IOSR Journal of Engineering (IOSRJEN) **www.iosrjen.org**
ISSN (e): 2250-3021, ISSN (p): 2278-8719
Vol. 05, Issue 04 (April. 2015), ||V2|| PP 13-17

Review of III-V Based High Electron Mobility Transistors

Jun Zhu
Department of ECE The University of British Columbia

Abstract: - In this paper we give a review of the High Electron Mobility Transistor (HEMT). Limitation of the Silicon counterpart (MOSFET) and III-V predecessor (MESFET) are put forth as the motivations for the HEMT. Its basic working principles are presented using the AlGaAs/GaAs material system. A brief literature review of the early development of the device is given. More recent developments in the GaN material system and the MOSHEMT structure are also examined.

Keywords: *-High Electron Mobility Transistor, two dimensional electron gas, modulation doping, triangular quantum well*

I. A QUEST FOR HIGH MOBILITY

Mobility is defined as the velocity of charge carrier per unit strength of electric field:

$$\mu = {}^{v_d}/_{E} \; [{}^{cm^2}/_{Vs}]$$

For devices such as the field effect transistor (FET), where the current conduction is dominated by drift of the majority carrier, it is an essential parameter limiting the transconductance:

$$g_m = \frac{dI_{DS(sat)}}{dV_{GS}} \propto \frac{\mu}{L}$$

where L refers to the channel length of the FET structure. This is a measure of variation in the channel current per gate bias change. With less charge transport to the gate electrode to achieve a fixed change in the channel current, high transconductance allows fast switching and large signal to noise ratio, making it an important figure of merit in high frequency FET applications. Therefore, carrier mobility is the target for extensive engineering efforts. In Si, electron mobility of 1500 cm^2/Vs is a typical value at low doping level. To improve this, III-V compounds (GaAs in particular) are used for their higher intrinsic mobility in MESFET [1]. However, the absence of a native oxide on III-Vs sacrificestheir advantages over Si MOSFET. The doping dependence of the carrier mobility remains an issue with III-V substitution. Unlike the oxidation problem, this was fundamental to semiconductor crystal lattices.

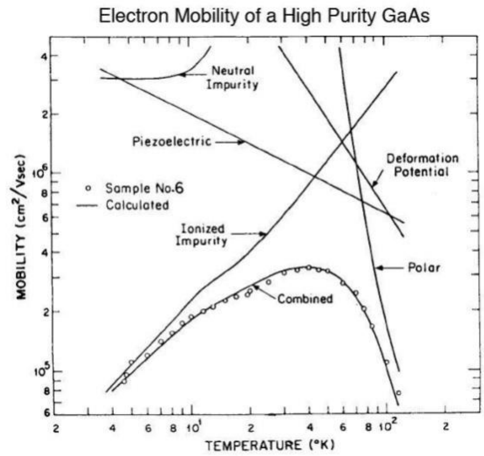

Fig.1: Mobilityversustemperatureina GaAssample with dependenceofeachscattering phenomenon.

As shown in Fig. 1, the limiting scattering event around 300 K is ionized impurity (dopant) scattering, decreasing the mobility exponentially toward lower temperatures. The next scattering event, piezoelectric, allows for order of magnitude higher mobility [2]. Hence a way to eliminate ionized impurity scattering will greatly improve device performances.

II. THE HEMT

Like many other revolutionary innovations, the solution to the mobility problem is very intuitive: spatially separating the electrons from their parent donors. This gave rise to the High Electron Mobility Transistor (HEMT). In this section, we introduce the operating principles of this device.

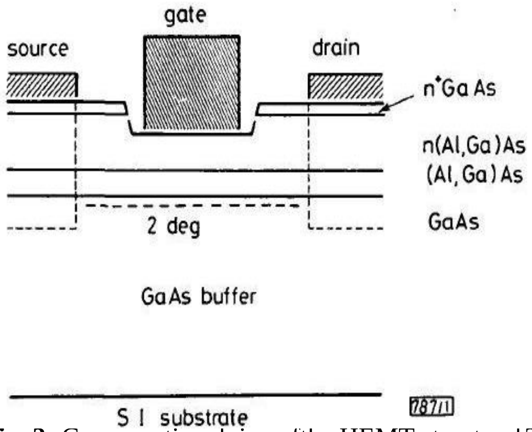

Fig. 2: Cross-sectionalviewofthe HEMT structure[3].

Above is a typical structure of the HEMT. Directly below the gate is a heavily doped AlGaAs layer. This layer houses parent donors for the conduction electron. A spacer layer of thin undopedAlGaAs sits between the donor layer and the undopedGaAs channel. Device operation can be thought of, in the simplest manner, as pushing electrons from the doped layer into the undoped channel, where electrons conduct current under a horizontal electric field but are unhindered by scattering with ionized impurities, which are left in the barrier layer (AlGaAs layer). This is summarized in the band diagram below [4].

