Chapter 7
High Electron Mobility Transistors (HEMTs)

High electron mobility transistors (HEMTs) also known as Modulation Doped Field Effect Transistors (MODFETs) or Heterostructure Field Effect transistors (HFETs) were first introduced in 1980s. These devices take advantage of the formation of 2-Dimensional electron gas at the vicinity of a wide bandgap and small bandgap material junction. The formation of the 2-D channel boost the transport properties inside the channel resulting in excellent high frequency and noise properties for these devices as shall be discussed in details in this chapter. HEMTs can be made of different material systems in lattice-match, pseudomorphic and metamorphic fashions.

Basic Structure

Fig. 7.1 shows a conventional AlGaAs/GaAs HEMT structure with a recess gate technology. Note that unlike MESFETs where recess gate is used to change the threshold voltage of the transistor, the recess gate technology for HEMTs is necessary for the proper device operation. HEMT layers are grown on top of semi-insulating GaAs substrates with typical resistivity of 10^8 Ωcm. The un-doped or lightly p-doped GaAs buffer layer is used for the formation of the two

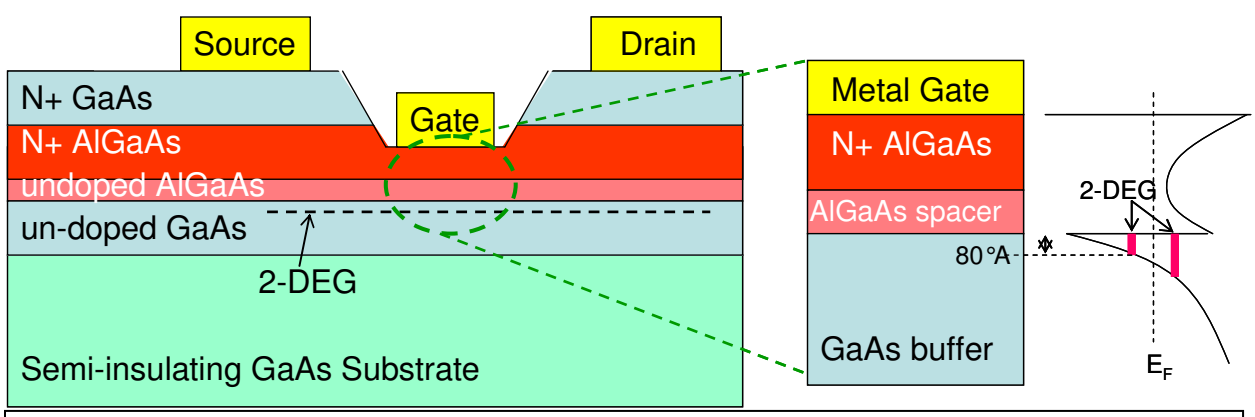

Fig.7.1. Cross section of a conventional lattice-matched AlGaAs/GaAs HEMT with the formation of a 2-D Electron Gas (2-DEG) channel in the undoped GaAs region. Quantization helps improving the transport properties of GaAs resulting in excellent speed and noise characteristics for the device.

dimensional electron gas. The fact that the buffer layer is undoped helps suppressing the ionized impurity scattering in the channel, thus improving the mobility. This is evident at reduced temperatures where ionized impurity scattering is the dominant scattering mechanism. The mobility of undoped GaAs improves from 8000 cm^2/V-sec at room temperature to 200,000 cm^2/V-sec at 77K and 1.5×10^6 cm^2/V-sec at 4K. The undoped AlGaAs spacer layer grown on top of the GaAs buffer layer has a typical thickness of 20°A and is used to balance the requirement of high mobility and high current capability. Thick spacer layer separates the carriers in the 2-DEG channel from ionized impurities in the N+ AlGaAs layer resulting in an increase in their mobility. At the same time due to a wide separation of the N+ AlGaAs layer and the 2-DEG due to thick spacer layer, the number of free electrons in the channel drops resulting in lower current capability as well as lower device transconductance. The AlGaAs layer above the spacer layer is called donor layer and is a heavily doped N+ region. If the AlGaAs donor layer is too thick, or is doped above the required level, it will be partially undepleted under the gate contact resulting in a leakage current from source to drain through this layer. If the donor layer is too thin or is doped too low, the 2-DEG electron density falls below the maximum value typically around $1\times10^{12}cm^{-2}$ observed in HEMTs.

