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Design and Simulation of High Electron Mobility Transistor using Silvaco TCAD

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Abstract: **We have design and simulate GaN High electron mobility transistors (HEMTs) for high voltage and high speed applications. Simple AlGaN/GaNon sapphire substrates HEMT and HEMT with oxide layer was proposed for achieving high current carrying capability as well as high speed switching capability and analyzed using ATLAS (SILVACO) simulator. The device characteristics suggest that the MOS-HEMT has better performance compared to the conventional HEMT. Advantages of HEMT on the basis of band gap, electron mobility, saturation drift velocity and power handling capacity has also been discussed. Simulation result shows the effect of temperature on the cutoff frequency, for temperature 248k the technology 90nm has the cutoff frequency of 24.1GHz while for the same technology at higher temperature of 373k the cutoff frequency decrease to 9 GHz.**

Keywords: **HEMT, Gallium Nitride (GaN), MOSHEMT, Silvaco TCAD, Heterojunctions.**

I. INTRODUCTION

In the past few years, Gallium Nitride (GaN) has been a matter of attraction over Silicon (Si) due to several advantages such as large band gap energy, high critical electric field, high electron mobility, high saturation drift velocity and melting point. [1]Few applications of GaN includes light emitting diode for display technology, LASERS, Microwave amplifiers, radiation hardness devices, power devices, switching devices etc. [2]Due to high mobility, GaN on Si technology is emerging as one of the best alternate to the well-developed Si technology for switching devices[3, 4].

In conversion of power, transistors basically work as an ideal switch. For the power devices the main requirement is high breakdown voltage and low energy loss. [5] The energy loss can be classified into two forms static and dynamic, static losses occur when the transistor is in the on-state and off-state. [6]

Ideally in the on-state a transistor should have a very low on-resistance in order to decrease the power losses and in the off-state the transistor should behave as a perfect open circuit offering infinite current but, inevitably, results in some residual current, or leakage current flows. This leakage current should be very small in order to reduce the static power dissipation to zero. Another is the dynamic power dissipation in which the loss is due to the parasitic capacitance and inductance. Gate turn-off thyristor (GTO) and insulated gate bipolar transistor that works between Hz and kHz while GaN and Si-MOSFET devices have a frequency response of MHz. The GaN technology resulted in not only extends the operational frequency but also, in the switching capacity of the MOSFET devices. [7]

As the power devices require high breakdown voltage for the high voltage operation, lower resistance for low loss and low capacitance for low dynamic power dissipation. [8] These properties can't be fulfilled by the silicon and germanium in terms of breakdown voltage and speed of device. So we need those materials which have higher energy band gap than these electronic dominating materials. Such materials are popularly known as the Wide Band Gap Semiconductors. Example of such materials is Silicon Carbide, Gallium Nitride and its various related heterostructures. These wide gap materials have very high band gap that results in high breakdown voltage and thus help to increase the RF power [9-10]. In this paper we have investigated the properties of semiconductor materials for the power devices and various problems associated with the devices. Further, the physics of heterostructures and heterojunctions is explained and simulated.

II. HEMT STRUCTURE

For the fabrication of an efficient high electron mobility transistor, the material must possess wide band gap energy, low dielectric constant, high thermal conductance and high critical electric field. Few materials suitable for the fabrication of HEMT devices are given in Table 1.

Table 1.1:
Bandgap, dielectric Constant, thermal conductivity and critical electric field. [11]

Materials	Material Properties			
	Band Gap (Eg)	Dielectric Constant	Thermal Conductivity (K(W/m^3))	Breakdown Field (*10^5 V/cm)
Si	1.12	11.9	1.5	3.0
GaAs	1.43	12.5	0.54	3.0
InP	1.34	12.4	0.67	4.5
3C-SiC	2.3	9.7	4.0	1.8
4H-SiC	3.2	10.0	4.0	3.5
6H-SiC	2.86	10.0	4.0	3.8
GaN	3.4	9.5	1.3	2.0
Diamond	5.6	5.5	20-30	2.0

As per the energy band gap, heterostructures are classified as the type I, type II, and type III. In type I heterostructures the total sum of the conduction band and valence band edge discontinuities is equal to the energy gap difference. Example of such heterostructure is GaAs-AlGaAs, GaN-AlGaN, and their band diagram shown in figure 1.

