

## IV. HEMTs and PHEMTs

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GaAs-based high-electron mobility transistors (HEMTs) and pseudomorphic HEMT (or PHEMTs) are rapidly replacing conventional MESFET technology in military and commercial applications requiring low noise figures and high gain, particularly at millimeter-wave frequencies. The application of PHEMTs for high-efficiency power amplification is gaining popularity. Other commonly used names for HEMTs include MODFET (modulation doped FET), TEGFET (two-dimensional electron gas FET) and SDHT (selectively doped heterojunction transistor).

Since HEMTs and PHEMTs are field-effect transistors, the basic principles of their operation are very similar to those of the MESFET described in Section 3-III. The main difference between HEMTs and MESFETs is the epitaxial layer structure. In the HEMT structure, compositionally different layers are grown in order to optimize and to extend the performance of the FET. For III–V semiconductors using a GaAs substrate, the common materials used are  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  and GaAs. For most device applications, the  $\text{Al}_x\text{As}$  mole fraction is between  $0.2 < x < 0.3$ . The PHEMT also incorporates  $\text{In}_x\text{Ga}_{1-x}\text{As}$ , where  $\text{In}_x\text{As}$  is constrained to  $x < 0.3$  for GaAs-based devices. These different layers form heterojunctions since each layer has a different band gap. Structures grown with the same lattice constant but different band gaps are simply referred to as lattice-matched HEMTs. Those structures grown with slightly different lattice constants are called pseudomorphic HEMTs or PHEMTs. Figure 3-14 shows the band-gap energy as a function of lattice constant for the III–V semiconductors. In this section, a simple epitaxial layer structure for HEMTs will be described with reference to MESFETs where appropriate. Some salient features of HEMT and PHEMT device physics will be highlighted. Lastly, the effects of the epitaxial structure and the device operation on reliability will be discussed.

### A. Device Physics

The epitaxial structure of a basic HEMT is illustrated in Figure 3-15. Similar to the MESFET, the HEMT structure is grown on a semi-insulating GaAs substrate using molecular beam epitaxy (MBE), or less common, metal–organic chemical vapor deposition (MOCVD). Table 3-2 contains the common MESFET, HEMT, and PHEMT epitaxial structures.

The buffer layer, also typically GaAs, is epitaxially grown on the substrate in order to isolate defects from the substrate and to create a smooth surface upon which to grow the active layers of the transistor. Many PHEMT structures contain a superlattice structure to further inhibit substrate conduction. A superlattice structure is a periodic arrangement of undoped epitaxial layers used to realize a thicker epitaxial layer of a given property. For example, alternating layers of  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  and GaAs form a typical PHEMT superlattice. The  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  has a larger band gap than GaAs, making it superior to GaAs as a buffer. However, due to strain problems, the  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  layer thickness is limited. To resolve this problem, the  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  is grown to just below its thickness limit and a thin layer of GaAs is grown on top. The GaAs relieves the strain and allows another layer of  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  to be grown. This process is typically repeated 10 to 15 times, creating a layer that is “essentially” a thick buffer of  $\text{Al}_x\text{Ga}_{1-x}\text{As}$ .

