Chapter 5

# Group III–V Semiconductor High Electron Mobility Transistor on Si Substrate

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Additional information is available at the end of the chapter

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**Abstract**

High electron mobility transistor (HEMT) is the futuristic development of the transistor in migration of the nm technology for integration of many devices in a single chip. Moving beyond the silicon-based devices to reach out the bottlenecks in the scaling and sizing of transistors has become an interesting topic of research. This research area includes the novel approach towards new materials and device structures. Materials focus is on composites made of binary, ternary and quaternary elements. Nanostructures made of two-dimensional electron gas (2DEG), quantum well and tunnel barrier make the electron transport in devices interesting. A similar approach is adopted in the present work to make the device more suitable for faster device operation with high frequency.

**Keywords:** high electron mobility transistor, two-dimensional electron gas, heterojunction, ternary composite

## 1. Introduction

High electron mobility transistors (HEMTs) have become the vital device in high-speed operation for microwave applications. Group III–V devices are generally used as HEMT due to the high electron mobility and electron density. Higher charge density in the device makes a changeover in the conductance oscillation of the device with the variation in the electrons behaviour [1]. These properties make the device operate at higher switching speed and low power. Higher switching speed with low power requirement of the devices makes it more suitable for integration of many devices on a single chip. Scaling and sizing of the device without compromising the performance will make the device more suitable for the advanced application in electronics [2]. Heterojunction is formed when different materials are placed on over the other. Generally, these heterojunctions are formed with the superlattice structures, which normally are made of different materials. Group III–V elements such as AlGaAs/GaAs, AlGaN/GaN and InGaAs/GaAs were used in the fabrication of HEMT devices [3–5]. Traditional HEMTs have achieved higher operating speed of 60 GHz and the data rates higher than 10 Gbit/s [6]. Moving beyond the rated speed of operation and data rates, the material and device structure should be worked on further. Group III–V elements have higher electron densities that help in faster movement of electrons. Among III–V elements, InSb has very good electronic property with less effective mass and higher electron concentration, and better lattice constant and narrow energy gap as shown in **Figure 1**.

InSb has very good magnetic property with spin-dependent phenomenon to explore the spin orientated applications such as modulators, memories, sensors, etc. based on the ferromagnetic heterostructures [8]. InSb has narrow band gap of 0.17 eV with a low effective mass of 0.014 ME, which makes the room temperature electron mobility almost 7000 $cm^2/V$ s, and makes the device more suitable for high-speed operation. InSb have high carrier mobility with good surface morphology [9]. The narrow band gap InSb semiconductor when doped with other elements has interesting properties, which can be used for various electronic applications. Doping of Mn into InSb results in the dilute magnetic semiconductor (DMS) property of the material with different doping ratios. Mn doping results in the increased carrier-mediated magnetic coupling in the ferromagnetic semiconductor [10]. Several works have been reported on Mn doping into InSb for analysis of the dilute magnetic semiconductor application with ferromagnetic nature in the hysteresis curve. The magnetic property analysis for the InMnSb compound was made for both powder samples and thin films with varying compositions of doping. Mn doping into InSb results in some interesting properties such as photo-induced spin effect, optical response, cyclotron resonance and magneto transport [11–17].

InSb and doped InSb composites are used for various applications due to its better electronic property. InSb-based devices involve field effect transistors (FET), quantum well transistors, micro hall device, nanowire FET, quantum dot device and heterostructure device. A single crystalline InSb nanowire synthesized by pulsed laser chemical vapour deposition demonstrates a good n-type semiconductor behaviour, which makes it suitable for FET device property [18].