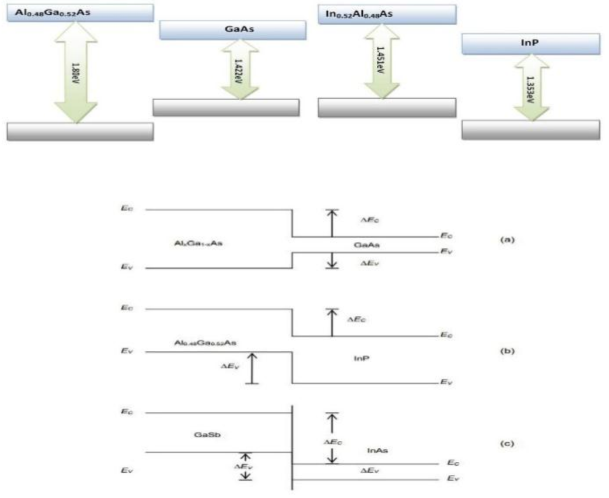


Figure1. Energy Band diagrams of various heterostructures. All the values are in eV.

The basic structure of AlGaN/GaN HEMT with nucleation layer, buffer and the channel layers, the finally the barrier layer and as well as a capis shown in figure 2.

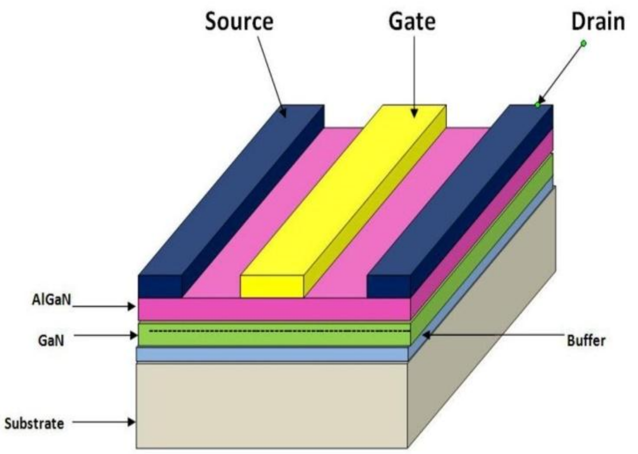
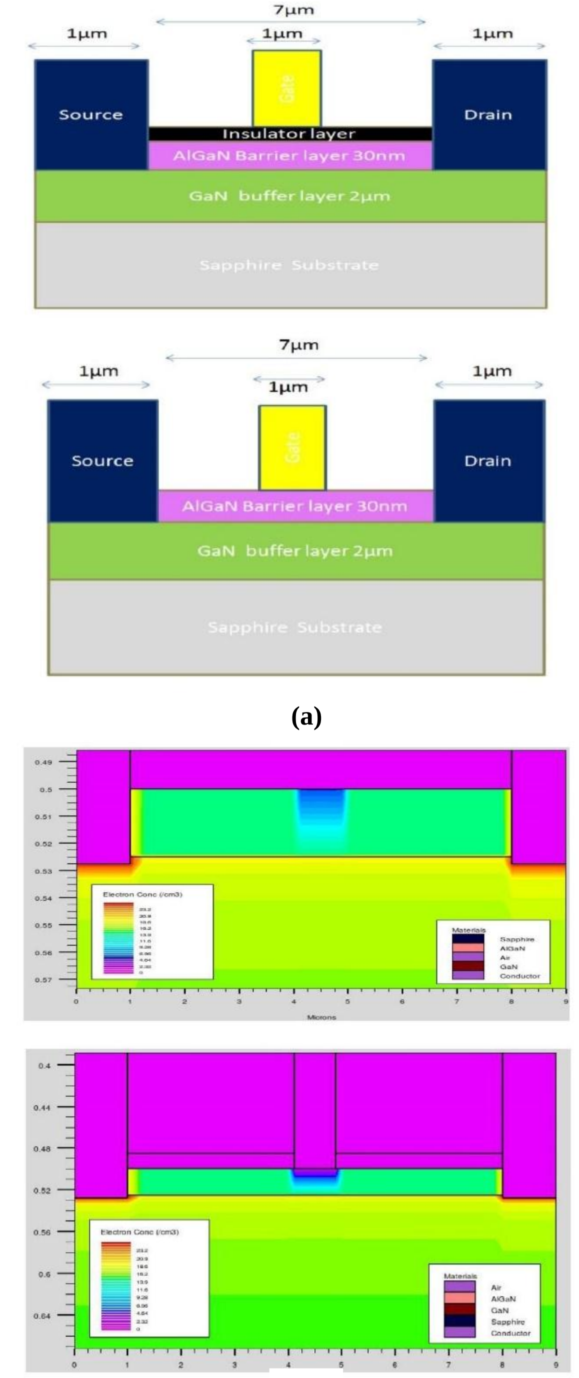


