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AlGaN/GaN HFET: Operating Principle And Noise Performance

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ABSTRACT

The operating principle and noise performance in AlGaN/GaN HFETs has been studied. In particular, it has been demonstrated that substrate material selection plays a great role in device performance for application point of view. Polarization induced surface states plays key role in formation of 2 DEG. Performance parameters study of device is related to noise study in devices because low frequency noise affects the device performance. Different types of noise and their possible reasons has been studied.

Key words: AlGaN/GaN hetrostructure field-effect transistors, 2 Dimensional Electron Gas (2 DEG).

1. mm WAVE FREQUENCY TECHNOLOGY

Application spectrum in wireless communication technology shows MESFET spectrum range to around 4 GHz and CMOS spectrum range upto around 10 GHz. Analog CMOS performance logic have low standby power, low gain, low noise figure etc. mm-Wave technology are dominated by III-V materials i.e GaAs MESFET, GaAs PHEMT, GaAs MHEMT, GaN HEMT, InP HEMT and InP HBT and SiGe HBT etc. These devices are power devices and low noise amplifiers. GaN HEMTs have advantage of significant power density over other existing technologies. These devices have power densities of 10W/mm with drain bias of 40 V at 40 GHz [1]. AlGaN/GaN HFETs are used in applications where devices at high voltage, temperature and frequency such as telecommunication, radio frequency generators etc. are required. These devices have applications in microwave, power switching and wide band power amplifiers. These devices have high breakdown fields and hence have high power and high speed. Due to high saturated electron drift velocities these devices have high speed and wide bandwidth. These devices have high melting points and low intrinsic carrier concentration, hence are used in high temperature operations. Due to strong piezoelectric effect, these devices have high sheet carrier concentration. Due to high sheet carrier concentration, these devices have high power and high current. Figure 1 shows wireless communication spectrum.

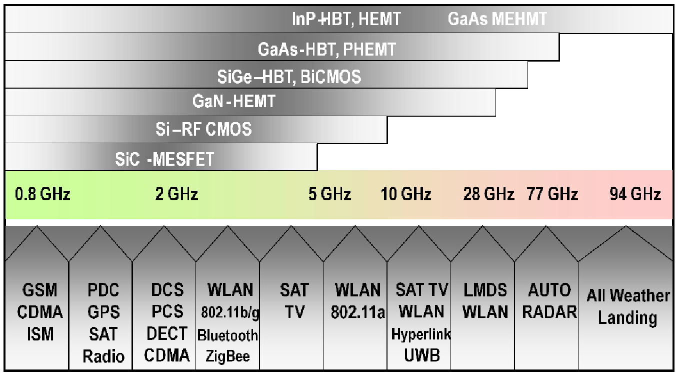
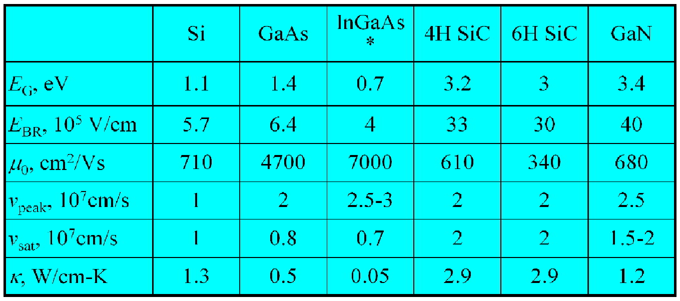


Figure 1: Wireless Communication Application Spectrum [5]

For high output power, wide band gap materials (high breakdown potential and field) and high thermal conductivity is required. For higher f_{max} and f_T, higher carrier mobility is required. Higher carrier mobility (μ_0) is dependent on peak voltage (v_{peak}) and saturated voltage (v_{sat}). Figure 2 shows material properties comparison.



	Si	GaAs	InGaAs*	4H SiC	6H SiC	GaN
E_G, eV	1.1	1.4	0.7	3.2	3	3.4
E_{BR}, 10^5 V/cm	5.7	6.4	4	33	30	40
μ_0, cm^2/Vs	710	4700	7000	610	340	680
v_{peak}, 10^7cm/s	1	2	2.5-3	2	2	2.5
v_{sat}, 10^7cm/s	1	0.8	0.7	2	2	1.5-2
κ, W/cm-K	1.3	0.5	0.05	2.9	2.9	1.2

Figure 2: Material properties comparison [2]

The properties of different materials i.e. GaAs, GaSb, AlAs, AlSb, InGaAs, InAs, InP are shown in figure 3. The material properties i.e. energy gap in eV, wavelength in µm and lattice constant in µm are compared for different materials with help of figure 3.