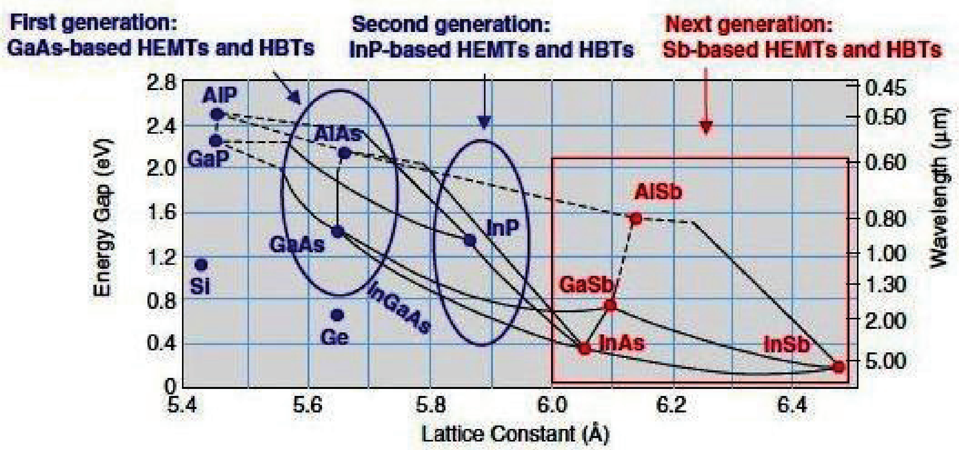


**Figure 1.** Lattice constant and band gap of Group III–V compound semiconductors, Source: Bennett et al. [7].

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InSb-based device was made of metal organic vapour phase epitaxy for fabricating heterostructures of InSb and InAs. Measurement of the fabricated quantum dot device has coulomb blockade effect of 4.2 kA [19]. Fabricated InAs/InSb nanowire heterostructure FET shows unipolar and bipolar operation with the temperature-dependent electrical measurements by applying bias on the InAs side and InSb side. Conductivity is increased very strongly due to the electron transport across the heterostructure junction. InSb nanowire FETs are used for high-speed ultra-low power applications with the analysis based on the performance for varying nanowire diameters. This low power and high-speed operation makes the device more suitable for low power digital logic application when fabricated as enhancement and depletion of InSb-based quantum well transistor.

To make the device perform better the gate length of the InSb quantum well transistors was reduced to 0.2 μm, which resulted in the device exhibiting high electron mobility of 30,000 $cm^2/V$ s with a sheet carrier density of 1 ×1012 $cm^{-2}$ [19, 20]. Modified approaches have been adopted to improve the performance of the device such as strained P channel quantum well InSb transistor. The performance metrics compared with the standard P channel MOSFET show that InSb-based device exhibits low power dissipation and high transconductance [20, 21]. Device fabrication involves some tedious process involved like deposition, etching and lithography. Hence before getting into the process of fabrication, an alternative approach was used to analyse the device by device modelling. Similar approach was adopted based on atomistic modelling for the thickness dependence (3–16 nm) for electron transport in the quantum well FET [22].

Quantum well devices made of InSb have vital magnetic sensing application, which can be used as micro hall magnetic field sensor for detecting pT. Similar to the magnetic sensing application, InAs/InSb nanowire FET devices have application in detecting THz frequencies [23, 24]. Similar to the nanowire FET, Tunnel FET made of InSb has a very good mobility due to the narrow band gap when fabricated. This higher mobility of the device makes a faster switching speed, which is a good property to be considered to look into the device scaling with InSb-based device structures. It is observed that InSb is a vital composite to be used in transistor applications. Proposed method deals with the InMnSb compound and Si made of P, N-type to form a HEMT device. The composite was made as a thin tunnel layer to be formed between the source and the drain regions to make the charge carriers flow through the channel with an electron spin.

InMnSb compound exhibits an exceedingly good DMS property with the doping concentration and works as dilute magnetic semiconductor (DMS). The HEMTs made of magnetic tunnel junction has an improved electron transport when compared to the existing device structures. Magnetic tunnel junctions were made by inserting the magnetic materials between the source, channel and the drain of the high electron mobility transistor (HEMT) to enhance the performance. Conductivity of the proposed device structure reveals that the device has a very good electron transport due to the magnetic materials and will amplify low-frequency signals. The proposed device structure with the InMnSb tunnelling layer is shown in **Figure 2**. Functionality of the device was tested with different architectures to identify the better device operation for high-speed application. Density functional theory (DFT) calculations were performed to identify the device performance. Charge density was considered as vital factor to analyse the device performance.

