temperature, devices offers high mobility therefore in order to enhance the device performance, authors incooperated the calculated mobility in the simulation model at different low temperatures [17].

At lower temperature one can achieve high electron mobility and thereby increasing the possibility of the device to be ballistic. The model used in the simulation incorporated the temperature dependent mobility due to the presence of each scattering mechanism (impurity, acoustic phonon, optical phonon and alloy).The total mobility is then found by adding mobility due to each scattering mechanism, in accordance to "Matthiessen rule" [17, 24];

$$\frac{1}{\mu(T)} = \frac{m^*}{q}\frac{1}{\langle \tau_{ion}(T)\rangle} + \frac{m^*}{q}\frac{1}{\langle \tau_{def}(T)\rangle} + \frac{m^*}{q}\frac{1}{\langle \tau_{piezo}(T)\rangle} + \frac{m^*}{q}\frac{1}{\langle \tau_{PO}(T)\rangle} + \frac{m^*}{q}\frac{1}{\langle \tau_{alloy}(T)\rangle} \quad (1)$$

where, m^* is the effective mass of the electron, q is the electronic charge, $\tau_{ion}(T)$ is the relaxation time of impurity scattering, $\tau_{def}(T)$ is the relaxation time of deformational potential scattering, $\tau_{piezo}(T)$ is the relaxation time of piezoelectric scattering, $\tau_{PO}(T)$ is the relaxation time of polar optical scattering and $\tau_{alloy}(T)$ is the relaxation time of alloy scattering.

Suitable numerical techniques are used to obtain the solutions. The Current-Voltage characteristics are obtained under the influence of varying gate voltage. Several authors have developed models in order to account for the current voltage characteristics of HEMTs [25-27]. The convention expression for drain to source current proportional to the density of electrons in the channel is given as follows [28, 29]

$$I_{DS}(T) = W\mu(T)n_S(T)qE(x) \quad (2)$$

where, W is the width of the device, μ(T) is the mobility due to different scattering mechanism. E(x) is the field and $n_s(T)$ is the temperature dependent sheet carrier concentration which is calculated as done in our previous paper by using numerical techniques and the method given by Nandita das et.al [17,30].

III. RESULT AND DISCUSSION

The radical decrease in geometrical size of semiconductor devices has led to the need for incorporating ballistic transport in the drift diffusion model implemented in simulation tools. Generally carrier mobility is defined at equilibrium in TCAD simulation. The Ballistic transport is a non equilibrium problem and associated mobility i.e., ballistic mobility does not have a clear definition. This is the limitation of the ballistic mobility approach in drift diffusion model. This paper deals with this problem considering the transport in nano-dimensional devices to be ballistic i.e., scattering free transport. The authors have earlier developed a temperature dependent mobility model for scattering limited electron transport in a nano-dimensional $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ heterostructure [17]. This model was used to establish almost scattering free carrier transport at cryogenic temperatures and hence increased mobility. Present work is an extension of this analytical model as a result, this analytical work were used to simulate ballistic transport at cryogenic and near cryogenic temperatures by modifying the Visual TCAD simulation program

Most of the functional and material parameters of the device are greatly affected by lowering down the temperature. This simulation deals with the effect of operating temperature on schotkky barrier height and Fermi level. Fig. 5 shows the variation of Fermi level as function of temperature. An almost linear increase in the position of the Fermi level is observed as the temperature drops to and below cryogenic. Fig. 6 shows the variation of Schotkky barrier height with temperature. Schottky barrier for electrons in heterostructure based devices formed at metal-semiconductor junction posses rectifying characteristics. It provides the barrier high resistance at small voltage. To first approximation current rises gradually with reverse bias due to a weak barrier lowering. At very high biases, the depletion region breaks down. Fig. 7 shows the simulated Drain Current (I_D) as a function of drain to source voltage (V_{DS}) at 100K and 300K for 100 nm Single Gate HEMT at Vgs = 0V,-0.1V and -0.2 V. The drift diffusion model incorporated with numerical techniques and few iterative solutions shows an appreciable increase in the channel current at Vgs = 0V resulting in the device being in on state at Vgs = 0V.