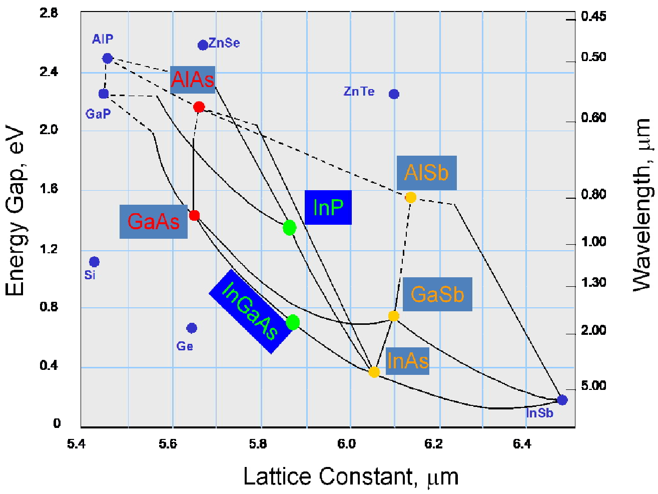


Figure 3: Material Properties Comparison

2. SUBSTRATE MATERIAL COMPARISON [3]

The different substrate materials used in HEMT devices are silicon, sapphire, silicon carbide. Sapphire is most widely used substrate material. Sapphire materials are good quality and cheap commercial wafers. These materials have poor thermal conductivity. These materials have high amount of dislocations. Silicon Carbide materials are expensive materials. These have high thermal capacity and low lattice mismatch. Silicon Carbide materials are expensive materials. These materials have high thermal capacity and low lattice mismatch. Silicon is most common semiconductor material. These materials have acceptable thermal conductivity. These materials are available in large quantities. Figure 4 shows RF power overview of GaN devices with different substrate.

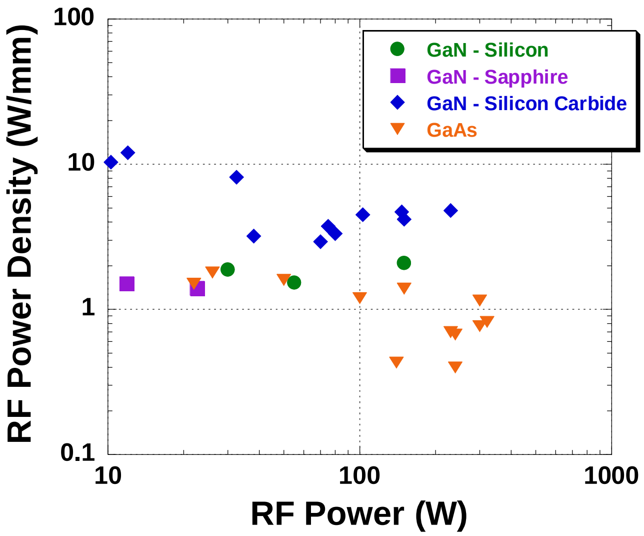


Figure 4: RF Power Overview Of GaN Devices With Different Substrates

GaN devices offer high RF power densities in comparison of GaAs devices. GaN devices have high operating voltage of about 48 V, high packaging density and high operating temperature.

3. 3. OPERATING PRINCIPLE

The operation of GaN/AlGaN is based on principle of two dimensional electron gas, polarization and charge control. Figure 5 shows charge transport mechanism in these devices with help of energy band diagram.

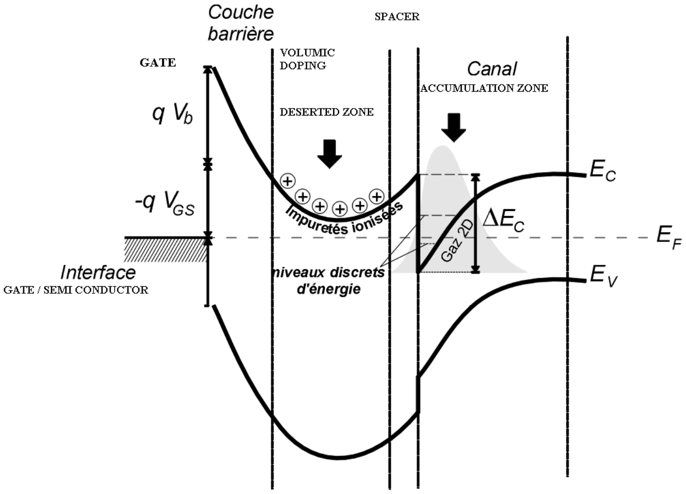


Figure 5: Transport mechanism in device [2]