As it is obvious from the conduction band alignment shown in Fig. 7.1, HEMTs benefit from large difference in conduction band discontinuity (ΔE_C), meaning that AlGaAs/GaAs is a better material choice than InGaP/GaAs for HEMTs. However, the problem of DX-centers in AlGaAs material has been an issue as it has resulted in an undesired time-dependent transconductance and large 1/f noise of HEMTs. As mentioned in Chapter 4, for $Al_xGa_{1-x}As$/GaAs heterostructure for x<0.45 (direct bandgap material), the difference in the band gap of $Al_xGa_{1-x}As$ and GaAs is $\Delta E_g(eV)=1.247x$. Out of this bandgap difference, a conduction band discontinuity $\Delta E_C(eV)=0.797x$ and a valence band discontinuity $\Delta E_V(eV)=0.45x$ are observed. The larger the conduction band discontinuity, the better is the electron confinement in the 2-DEG potential well at the heterointerface. A larger ΔE_C can be achieved by using AlGaAs/InGaAs heterostructure, resulting in much better electron confinement. Note that in this case InGaAs channel can be under strain (pseudomorphic) resulting in excellent transport properties in already high mobility InGaAs 2-DEG channel. At $In_yGa_{1-y}As$/GaAs heterojunction, a conduction band discontinuity of

ΔE_C(eV)=-0.8y is achieved. From this equation, one can calculate the discontinuity of AlGaAs/InGaAs heterointerface.

The operation principle of HEMTs is based on generating a 2-DEG channel in an undoped material to essentially prevent ionized impurity scattering. The 2-DEG has higher mobility due to the fact that degeneracy in the conduction band is lifted. Additionally, electrostatic screening by the high electron density in the channel further reduces ionized impurity scattering. The 2-DEG is confined to within ~100°A of the interface with a maximum sheet carrier density of around ~10^{12}cm^{-2} (corresponds to ~10^{18}cm^{-3} electron concentration). As explained before the electron mobility can be further increased by inserting the undoped AlGaAs spacer layer between the channel and doped AlGaAs donor layer. This leads to a reduction in the electron density. The electron density and mobility are also a function of the conduction band discontinuity ΔE_C at AlGaAs/GaAs interface. This increases with increasing Al mole fraction in the AlGaAs. The tradeoff in this case is that the high mole fraction AlGaAs has higher concentration of DX centers. The scattering of electrons not only limits the low field mobility, but also causes the removal of carriers from the lowest subband of 2-DEG. Real space transfer of electrons from the 2-DEG to AlGaAs layer occurs by thermionic emission and thermionic field emission.

DC Characteristics

For a HEMT with a large ΔE_C discontinuity, the channel electron density can be found according to

$$n_{s_superthreshold} = \frac{\varepsilon_i \left(V_{GS} - V_T\right)}{q\left(d_d + d_i + \Delta d\right)} \tag{7.1}$$

$$n_{s-subthreshold} = n_0 e^{\left(\frac{V_{GS}-V_T}{\eta V_{th}}\right)} \tag{7.2}$$

where $n_{s_superthreshold}$ is the sheet electron density when gate voltage is above the threshold voltage $V_{GS} > V_T$ (channel is densely populated with electrons from the donor layer) and $n_{s-subthreshold}$ is the sheet electron density when gate voltage is below the threshold voltage $V_{GS} < V_T$ and ε_i and d_i are the dielectric constant and the thickness of the wide-bandgap semiconductor, respectively. d_d is the thickness of donor layer after the gate recess process, η is the ideality factor and V_{th} is

the thermal voltage kT/q. Δd represents the effective thickness of 2-DEG with a typical value of 40 to 80°A. n_0 represents the sheet density of electrons at threshold and is given by

$$n_0 = \frac{\varepsilon_i \eta V_{th}}{2q\left(d_d + d_i + \Delta d\right)} \tag{7.3}$$