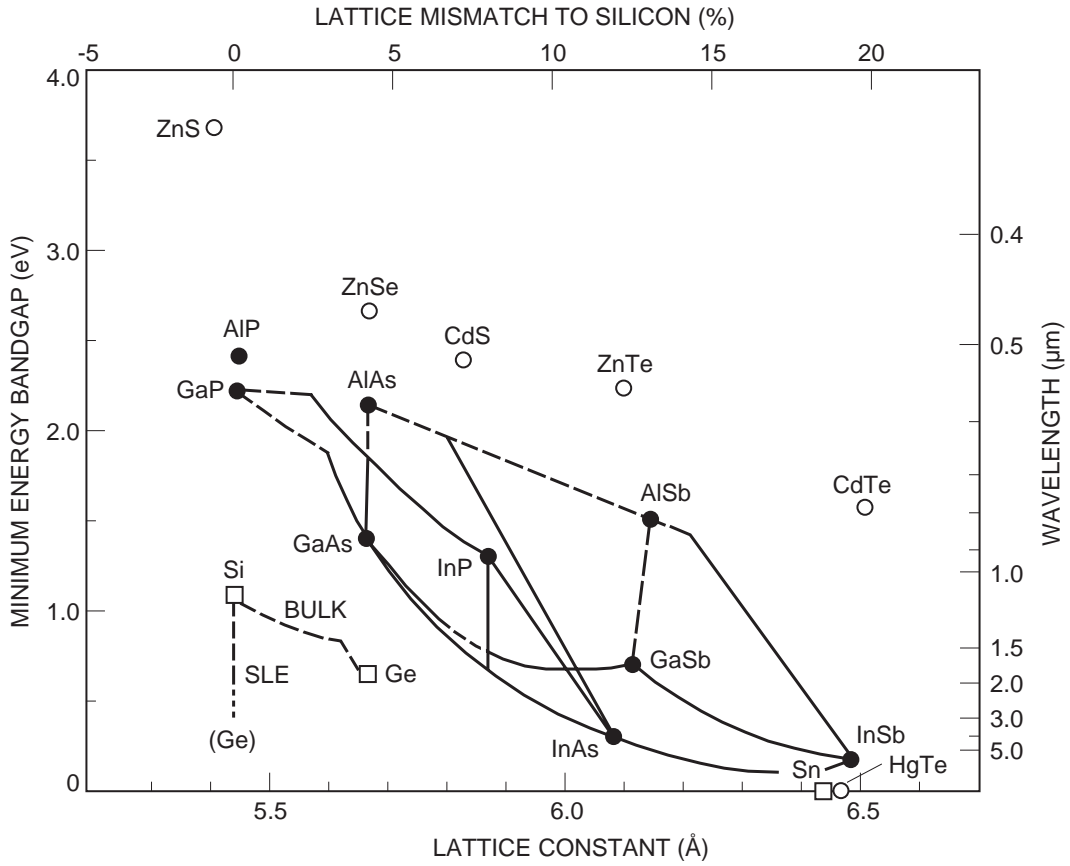


Figure 3-14. Minimum band-gap energy vs lattice constant data for III-V semiconductors. The right axis indicates the wavelengths of light that would be emitted by a laser or LED for a material of the corresponding bandgap. Connecting lines give information for alloys of the materials at the endpoints of a given line segment. Solid lines indicate a direct bandgap and dashed lines an indirect bandgap. For Ge-Si, the line denoted BULK corresponds to unstrained, lattice-mismatched growth and the line SLE to strained layer epitaxy of Ge-Si on unstrained Si. (From [1]; reprinted by permission of John Wiley & Sons, Ltd.)

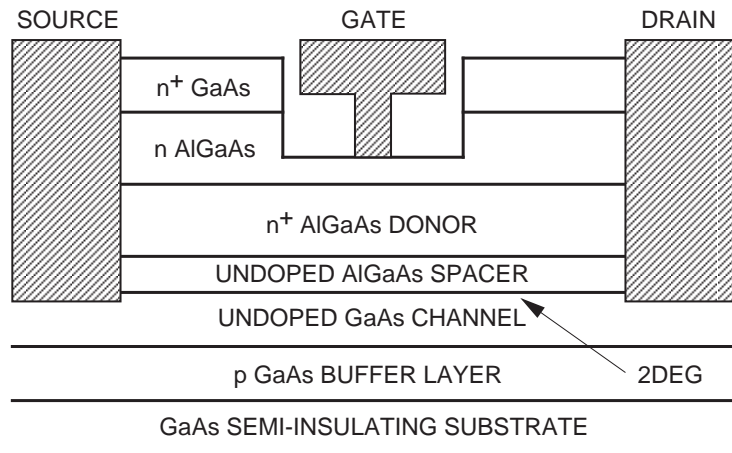
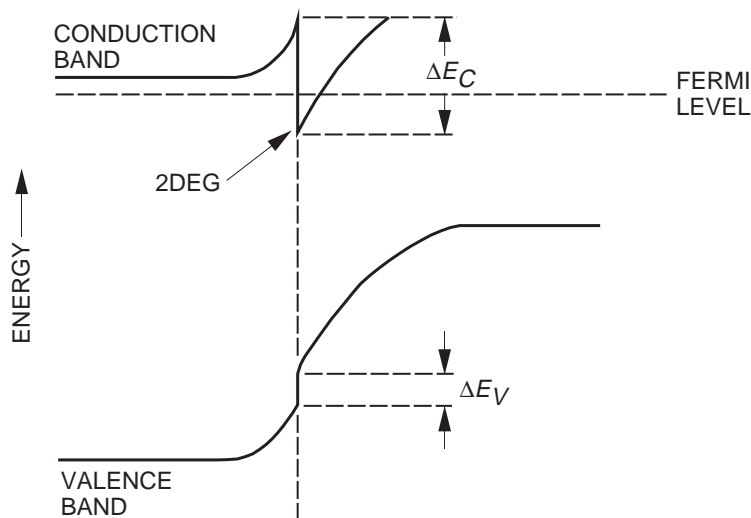


