6-3 HIGH ELECTRON-MOBILITY TRANSISTORS (HEMTs)

The evolution of high-speed GaAs integrated circuits (ICs) is the result of continuous technological progress utilizing the superior electronic properties of gallium arsenide compared with those of silicon. Electron mobility in the MESFET channel with typical donor concentrations of about 10^{17} cm^{-3} ranges from 4000 to 5000 cm^2/V·s at room temperature. The mobility in the channel at 77° K is not too much higher than at room temperature because of ionized impurity scattering. In undoped GaAs, however, electron mobility of 2 to 3 × 10^5 cm^2/V·s has been achieved at 77° K. The mobility of GaAs with feasibly high electron concentrations for facilitating the fabrication of devices was found to increase through modulation-doping techniques demonstrated in GaAs–AlGaAs superlattices [8]. A high electron-mobility transistor (HEMT), based on a modulation-doped GaAs–AlGaAs single heterojunction structure, was developed [9]. HEMTs have exhibited lower noise figure and higher gain at microwave frequencies up to 70 GHz, and it is possible to construct HEMT amplifiers at even higher frequencies of operation. The major improvements over MESFETs include shorter gate lengths, reduced gate and source contact resistances, and optimized doping profiles.

6-3-1 Physical Structure

The basic structure of a HEMT is a selectively doped GaAs–AlGaAs heterojunction structure as shown in Fig. 6-3-1.

An undoped GaAs layer and an Si-doped *n*-type AlGaAs layer are successively grown on a semi-insulating GaAs substrate. A two-dimensional electron gas (2-DEG) is created between the undoped and *n*-type layers. A buffer layer is sandwiched between the undoped GaAs layer and the semi-insulator substrate.

The HEMT can be fabricated by using the integrated-circuit techniques. Fig. 6-3-2 indicates the sequence for the self-aligned gate procedures in the fabrication of large-scale integration HEMTs, including the E-(enhacement-mode) and D-(depletion-mode) HEMTs.

The processing steps include the following:

1. Ohmic contact formation: The active region is isolated by a shallow mesa step (180 nm), which is almost achieved in a single process, and can be made nearly planar. The source and drain for E- and D-HEMTs are metallized with

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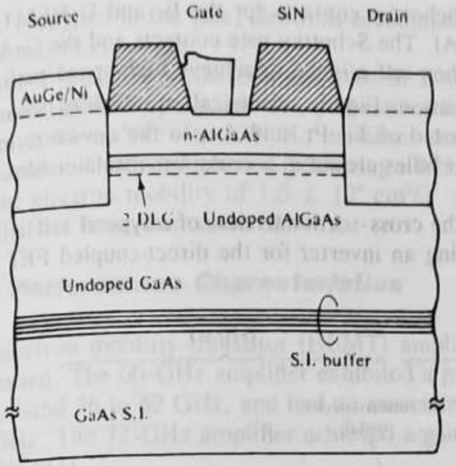

Figure 6-3-1 A cross section of a HEMT (*From K. Togashi et al. [10]; reprinted by permission of* Microwave Journal.)

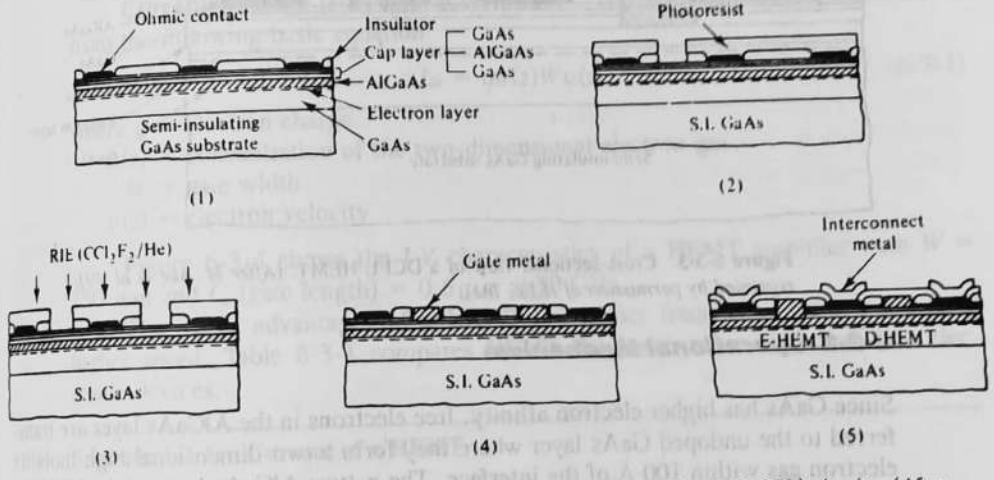

Figure 6-3-2 Processing steps for HEMT direct-coupled FET logic (DCFL) circuits. (*After M. Abe and others [9]; reprinted by permission of IEEE, Inc.*)

an AuGe eutectic alloy and an Au overlay alloy to produce ohmic contacts with the electron layer.