One can combine equations (7.1) and (7.2) to achieve

$$n_s = 2n_0 \ln\left[1 + \frac{1}{2} e^{\left(\frac{V_{GS}-V_T}{\eta V_{th}}\right)}\right] \tag{7.4}$$

In an actual HEMT there is a maximum limit for sheet carrier density. This is due to the fact that the electrons are confined with rather small ΔE_C barrier. For AlGaAs/GaAs HEMT, this value $n_{max}=2\times10^{12}cm^{-2}$. The actual 2-DEG density $n_s^{'}$ can then be calculated according to

$$n_s^{'} = \frac{n_s}{\left[1 + \left(n_s / n_{\max}\right)^{\gamma}\right]^{1/\gamma}} \tag{7.5}$$

where γ is a characteristic parameter for the transition to $n_s^{'}$ saturation and n_s is calculated from equation (7.4). Once we know the sheet carrier density at a given gate voltage, we are able to find the IV characteristics according to

$$I_{DS} = \frac{g_m V_{DS}\left(1 + \lambda V_{DS}\right)}{\left[1 + \left(g_m \cdot V_{DS} / I_{sat}\right)^{\gamma}\right]^{1/\gamma}} \tag{7.6}$$

The additional $\left(1 + \lambda V_{DS}\right)$ is introduced to account for the finite output conductance in the saturation regime. g_m is related to the intrinsic transconductance $g_{mi} = q n_s^{'} W \mu_n / L$ according to

$$g_m = \frac{g_{mi}}{1 + g_{mi}\left(R_S + R_D\right)} \tag{7.7}$$

and I_{sat} in equation (7.6) is the saturated current calculated from the following equation

$$I_{sat} \approx \frac{g_{mi}\left(V_{GS} - V_T\right)}{1 + g_{mi} R_S + \sqrt{1 + 2 g_{mi} R_S}} \tag{7.8}$$

Various HEMT Designs

In addition to the conventional HEMT shown in Fig. 7.1, there are a variety of alternate HEMT designs as shown in Fig. 7.2 proposed and implemented by various researchers. Some of these designs are used in the production lines.