Figure2. AlGaN/GaN HEMT basic structure showing all layers. [12]

There are two types of contacts were used for the simulation of HEMT i.e.Ohmic and the Schottky.The AlGaN/GaN MOS-HEMT structure consists of undoped $Al_{0.27}Ga_{0.73}N$ barrier layer. This layer is some time doped also but due to in advanced technology it unintenally doped with p type having concentration around 10E13cm^3.The width of this layer is taken to be 30nm. Below AlGaN layer an undopedGaN layer is used which act as the buffer layer. This layer is undoped always and having thickness of 2µm and the bottom most layer acting as a nucleation layer is made up of sapphire substrate. Sapphire was used as it has better thermal conductivity than any other substrate like Si, GaN. Main reason for using high thermal conductivity material used as substrate because of high temperature created in the RF power applications. For the drain and the source contacts Ohmic type contacts are used and for the gate Schottky contacts is being used. The width of the source and drain contacts as well as for the gate length are 1µm and the channel length is made to be 7µm. MOS-HEMT and the conventional HEMT structure are designed in the ATLAS, shown in figure3 (a) and (b) respectively.



(a)

(b)

Figure3. MOSHEMT and conventional HEMT with and without insulating layer (a) Model structure, (b) Structure on Silvaco. The gate length is kept to be 1μm and the channel length is 7μm.

III. RESULTS AND DISCUSSION

Figure 4 shows the Output (Drain Current Vs Drain Voltage) characteristic of the MOS and conventional HEMT, the gate length of the device is 1000nm with drain to source spacing of 7μm.

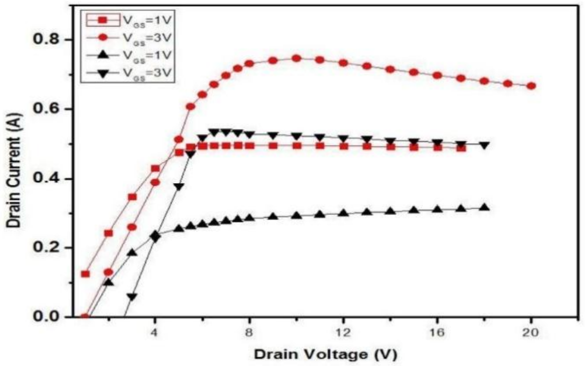


Figure 4: I_D vs. V_{DS} MOS -HEMT and Conventional HEMT at 1μm gate length. RED lines represent the drain current for the MOS HEMT and BLACK lines for the Conventional HEMT.

Initially the current is approximately zero for the very low drain voltage. But as the drain voltage increases the drain current also increases linearly and finally gets saturated after much higher drain voltage. Thus the linear region of the characteristic is up to V_{DS}=5V for V_{GS}=3V.Beyond the V_{DS}=5V the drain current starts saturating. The electrical characteristics shows higher drain current and lower gate leakage in the MOS HEMT as compared to the conventional HEMT, which is due higher degree of 2DEG at the interface of AlGaN/GaN. The transfer characteristics of the two devices are shown in figure 5.