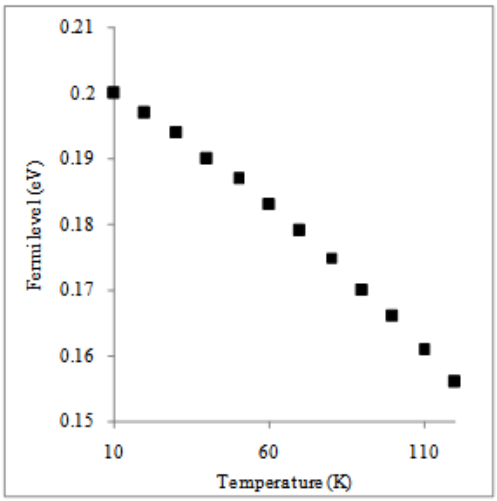

Figure 5. Variation of Fermi level with temperature.

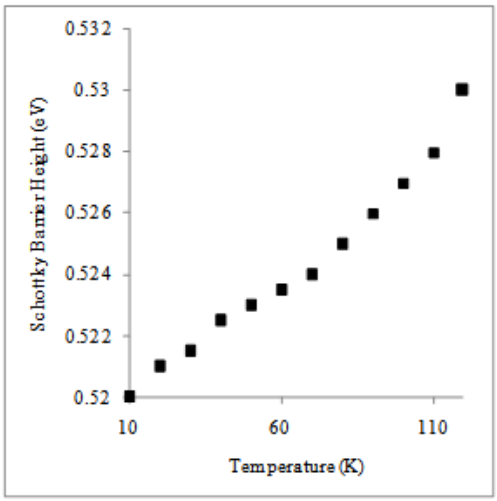

Figure 6. Variation of schottky barrier height with Temperature.

For millimeter wave-range applications, InAlAs/InGaAs HEMTs are considered to be the best device at cryogenic temperatures because the probability of various scattering processes which limit the performance of nano-dimensional devices (ionized impurity, deformation potential, piezoelectric potential, polar and alloy scattering in a 2DEG) are reduced with temperature thereby increasing the overall mobility of the device at lower temperature. Expression for the electron mobility was presented in our previous paper where degradation of total mobility with increasing temperature concludes that there is a great possibility of the InAlAs/InGaAs heterostructure based devices moving from non-ballistic to ballistic carrier transport at near cryogenic temperatures [17].

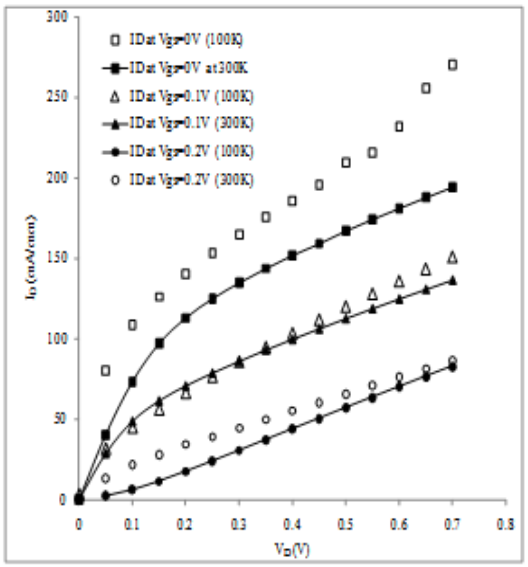

Figure 7 Id-Vd characteristics for SG HEMT at 300K and 100K at Vgs=0V,-0.1V and -0.2 V.