Figure 3-15. Epitaxial structure of a basic AlGaAs/GaAs HEMT.

**Table 3-2. Epitaxial layer compositions for basic GaAs-based HEMT and PHEMT devices compared with those of MESFET.**

Device Layer	MESFET	HEMT	PHEMT
Ohmic contact	n <sup>+</sup> GaAs	n <sup>+</sup> GaAs	n <sup>+</sup> GaAs
Schottky contact	n GaAs	n AlGaAs	n AlGaAs
Donor		n <sup>+</sup> AlGaAs or Si pulse doping	n <sup>+</sup> AlGaAs or Si pulse doping
Spacer		Undoped AlGaAs	Undoped AlGaAs
Channel	n <sup>+</sup> GaAs	Undoped GaAs	Undoped InGaAs
Buffer	p <sup>-</sup> GaAs	p <sup>-</sup> GaAs	p <sup>-</sup> GaAs

In the conventional HEMT structure, the channel is grown next. In the ideal system, all of the electron conduction would take place in this channel. The most important point about the channel layer in the HEMT and PHEMT devices is the two-dimensional electron gas (2DEG) that results from the band-gap difference between Al<sub>x</sub>Ga<sub>1-x</sub>As and GaAs (or Al<sub>x</sub>Ga<sub>1-x</sub>As and In<sub>x</sub>Ga<sub>1-x</sub>As, in the case of the PHEMT). Illustrated in Figure 3-16 is the band diagram of a generic HEMT showing the 2DEG formed by the different band gaps. The 2DEG is formed since the higher band gap of Al<sub>x</sub>Ga<sub>1-x</sub>As allows free electrons to diffuse from the Al<sub>x</sub>Ga<sub>1-x</sub>As to the lower band gap GaAs (or In<sub>x</sub>Ga<sub>1-x</sub>As) near the interface. A potential barrier then confines the electrons to a thin sheet of charge known as the 2DEG. In contrast to the MESFET, which has a doped channel and consequently lots of ionized donors, the 2DEG has significantly less Coulomb scattering, resulting in a very high mobility device structure.



**Figure 3-16. Energy band diagram of a generic AlGaAs–GaAs HEMT showing the 2DEG quantum well channel.**

The remainder of the HEMT structure contains an Al<sub>x</sub>Ga<sub>1-x</sub>As spacer layer, a donor layer n<sup>+</sup> Al<sub>x</sub>Ga<sub>1-x</sub>As, an n Al<sub>x</sub>Ga<sub>1-x</sub>As Schottky contact layer, and a highly doped n<sup>+</sup> GaAs layer. The spacer layer serves to separate the 2DEG from any ionized donors generated by the pulse doping or n<sup>+</sup> active layer. The drawback of the spacer layer,

however, is that the sheet carrier concentration (total amount of charge) in the channel is reduced as the spacer layer thickness is increased. The donor layer or Schottky layer is an  $n^+$   $\text{Al}_x\text{Ga}_{1-x}\text{As}$  layer and serves as the source of electrons. To avoid the possibility of electron conduction in the  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  (which has a low electron mobility), the thickness of the Schottky must be chosen so that the depletion region of the gate overlaps the depletion at the  $\text{Al}_x\text{Ga}_{1-x}\text{As}/2\text{DEG}$  interface for depletion mode devices. The  $n^+$  GaAs is present to realize low-resistance ohmic contacts.