3.1 2 DEG [4]

Two semiconductor materials i.e. GaN and AlGaN are having different doping profiles and have discontinuity through conduction band which creates a potential difference between two known as triangular potential which determines charge transfer in device. Charge carriers i.e. electrons get confined in discrete quantum state in triangular potential. Electron mobility is higher in 2DEG than in bulk.

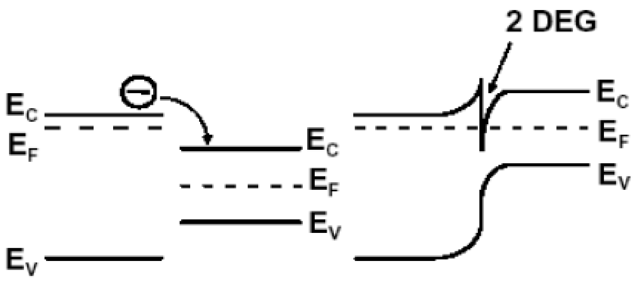


Figure 6: 2 DEG Formation

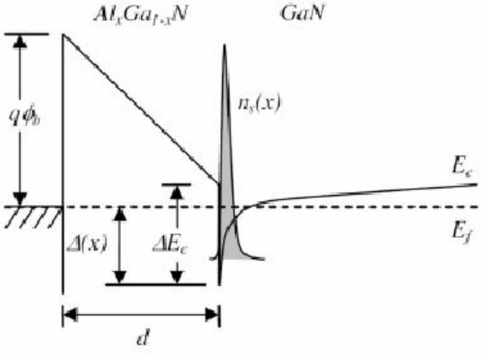


Figure 7: Triangular Potential Formation

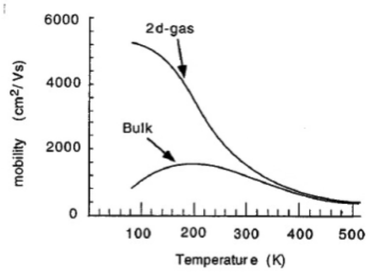


Figure 8: Electron Mobility comparision in 2DEG And Bulk

3.2 POLARIZATION [6]

Two types of polarization exist in AlGaN/GaN devices i.e. spontaneous polarization and piezoelectric polarization. Device has wurtzite structure. Spontaneous polarization occur in both barrier layers due to lack of symmetry. This type of polarization occurs at zero strain. Piezoelectric polarization occurs due to lattice constant difference of GaN and AlGaN barrier layers and Pseudomorfic growth of AlGaN.

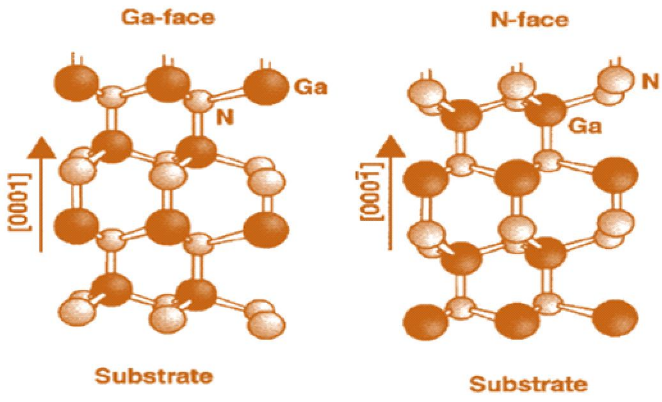


Figure 9: Crystal structure of GaN

The development of spontaneous and piezoelectric polarization is shown in figure 11. Due to these polarizations, surface states increase and hence add up in formation of 2 DEG.