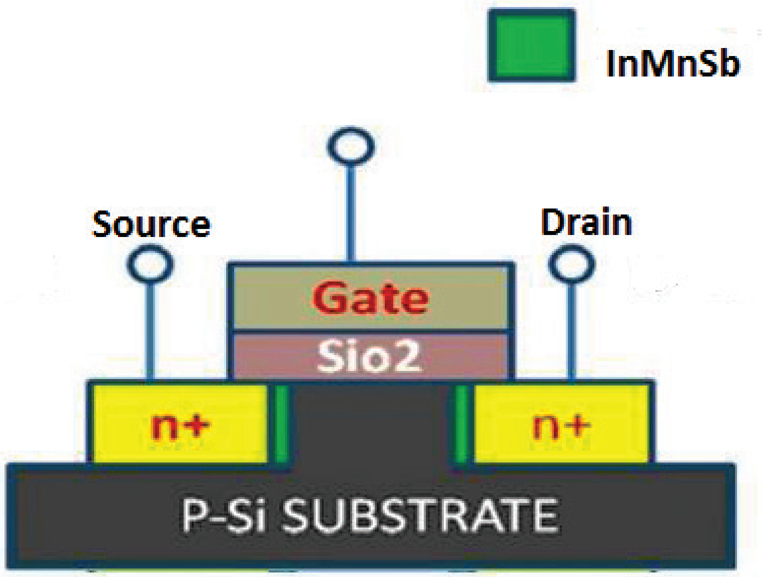


**Figure 2.** Proposed HEMT device structure.

## 2. HEMT with InMnSb tunnel layer

Propose HEMT device structure has a P type Si substrate and over that **N-**type Si deposition with the intermediate InMnSb layers in between the source/channel and channel/drain regions of the transistor. The P type Si substrate is made of trivalent boron doping in the intrinsic silicon and N-type Si was made with the pentavalent phosphorus doping. Due to the spin alignment of electrons in an InMnSb layer the conductivity of the device is increased by 10-folds when compared to the NPN device structure. **Figure 3** shows the conductivity of the NFPFN device that is 64.5 mS, which is 10-folds more than the conductivity of the NPN device of 6.5 mS.

Electron transport in the proposed device structure is understood that the electron travels through the two tunnel layers and two DMS layers, which is represented by Eq. (1).

$$\Delta F1 * \mu es + \Delta F2 * \mu es \tag{1}$$

$\Delta F1$ and $\Delta F2$ describe the tunnelling at junctions 1 and 2, respectively. μes represents the magnetic moment of the DMS layer at the source and the drain regions. The carriers travel through both the junctions and the DMS layer to travel from the source to drain region. The rate at which the particle tunnels through the region is represented by the tunnel rate and is represented by Eq. (2). The magnetic moment when the electron travels in the DMS layer is described by Eq. (3). Tunnelling at the junction $\Delta F1$ and $\Delta F2$ is expressed in Eqs. (4) and (5).

$$\tau(\Delta F) = \frac{\Delta F}{e^2 R\tau\left(\exp\left(\frac{\Delta F}{KT}\right) - 1\right)} \tag{2}$$

$$\mu es = \gamma(e2m)\, S \tag{3}$$

$$\Delta F1 = eC\Sigma\left\{e2 + \left(vb2\,[\,2C2 + Cg\,] - VgCg + ne\right)\right\} * \mu es \tag{4}$$

$$\Delta F2 = eC\Sigma\left\{e2 + \left(vb2\,[\,2C1 + Cg\,] + VgCg - ne\right)\right\} * \mu es \tag{5}$$