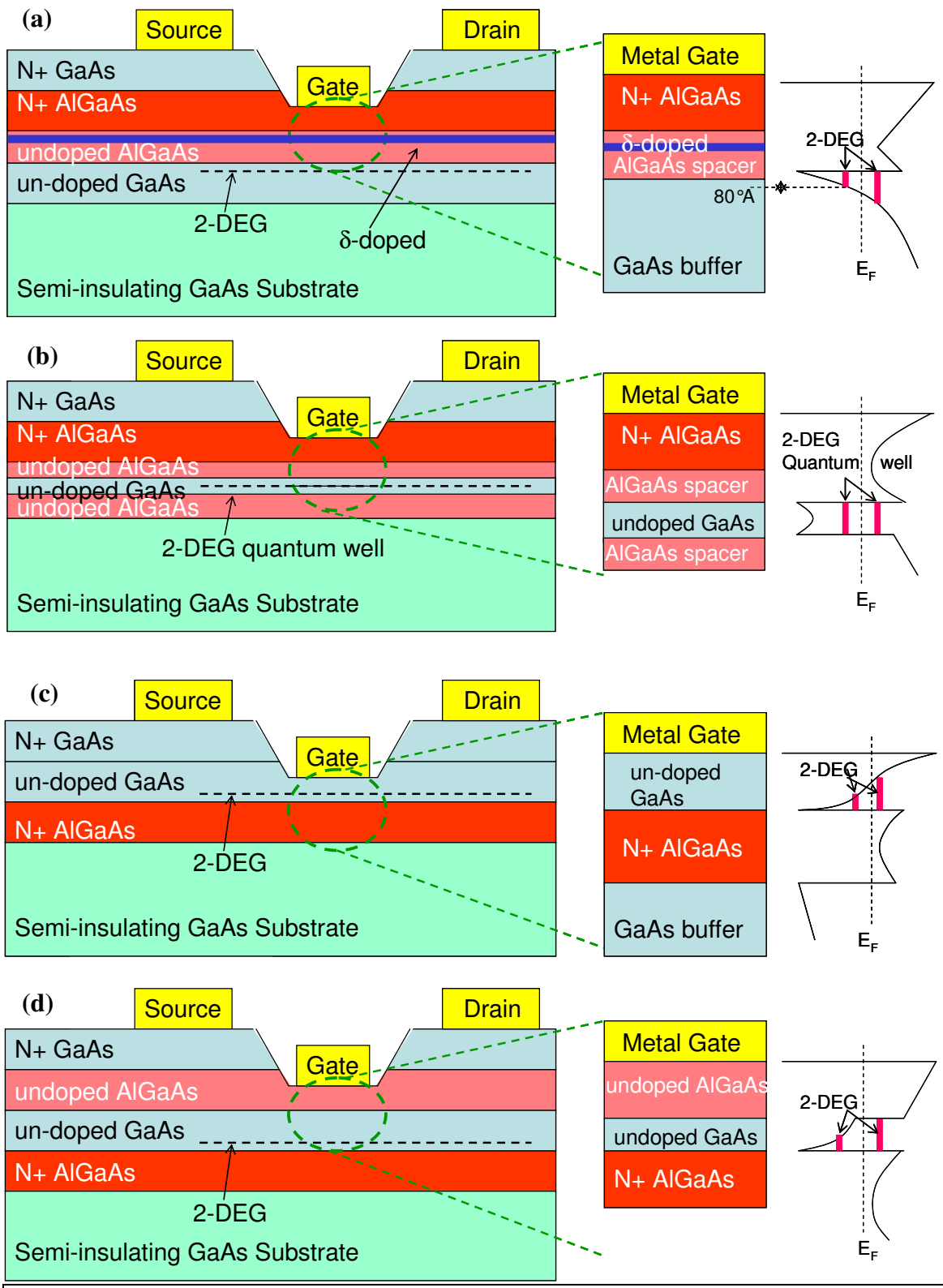

Fig. 7.2. Some of the common HEMT structures reported in the literature. (a) δ-doped HEMT. (b) quantum well HEMT. (c) Inverted HEMT (IHEMT). (d) Insulated gate Inverted HEMT (I^2 HEMT)

The threshold voltage in the conventional HEMT is controlled by the doping in the AlGaAs donor layer as well as its thickness under the gate d_d which is determined by the gate recess technology and may not be constant across the wafer due to process variations. Additionally, in the conventional structure, the DX centers in AlGaAs donor layer capture and release the electrons from the 2-DEG through real space transfer scattering. As a result, the current and transconductance of the conventional HEMT fluctuates with time. Conventional AlGaAs/GaAs HEMTs show high levels of flicker noise. To remedy these problems the δ-doped structure shown in Fig. 7.2 (a) is proposed. Here, the threshold voltage is solely controlled by the doping in the δ-doped region, thus it is not sensitive to the gate recess technology. Additionally, the DX centers are less of a problems compared to the conventional structure.

Fig. 7.2 (b) shows the structure and conduction band alignment of a quantum well HEMT. In this structure, due to the availability of two AlGaAs spacers that are sandwiching a thin GaAs quantum well channel, better localization of 2-DEG is achieved. This results in higher current capability of the device and less short-channel effects. Output resistance in this structure is typically high with small leakage current below the threshold voltage.

Fig. 7.2 (c) shows an inverted HEMT (IHEMT). In this structure the undoped GaAs layer is on top while the doped AlGaAs donor layer is buried. There is no threshold voltage dependence on the gate recess technology. Additionally, there is no parasitic MESFET conduction as it is seen in conventional HEMTs. Since the gate metallization and the 2-DEG channel are very close, the transconductance of the IHEMT is typically very high.