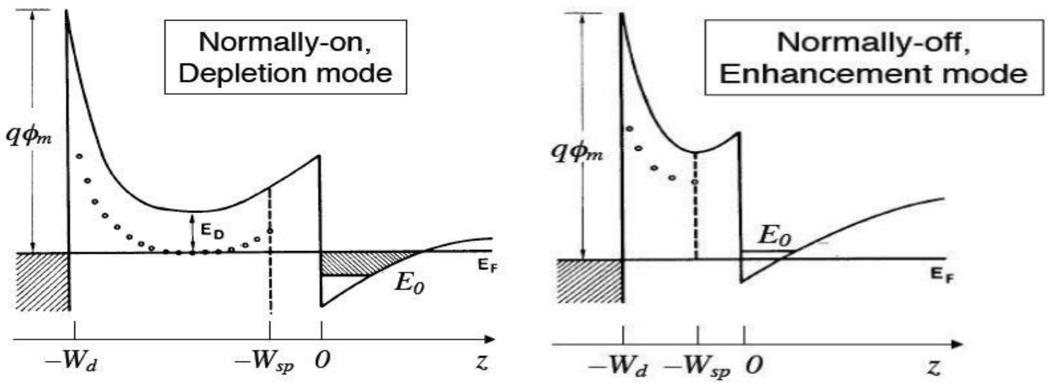

Fig.3: Banddiagramoftheheterojunctionof theHEMT. The left figure shows depletion mode and the right figure shows enhancement mode.

At the conduction band interface of the AlGaAs/GaAs structure, a spike barrier and triangular well is formed, typical of type-I band alignments. Electrons escape the doped layer and are trapped inside the triangular well on the undoped side, forming a pseudo two dimensional electron gas (2DEG) and leaving behind a depletion region on the doped side. This structure allows control of accumulation via gate voltage. By engineering the conduction band discontinuity and the relative position of the Fermi level to the triangular well ground state, enhancement mode and depletion mode devices are possible. Not only does the 2DEG suffer less ionized impurity scattering, the depletion layer serves as an insulator between the gate and the conduction channel. High mobility and the advantages of the MOSFET are combined.

In a more thorough consideration, Coulomb interaction between the 2DEG and the ionized donors in the AlGaAs layer must be included. This is more pronounced and limits carrier mobility at high barrier layer doping. The solution is again intuitive, since the Coulomb interaction falls off as the square of the distance, introducing an undoped spacer layer will significantly reduce the strength of this interaction. Other scattering events relevant to the HEMT heterojunction include interface roughness scattering which presented a challenge to growth techniques in the early stages of the HEMT. This has been overcome with advancements in MBE systems [5]. When electrons occupy the excited states of the triangular well, scattering is more likely due to a wider distribution of electron momentum. A simple estimation gives the DoS of the triangular well.

$$DoS_{2D}(E) = \frac{m^*}{\hbar^2 \pi} \cong 2.7 \times 10^{13}/cm^2 eV$$

The ground state of the triangular well can be approximated as:

$$E_0 = \gamma N_s^{2/3} \approx 3.4 \times 10^{-12} N_s^{2/3}\ eV$$

For typical values of sheet carrier density of ~10^{11}/cm^2, the triangular well ground state evaluates to $E_0 \approx 0.214\ meV$. Therefore the ground and first excited state spacing is $\Delta E_{01} \approx 1.338 E_0 \approx 0.29\ meV$. At the heterojunction, the ground state of the triangular well supports the following number of states:

$$\Delta E_{01} \times DoS \approx 7.8 \times 10^9/cm^2$$

We see that the ground state of the triangular well is saturated by a typical sheet carrier density. In real device performance, the first few energy levels of the triangular well are occupied, and inter-subband scattering is a pronounced effect that limits the mobility.

Electron mobility can be engineered to extreme values by reducing these scattering events. Having a very thick spacer layer will eliminate Coulomb interaction and limit the sheet carrier density. In 1982, the $10^7 cm^2/Vs$ mark in electron mobility was broken [6]. In 2007, the record value is $3.6 \times 10^7 cm^2/Vs$, and predictions exist on how to exceed 100 million [7]. These are impressive engineering and fostered the studied of some fundamental physics. The quest for high mobility is certainly successful. However, for real device applications, high mobility is not the only goal. A large sheet charge density of the 2DEG is required for low channel resistance and high current capacity. Therefore a compromise is made between mobility and N_s. Typical values for the spacer layer thickness are 25~30 Å.

A high sheet charge density can also be achieved through increasing the doping level of the AlGaAs layer. However, when using Si as the dopant, DX centers are formed in the AlGaAs depending on the Al composition. This degrades device performance and place constraints on band gap engineering at the heterojunction. A large doping level is also disadvantageous in that excess charges left in the AlGaAs layer form parallel conduction channels and degrades device reliability. To solve these problems, the delta-doping profile is applied [8]. To summarize, large conduction band discontinuity, high intrinsic material mobility and moderate sheet charge density are ideal for HEMT operation. In the next section we give a historical account of the invention of the HEMT structure and early developments.