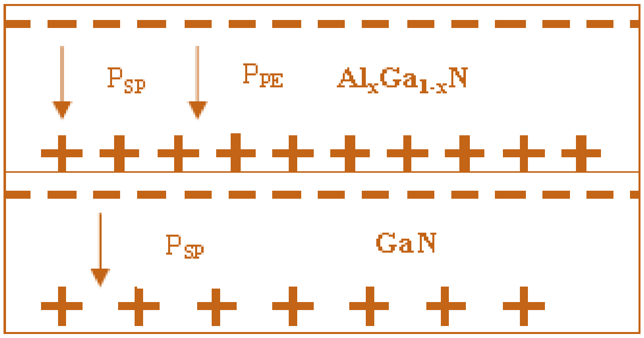


Figure 10: Combined piezoelectric and spontaneous fields for AlGaN grown on GaN

3.3 CHARGE CONTROL

Charge density is controlled by gate voltage. In AlGaN layer, acceptor states compensate silicon doping and hence decrease charge in the channel. In GaN layer, acceptor states lower Fermi level and hence reduce 2 dimensional electron gas. Acceptor states addition decrease saturation current and the sheet charge density in the channel.

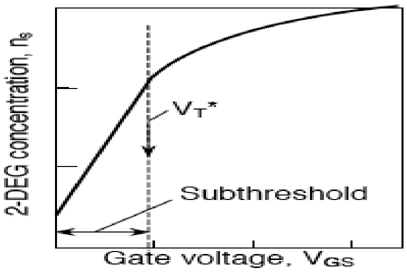


Figure 11: V_{GS} Vs 2 DEG

4.
5.
6.

4. NOISE IN DEVICE

The performance parameter FOM (figure of merit) is determined by low frequency noise. Noise is a limiting factor for HFETs. Transistor's performance is limited by conversion of low frequency noise to high frequency noise. Low frequency noise limits phase noise characteristics of device when used as mixers or oscillators. Analysis of low frequency noise is used to examine and yield crystal defects information. The noise sources in HFET devices are thermal noise, generation-recombination noise and 1/f noise. The effect of these noises on HFET devices is shown in figure 12.

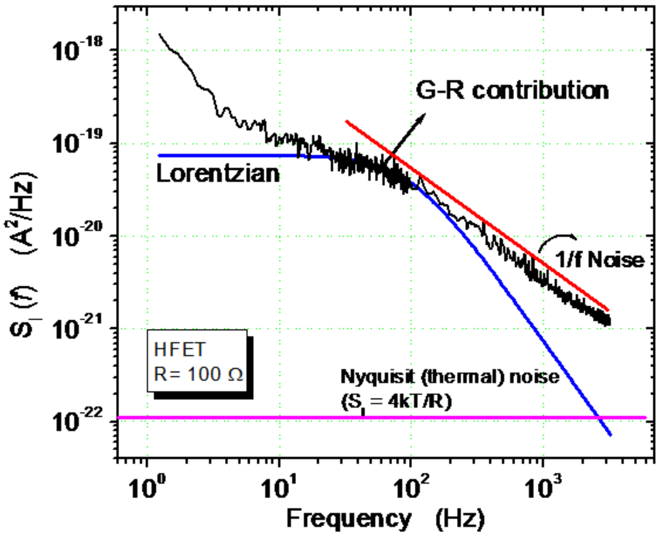


Figure 12: Noise Effect On Devices [10]

Mathematically, these noises are given by:

Thermal Noise: S = 4kTR

Generation- Recombination noise:

$$\frac{S_I}{I^2} = \frac{4N_T}{V_{olume} n^2} \frac{\tau F(1-F)}{1+(\omega\tau)^2}$$

$$\frac{1}{\tau} = \frac{1}{\tau_c} + \frac{1}{\tau_e}$$

Generation-recombination noise generally occur in MESFETs.

1/f Noise:

$$\frac{S_I(f)}{I^2} = \frac{S_V(f)}{V^2} = \frac{\alpha}{fN}$$

1/f noise can be due to contacts noise, surface noise, channel noise, noise due to gate leakage current, schottky barrier space charge region’s fluctuations etc.

5. CONCLUSION

In AlGaN/GaN devices, for better RF power utility and to use as in mm-wave applications, the substarate material selection is done for application and feasibility point of view. The AlGaN/GaN devices operating principle is based on polarization, 2DEG formation and charge control. Polarization induces the formation of surface states and helps in formation of a channel known as 2DEG. Performance parameters study of device is related to noise study in devices because low frequency noise affects the device performance. Different types of noise and their possible reasons are studied.

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