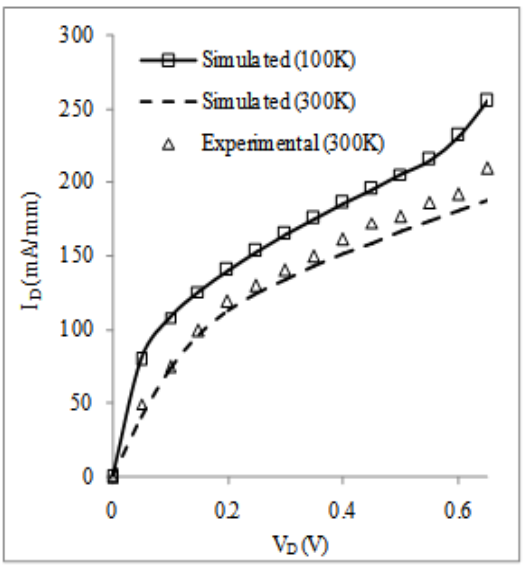

Figure. 8 Compared experimental and simulated Id-Vd characteristics for SG HEMT at 300K at Vgs=0V.

Incorporating analytical mobility model in simulation model results in rise of current at cryogenic temperature as compared to room temperature. Fig. 8 shows the comparison of the simulated drain current with experimental results [31] and a good match is observed thus validating the simulation. Fig. 9 shows the drain current dependence on the gate to source voltage for 100 nm single gate HEMT at constant Vds=0.5 V. A significant increase in drain current is observed at 100K as compared to 300K at V_{gs}>-0.1. Increase in channel current at lower operating temperatures suggests possible low temperature commercial application.

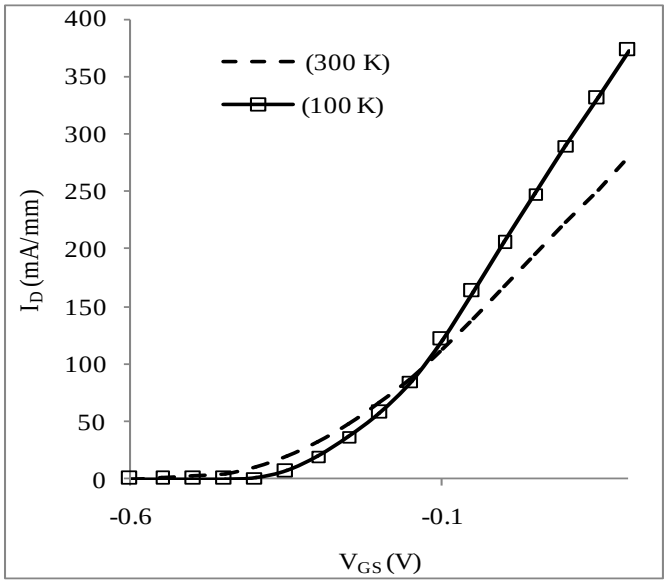

Figure 9. Comparison of Id-Vgs characteristics for SG HEMT at 300K and 100K at V_d=0.5V.

IV. CONCLUSION

To analyze the ballistic effects at low temperature, simulation model developed in this paper applies an alternative formulation for the impact of ballistic transport in the drift diffusion model. In the case of InAlAs/InGaAs nano dimensional heterostructure, electrons are isolated from the parent donor, making the impurity scattering negligible. This property explains the superior speed and noise properties of HEMTs because of the reduction of lattice scattering. In order to highlight the possible advantages that are expected from the operation of 100 nm InAlAs/InGaAs nano dimensional heterostructure at low temperature the authors simulated the current voltage characteristics by in incorporating temperature dependent mobility in the TCAD simulation. It is observed that the low-temperature operation results in higher current at 100K as compared to 300K. Furthermore, the operation of devices at moderately low temperatures has the advantage of an increased heat removal capability with the consequent increment in the maximum allowable density of integration. Thus higher currents predicted by this novel temperature dependent simulation model are a motivation for low temperature electronics (LTE) as solution to prominent drawbacks of technology scaling. The predicted ballistic behavior of the channel at low temperature due to near scattering free carrier mobility suggests possible applications of a 100 nm single gate InAlAs/InGaAs HEMT in low temperature commercial applications.

V. ACKNOWLEDGEMENT

The authors would like to thank University Grant Commission for providing financial support for this work.

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IOSR Journal of Engineering (IOSRJEN) is UGC approved Journal with Sl. No. 3240, Journal no. 48995.

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