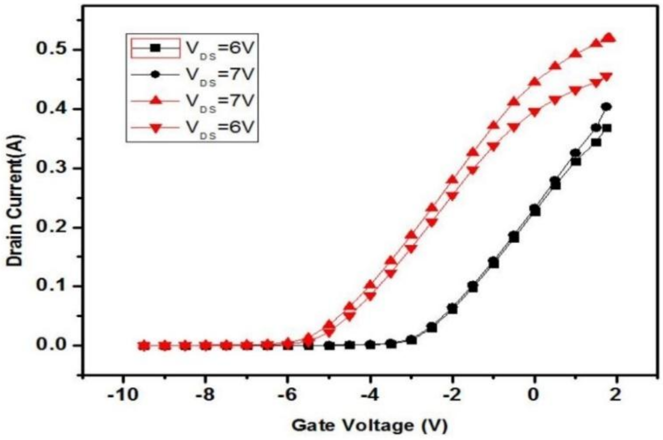


Figure5. I_D Vs V_{GS} of MOSHEMT and HEMT of1000nm gate length. RED lines represent the drain current for the MOS HEMT and BLACK lines for the Conventional HEMT.

The turn ON voltage of the MOS-HEMT is found to be -7V as compared to the conventional HEMT having TURN ON voltage of -3V, making it less prone to noise. The energy band diagram of the two devices is shown in figure 6.

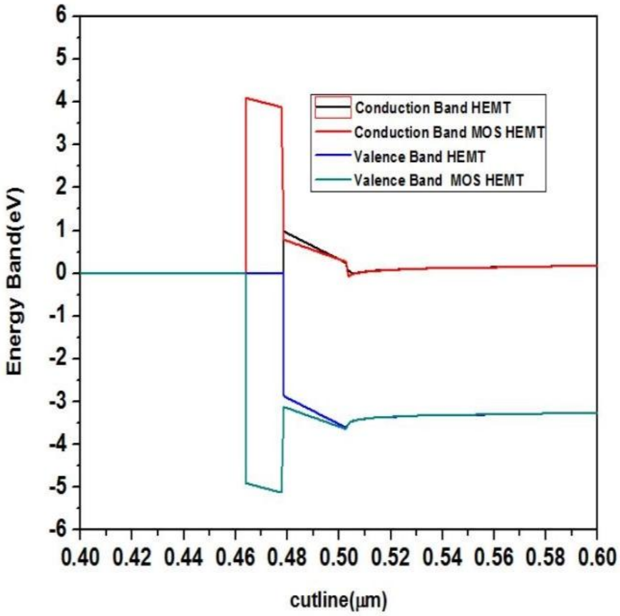


Figure 6: Energy Band Diagram of MOS HEMT and Conventional HEMT with 1000nm gate length and channel length 7µm using 3nmAl_2O_3 as insulation layer. For V_{GS}=3V and V_{DS}=20V.

The band gap in the channel i.e. GaN of MOSHEMT is found to be approximately 3.5eV while in the GaN of HEMT it nearly 3.2eV.The electric field and electron density in the channel of the two devices are shown in figure 7.