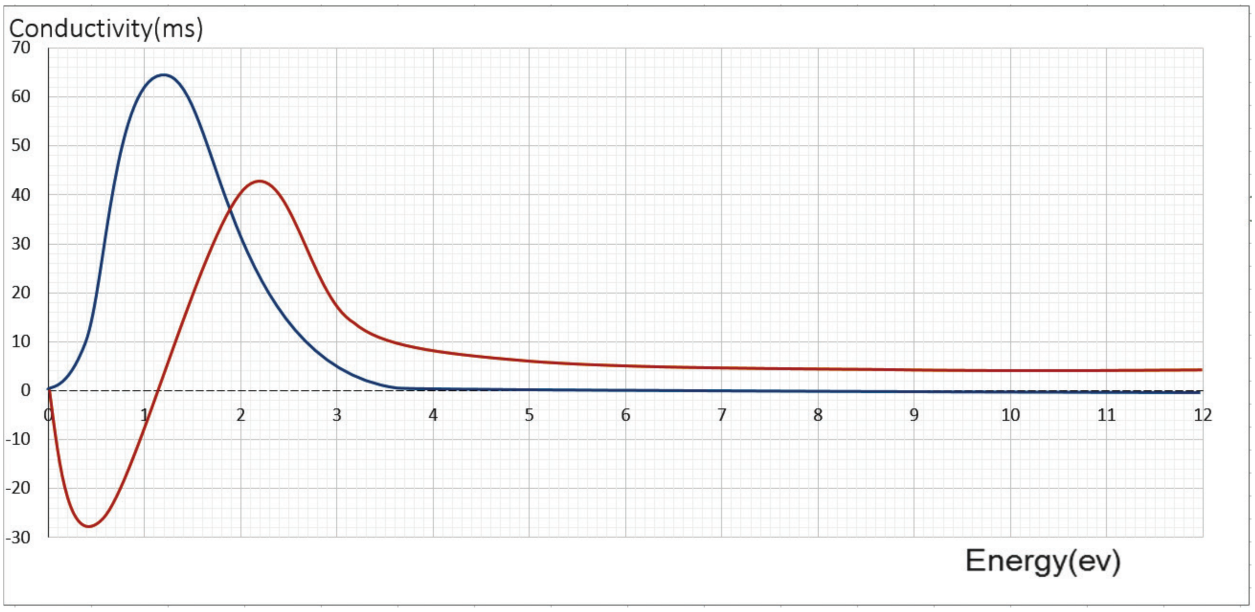


**Figure 3.** Conductivity graph of HEMT using DFT calculation.

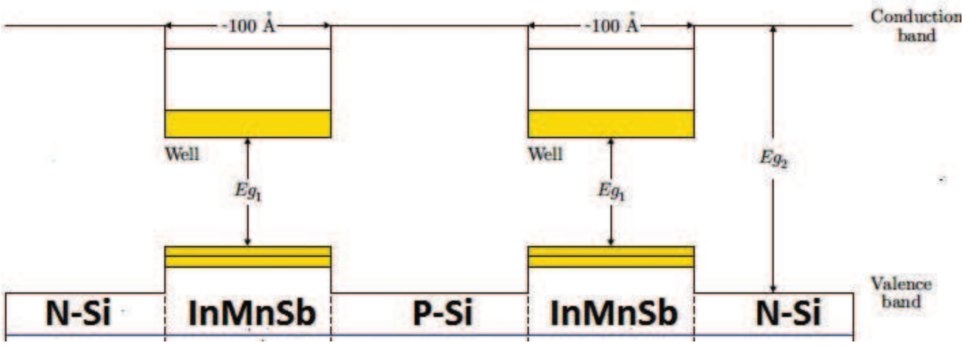


**Figure 4.** Band structure of the proposed device.

Tunnelling equation on both the junctions consider the gate capacitance, junction capacitances 1 and 2, gate voltage and the number of electrons. Considering all these factors and the magnetic moments, the electrons travel through the DMS layers and the channel from source to the drain of the HEMT. Band structure of the proposed device structure with the energy gap and the band alignment at stable condition with no applied voltage is shown in **Figure 4**.

The band structure reveals energy band gap between the conduction and valance band of each layer of the device. There is a narrow band gap in the InMnSb region when compared to the Si layer. This narrow band gap in the InMnSb layer allows the charge carriers travel faster from valance band to the conduction band. Since the InMnSb has dilute magnetic semiconductor (DMS) nature, it allows the electron to travel much faster with a spin magnetic moment. The layers are repeated structures rather than single, which makes the electron confined at the interface of the heterostructures called as heterointerference. Formation of the quantum well is always a possibility in the repeated structure. The depth of the well and the barrier thickness of the