The structure described above is a basic HEMT structure. Most of the structures used today are variants of this, having been optimized for performance and applications. For instance, many PHEMTs used for power applications will incorporate two silicon pulses, the second one below the channel, to increase the total charge available.

The fabrication and basic operation of HEMT and PHEMT devices are very similar to those for the MESFET. There exist some differences, mainly related to the presence of the  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  in the epitaxial structure. As mentioned previously,  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  has a larger band-gap energy than GaAs and the band gap increases with the AlAs mole fraction. HEMTs require ohmic contacts directly to the 2DEG, which is made more difficult with increased AlAs mole fraction. An advantage of the AlGaAs is the higher Schottky barrier height resulting from the deposition of the gate metal on the AlGaAs. Unfortunately, the high doping in the donor layer decreases the breakdown voltage. However, power HEMT and PHEMT structures with higher breakdown voltages ( $>10$  V) have been engineered using either double recess technology or by reducing the doping in the Schottky layer.

Under operation, HEMTs and MESFETs are biased similarly. When a negative gate bias is applied to the HEMT device, the Schottky layer becomes depleted. As the gate is biased further, the 2DEG becomes depleted. This results in the modulation of the channel (2DEG) by a negatively applied gate bias where gain and amplification occur until the channel is pinched off (i.e., fully depleted). The transconductance is given by

$$g_m = (\epsilon v_{sat} W_g) / d$$

where  $\epsilon$  = permittivity of  $\text{In}_x\text{Ga}_{1-x}\text{As}$ ,  $v_{sat}$  = saturated velocity of  $\text{In}_x\text{Ga}_{1-x}\text{As}$ ,  $W_g$  = unit gate width of the device, and  $d$  = distance from the gate to the 2DEG. Under high-electric-field conditions, the HEMT shows a higher saturated velocity over the MESFET. Since the conduction of electrons from the source to the drain takes place in a channel that is well confined,  $g_m$  will remain very high at low drain currents. This is somewhat contrasted with the MESFET because at low drain current, the distance  $d$  will increase because the edge of the depletion region enters the tail of the doping profile. This results in a compression of the  $g_m$ . The higher mobility of the HEMT results in lower parasitic drain and source resistances. As a result,  $f_t = g_m / (2\pi C_{gs})$  and  $f_{max}$  are increased from the MESFET case for a given gate length leading to a lower noise figure and higher gain.

## B. Reliability

The reliability of HEMTs and PHEMTs is affected by the epitaxial structure, device fabrication, and device geometry. One of the drawbacks of using  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  in the material structure is the occurrence of traps, called DX centers, for AlAs mole fractions around  $x = 0.26$ . These traps are deep donor levels that can lead to reduced drain current, an increase in low frequency noise and photoconductivity, and are particularly problematic at low temperature. Further, the creation of DX centers increases with higher doping of the  $\text{Al}_x\text{Ga}_{1-x}\text{As}$ . DX centers are avoided by keeping the

$\text{Al}_x\text{As}$  content below  $x = 0.24$  for n-type doped  $\text{Al}_x\text{Ga}_{1-x}\text{As}$ . A second possible reliability problem that can occur is the deconfinement of the 2DEG under high-temperature conditions. Thermally accelerated testing has shown that the Al can migrate laterally into the gate, resulting in a change in the conduction band discontinuity.

To take advantage of the high  $g_m$ , HEMTs and PHEMTs rely on small geometries for optimum performance. Paralleling the MESFET, HEMTs and PHEMTs suffer the same electromigration and metal interdiffusion reliability problems associated with the ohmic and gate metallizations under device operation. In addition, hot electron traps resulting from the generation of avalanche electrons are a problem for HEMTs and PHEMTs. The hot electrons cause a degradation in the current and in the gain and power under microwave drive as they become trapped in the passivation or the  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  passivation interface. For power devices, catastrophic failures or “burnout” can also be an issue due to the high channel temperatures resulting from the large currents required for high power.

## Reference

- [1] J. C. Bean, “Materials and Technologies,” in *High-Speed Semiconductor Devices*, S. M. Sze, Editor, John Wiley & Sons, New York, 1990.

## Additional Reading

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