Fig. 7.2 (d) shows the Insulated Gate Inverted HEMT structure (I^2HEMT). An additional undoped AlGaAs layer is grown on top of the GaAs channel layer of the IHEMT structure to improve the conduction band barrier and the electron confinement. There is almost no sign of short channel effect in this structure. The transconductance is slightly lower than the one achieved for IHEMT.

Another important structure derived from a conventional HEMT is known as HIGFET (heterostructure insulated Gate FET) or MISFET (Metal Insulator Semiconductor FET). This

structure is very similar to the conventional HEMT except that the top AlGaAs donor layer is undoped. Therefore, there is no trapping associated with the DX center. Neither there is a threshold voltage dependence on the gate recess technology. HIGFETs need to be fabricated in a deep submicron self-aligned technology to reduce the parasitic access resistances on source and drain contacts and allow the channel to be modulated doped through these contacts. Often, ion implantation is used to help reducing the parasitic access resistances. HIGFETs are also used with doped channels for higher current capabilities, but the device is not as fast as a conventional HEMT.

Choice of the Material System

AlGaAs/GaAs HEMTs were the first HEMT devices introduced due to rather easy material growth of the lattice matched HEMT structure. An alternative GaAs based HEMT device is made with InGaAs as the channel material. InGaAs with typically less than 15% In mole fraction is not lattice matched to GaAs or AlGaAs. Therefore the channel is under strain when it is grown to less than its critical thickness and the device is referred to as a Pseudomorphic HEMT. $In_{0.15}Ga_{0.85}As$ has smaller bandgap than GaAs, therefore the electron confinement in the channel is better than AlGaAs/GaAs HEMTs. Additionally, the structure is a double hetereostructure (similar to the quantum well design) which improves the confinement even further. $In_{0.15}Ga_{0.85}As$ has slightly higher mobility compared to GaAs. Strain in the layer further improves the mobility by lifting the degeneracy in the conduction band.

On InP substrate, one can grow both lattice matched and pseudomorphic HEMT structure. The lattice matched InP HEMT has a InAlAs as the wide-bandgap donor layer and spacer layer and InGaAs as the channel layer. Both InAlAs and InGaAs have mole fractions close to 50% to achieve a lattice matched structure. If the In mole fraction in the InGaAs channel is slightly increased, one can achieve a pseudomorphic InP HEMT which typically shows higher speed than the lattice matched InP HEMT structure. Both types of devices are grown on InP substrate and InP buffer layer and are so-called double heterostructure HEMTs.

Another material system often used for extremely high power amplifiers uses AlGaN as the wide-bandgap material on GaN channel. This AlGaN/GaN HEMT structure is often grown on GaN buffer layer on top of a SiC substrate. Si/Si/Ge/Si system is also used as a HEMT structure (often called MODFET) but has not shown much application due to its inferior characteristics compared to Si/SiGe heterojunction Bipolar Transistors.