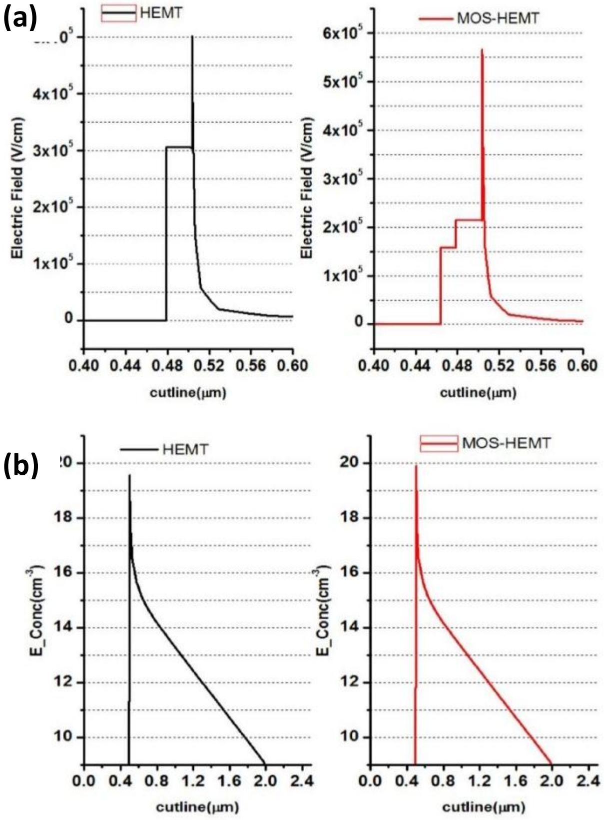
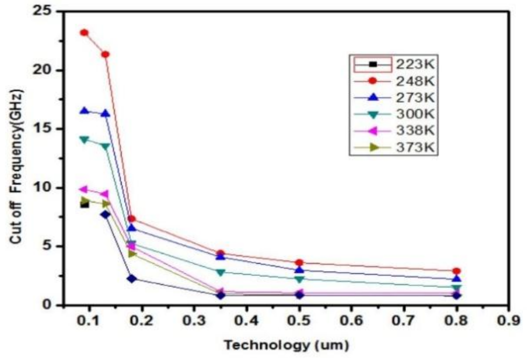


Figure 7: (a) Electric Field and (b) electron Concentration comparison of at the channel for the Conventional HEMT and MOS HEMT using Al_2O_3 as oxide layer. Channel length=7µm, gate length =1µm, For V_{GS}=3V and V_{DS}=20V.

Result shows that the electron in the Conventional HEMT suffers from the large amount of scattering. The electric field at the interface of the MOSHEMT is approximately 570KV/cm while at the interface of the Conventional HEMT it is found to be 490KV/cm. On comparing the electron density, we get electron concentration is higher in the MOSHEMTand is found to be nearly~10E20 which is quite greater than the conventional HEMT. The cutoff frequency of the MOSHEMT with various channel length is shown in figure 8.

(a)



(b

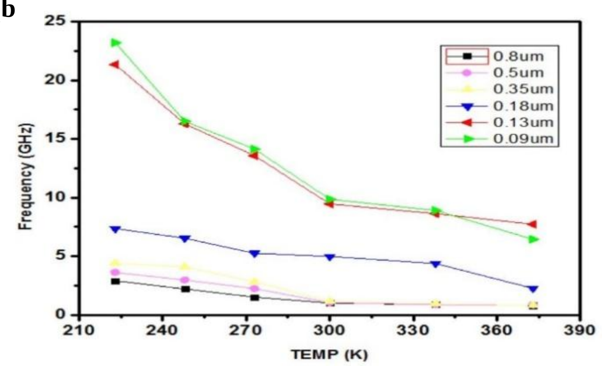


Figure 8 (a) (b): Cutoff Frequency Variation with various Technologies with the effect of temperature.

Reducing the technology parameter increases the cutoff frequency. Another advantage of decreasing the channel length is that the current carrying capability increases as the current flowing in the device is always indirectly proportional to the channel length. For a particular temperature, the frequency response decreases as the technology increases. As visible in the graph for temperature 248k the technology 90nm has the cutoff frequency of 24.1GHz while for the same technology at higher temperature of 373k the cutoff frequency decrease to 9GHz.

The main reason of decrease of the frequency response at the higher temperature is due to scattering.

IV. CONCLUSION

MOSHEMT and Conventional HEMT structures were simulated on the Silvaco TCAD. Results shows that the MOS-HEMT has better performance than the conventional HEMT. Moreover, it can replace the well-established technology of silicon in the field of power devices due to its large bandgap, high electron mobility and high saturation drift velocity of the 3rd -5th group materials compared to the 4th group materials. Effect of channel length and temperature on the cutoff frequency has also been investigated.

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