III. HISTORY OF DEVELOPMENT

The invention of the HEMT is often credited to Takashi Mimura at Fujistu but the work on modulation doped heterostructure by Raymond Dingle and company at Bell Lab were equally important [6]. While studying the optical and electrical properties of Multiple Quantum Wells (MQW) of the AlGaAs/GaAs material system, Dingle and Stormer came across the idea of modulation doping to reduce ionized impurity scattering. By placing dopants in the middle of the AlGaAs layer, unprecedented mobilities were observed in the heterostructure [9]. This work was published in 1978 and stirred much attention. Work at Bell Labs split into two groups, one of which extended the fundamental physical studies, which led to exciting findings. The other group started looking for device potentials.

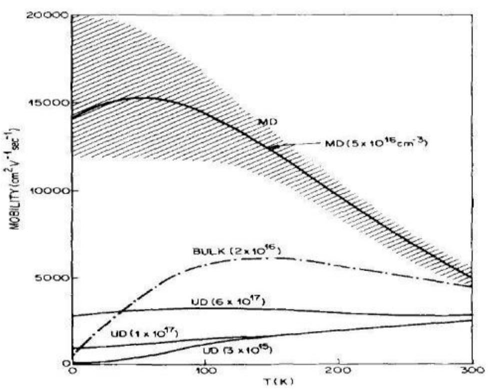

Fig.4: Electronmobilityvs.temperaturefor bulk GaAs,undopedandmodulationdoped (MD) AlGaAs/GaAssuperlattices.

Bell Lab was not the only one, competition soon followed. At Fujistu, Mimura was working on GaAs MOSFETs and was impressed upon hearing the work of Dingle *et al*, for achieving electron accumulation in the undopedGaAs potential wells. He soon came up with the idea of using a single doped AlGaAs and undopedGaAsheterojunction to achieve field effect control of electron accumulation at the interface. Mimura lead the team that first released the HEMT device in late 1980 [10]. At Thompson-CSF, France, a research team lead by Laviron released their device, termed the Two-dimensional Electron Gas Field Effect Transistor (TEGFET), in 1981. In their work both normally on (depletion mode) and normally off (enhancement mode) devices were demonstrated [3]. At Illinois, Su *et al*, reported their device, termed the Modulation-Doped Field Effect Transistor (MODFET), in 1982, achieving record level transconductance and electron saturation velocity [11]. The same year, Bell Lab's research team released their device, termed the Selectively Doped Heterojunction Transistor (SDHT) [12]. Over the years, the other terms faded and now the commonly accepted name for device of this nature is the HEMT.

Over the same period, HEMT integrated circuits were developing in furious competition. Fujitsu was the first to release a 27-stage HEMT-IC ring oscillator, with a switching speed of 17-ps at 77 K [10]. Bell Labs released an oscillator IC with switching speed of 9.4-ps at 77 K in 1984, making HEMT IC rival superconducting device such as Josephson Junction [13]. However, as with other III-Vs, the integrated circuit technology is still immature and nowhere near the very large scale integration achievable with Silicon technology.

Other material systems were also explored. As mentioned earlier, in the AlGaAs/GaAs system, conduction band discontinuity is limited by Al composition to avoid DX center formation. InGaAs has a lower band gap. Hence AlGaAs/InGaAsheterojunction is used to achieve higherΔE_c. The InGaAs layer is strained and this gave rise to pseudomorphic-HEMT (p-HEMT) [8]. In-rich materials have higher intrinsic electron mobility and dominate high speed applications.

IV. GANHEMT AND MOSHEMT

In more recent development, HEMTs fill another vacancy in the high temperature and high power applications left by MOS/MESFET technology. In this regime, a larger band-gap and higher breakdown voltage is given priority to high carrier mobility [14]. Hence the GaN material system is used. GaN material systems have also been studied extensively for LED and laser applications.

GaN material supports high power per unit width due to a higher sheet density of 2DEG. The devices can also be made smaller, giving advantages of smaller chips and higher device impedance. Impedance matching to other circuitry is made easier. High breakdown voltage eliminates the need for voltage conversion, which is typically required if using GaAs based HEMTs in commercial systems such as wireless base stations [15]. High band gap allows for high temperature operation and reduces cost of cooling systems.At high gate voltage, the inferiority of the depletion layer to insulator oxides is more pronounced. To increase breakdown voltage and reduce gate leakage current, oxides are deposited below the gate as in MOSFET technology [16]. Recent works using atomic layer deposited alumina have shown reduction of leakage current by 5 orders of magnitude compared to HEMTs [17]. LPCVD deposition of for GaN MOSHEMTs had been combined with 'self-aligned' fabrication process, allowing future work for high density integration of power circuits [18]. Other promising deposition methods include RF magnetron sputtering [19] and photochemical oxidation [20].

V. CONCLUSION

HEMT represents a significant improvement over its predecessors based on a simple idea. It combines the advantages of Si MOSFET technology and the superior material properties and flexibilities of the III-Vs. Through its invention, new fundamental physics were discovered. Since its birth in 1981, HEMTs had pushed the development of data communications by allowing the production of reliable high frequency, low noise amplifiers. Recent works using the GaN material system and oxide deposition techniques expanded the application of HEMTs into the high temperature and high power forefront of semiconductor technology where they will keep providing high speed and reliability.

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