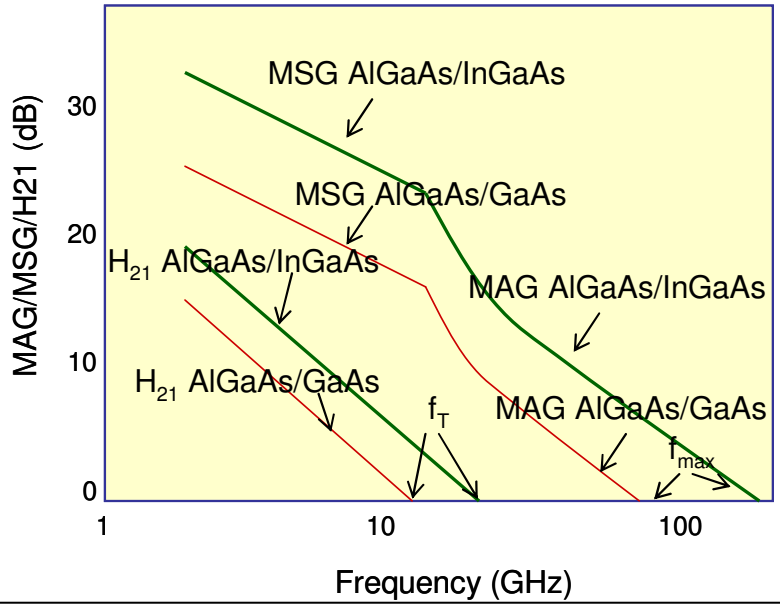

Fig. 7.3. Maximum Available Gain, Maximum Stable Gain and short Circuit Current Gain (H_{21}) of conventional lattice matched AlGaAs/GaAs HEMT and pseudomorphic AlGaAs/ $In_{0.15}Ga_{0.85}As$ HEMT for a 0.25µm technology.

Fig. 7.3 shows a comparison between a lattice matched and pseudomorphic GaAs based HEMT technologies with identical gate length of 0.25µm. Pseudomorphic devices typically have 20 to 50% higher speed when compared to their lattice matched counterparts.

HEMT Noise Performance

Fig. 7.4 compares the minimum noise figure F_{min} of a GaAs MESFET, a lattice matched GaAs HEMT and a Pseudomorphic GaAs HEMT all in a 0.25µm technology. HEMT devices are far superior to their MESFET counterpart especially at higher frequencies with

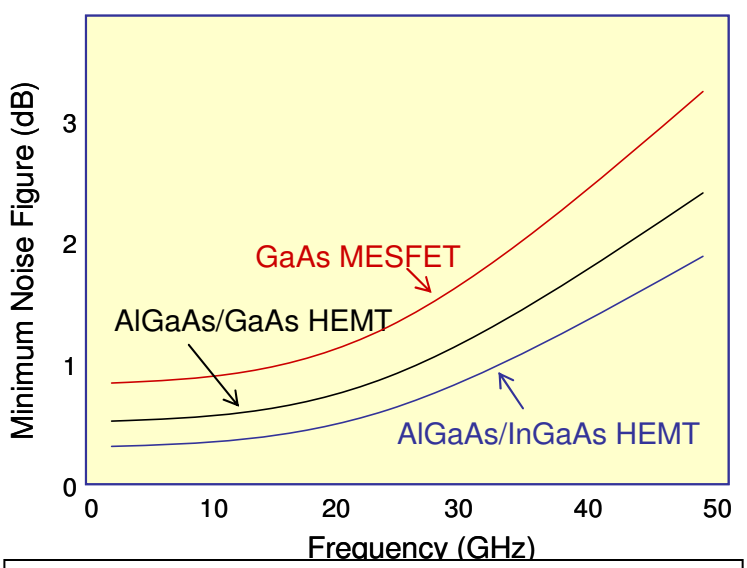

Fig. 7.4. Minimum Noise Figure (Fmin) of GaAs MESFET, lattice matched GaAs HEMT and Pseudomorphic GaAs HEMT in 0.25µm technology.

a difference of at least 0.3dB at lower frequency range.

For the purpose of HEMT noise modeling, the same model and same analysis carried out in Chapter 6 for MESFET applies to HEMT devices as well. Note that for HEMT devices the value of noise parameters γ and δ are typically lower for HEMTs compared to MESFETs.

HEMT Power Performance

For low to medium output powers, HBT devices are typically preferred over HEMT devices in the frequency range of up to Ka-bands (40GHz). Above 40GHz, HEMTs show better power performance as they are typically faster than their HBT counterpart. Of course the cost of fabrication for HEMT is typically higher than HBTs due to the requirement of electron beam lithography for HEMT devices with 0.25µm technology or better. Note that HBTs typically do not require submicron processing unless extremely high speeds are desired.

AlGaN/GaN HEMT devices have become the device of choice for extremely high power at lower frequency bands (<10GHz) due to relatively low mobility and speed limitations of GaN material. Nevertheless, AlGaN/GaN HEMTs have extremely high breakdown voltage due to very wide bandgap of GaN (~3.4eV) and can deliver powers in the range of tens of Watts at several GHz frequencies.

Note that the same large signal analysis performed for MESFETs in Chapter 6 can be applied to HEMT devices.