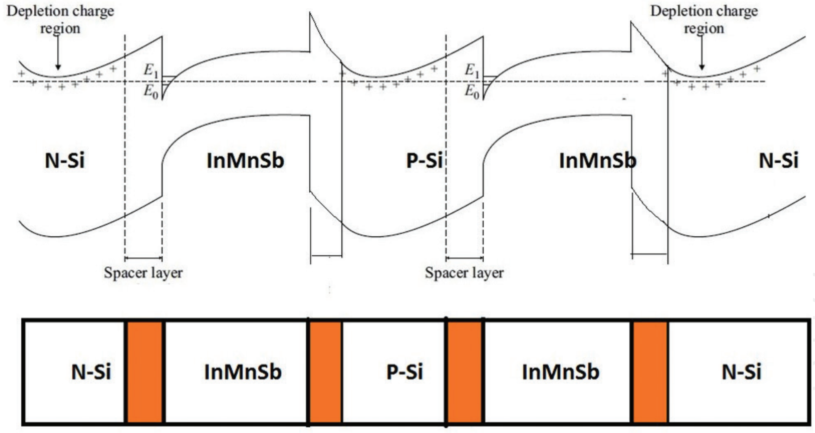


**Figure 5.** Band alignment and 2DEG.

device vary with the doping concentration. Confinement of the electron makes it at higher energies resulting in formation of discrete sub-bands. The confined structures make a two-dimensional electron gas (2DEG) resulting in less scattering and improved mobility. Considering the electron confinement and the 2DEG structure, the electron transport and band alignment is shown in **Figure 5**.

The number of electrons confined in 2DEG depends on the thickness of the layers and the doping concentration [25].

## 3. HEMT electron mobility

### 3.1. Mobility with low electric field

Electron mobility in the band of the different layers with low electric field depends on the doping density in regards to the ionized impurity scattering effects at rated temperature. Reduced ionized impurity scattering with modulated doping makes a smaller number of carriers with high mobility. Higher doping concentration of the doping in the HEMT devices makes the career screening resulting in higher mobility of the carriers. So the carrier concentration, mobility of the electrons, ionized scattering effect and the temperature have the correlation between each other factor resulting in the HEMT device conductivity.

### 3.2. Mobility with high electric field

The 2DEG electrons attain greater energy and become hot with the moderate or higher electric field. There will be an energy separation between the sub-bands, and the high mobility electrons in the lower sub-band get the needed energy from the applied electric field to move into the lower energy adjacent sub-band. Higher initial mobility in the lower sub-band results in the faster decay in mobility with the applied voltage [25]. Hence with the applied electric field, the electrons at different sub-bands get the needed energy to move from their initial

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state and to move into the next state. This process makes the generation and recombination rate much faster resulting in better conduction of the device.

## 4. Drain characteristics

Drain current and the drain source voltage characteristics of the proposed HEMT device is shown in **Figure 6**. The curve reached a stable drain current at 2.5 mA and continues to be stable. Further increase in the drain current will be achieved with the increasing gate source voltage of the device. The stable saturation region in the drain characteristics will make the device operate at stable Q point resulting in proper amplification of the device when used in amplifier applications. Increasing drain current with the lower gate voltage makes the device more suitable for faster switching operation. Faster switching speed makes the devices more suitable for the high frequency applications. This improved drain characteristics of the device proves the ability of the device to be used for the microwave application. Similar to the drain characteristics, proposed device transfer characteristics is also very high when compared to the other HEMT devices.


**Figure 6.** Drain characteristics of proposed HEMT.

## 5. Transfer characteristics

Transfer characteristics with the drain current versus gate source voltage graph are shown in **Figure 7**. The results reveal that the proposed HEMT device has very high drain current of 22 A. The transfer characteristics of the HEMT device made of different materials and architectures are shown in **Figure 8**.

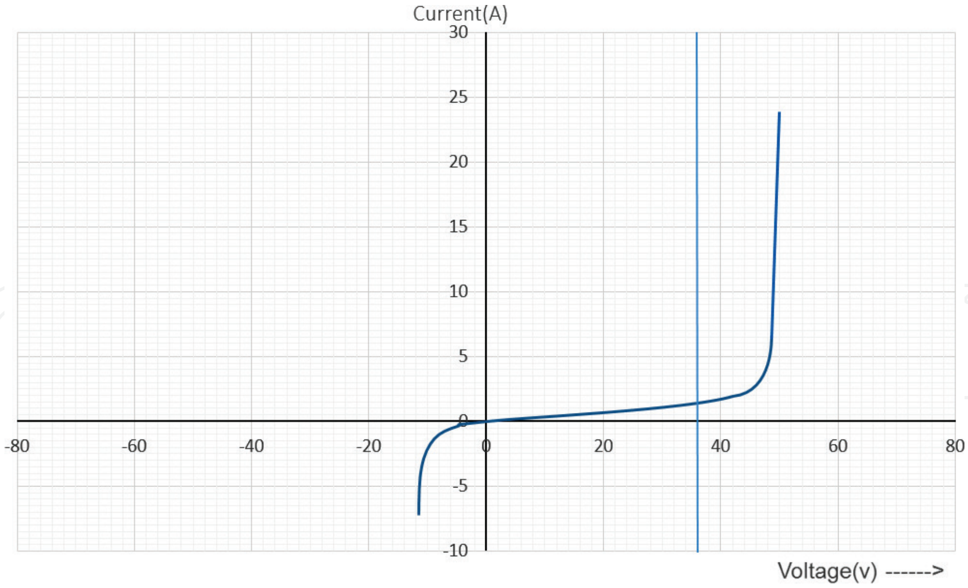


**Figure 7.** Transfer characteristics of the proposed device.

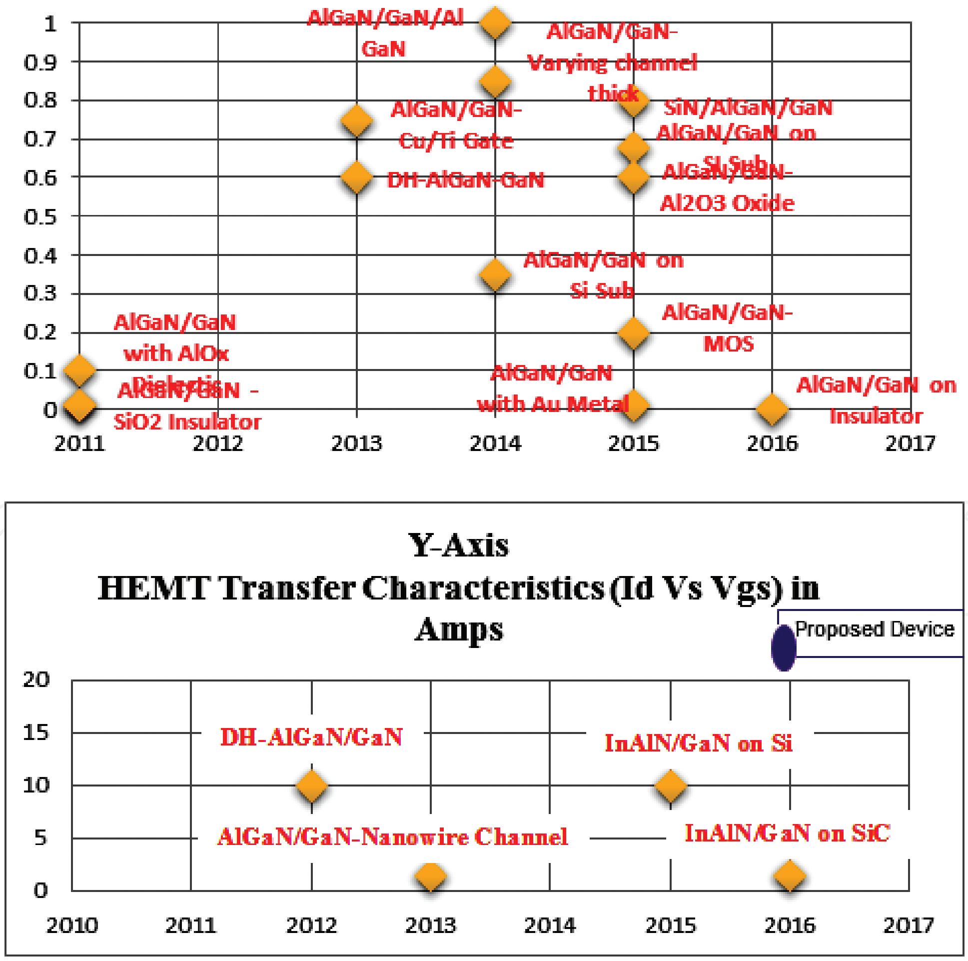


**Figure 8.** Transfer characteristics of other HEMT device in comparison with proposed HEMT device.

## 6. Conclusion

Superlattice structure for HEMT applications has shown good progress over the last few decades, to match the suitability of the device for high-speed applications. This chapter has dealt with the improved performance of the HEMT device due to the DMS layer made with the InMnSb layer resulting in improved conductivity and VI characteristics. The resulted band structure with the proposed device structure has made the low-dimensional structure with the 2DEG allowing the electron to travel without any collusion. The collision-free transport of the particle in the device structure is predicted to make a better conductivity resulting in better device performance. Comparison of the proposed HEMT device with the other existing devices has substantiated the improved device characteristics in par with the other HEMT devices. Hence it is evident that the proposed device will have a very good prospect in high-speed applications.

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