2. Opening gate windows: The fine gate patterns are formed for E-HEMTs as the top GaAs layer and thin $Al_{0.3}Ga_{0.7}As$ stopper are etched off by nonselective chemical etching.
3. Selective dry etching: With the same photoresist process for formation of gate patterns in D-HEMTs, selective dry etching is performed to remove the top GaAs layer for D-HEMTs and also to remove the GaAs layer under the thin $Al_{0.3}Ga_{0.7}As$ stopper for E-HEMTs.

4. Gate metallization: Schottky contacts for the E- and D-HEMT gate are provided by depositing Al. The Schottky gate contacts and the GaAs top layer for ohmic contacts are then self-aligned to achieve high-speed performance.
5. Interconnect metallization: Finally, electrical connections from the interconnecting metal, composed of Ti, Pt, and Au, to the device terminals are provided through contact holes etched in a crossover insulator film.

Figure 6-3-3 shows the cross-sectional view of a typical self-aligned structure of E- and D-HEMTs forming an inverter for the direct-coupled FET logic (DCFL) ciruit configuration [9].

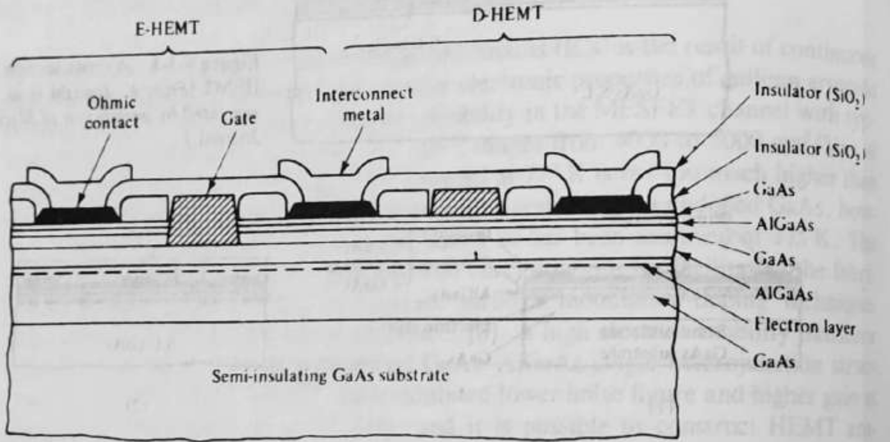

Figure 6-3-3 Cross-sectional view of a DCFL HEMT. (*After M. Abe et al. [9]; reprinted by permission of IEEE, Inc.*)

6-3-2 Operational Mechanism

Since GaAs has higher electron affinity, free electrons in the AlGaAs layer are transferred to the undoped GaAs layer where they form a two-dimensional high-mobility electron gas within 100 Å of the interface. The *n*-type AlGaAs layer of the HEMT is depleted completely through two depletion mechanisms (11):

1. Trapping of free electrons by surface states causes the surface depletion.
2. Transfer of electrons into the undoped GaAs layer brings about the interface depletion.

The Fermi energy level of the gate metal is matched to the pinning point, which is 1.2 eV below the conduction band. With the reduced AlGaAs layer thickness, the electrons supplied by donors in the AlGaAs layer are insufficient to pin the surface Fermi level, and the space-charge region is extended into the undoped GaAs layer. As a result, band bending is moving upward and the two-dimensional electron gas (2-DEG) does not appear. When a positive voltage higher than the threshold voltage is applied to the gate, electrons accumulate at the interface and form a two-dimensional electron gas.

The electron concentration can control D-(depletion-mode) and E-(enhancement-mode) HEMT operations. As temperature decreases, electron mobility, which is about 8000 cm²/V · s at 300° K, increases dramatically to 2×10^5 cm²/V · s at 77° because of reduced phonon scattering. When the temperatures decrease further, the electron mobility of 1.5×10^6 cm²/V · s at 50°K and 2.5×10^6 cm²/V · s at 4.5°K have been demonstrated.

6-3-3 Performance Characteristics

High electron mobility transistor (HEMT) amplifiers for 40 to 70 GHz have been constructed. The 60-GHz amplifier exhibited a gain of 4.5 to 6.5 dB across the frequency band 56 to 62 GHz, and had an associated noise figure of 6 dB measured at 57.5 GHz. The 72-GHz amplifier achieved a gain of 4 to 5 dB with a bandwidth of 2.5 GHz [11].

Current–voltage (*I–V*) characteristics. The drain current can be evaluated from the following basic equation

$$I_{ds} = qn(z)Wv(z) \tag{6-3-1}$$

where q = electron charge
$n(z)$ = concentration of the two-dimensional electron gas.
W = gate width
$v(z)$ = electron velocity

Figure 6-3-4 shows the *I-V* characteristics of a HEMT amplifier with $W = 150\ \mu\text{m}$ and L_g (gate length) = 0.6 μm at 30 GHz.

The major advantages of a HEMT are higher frequency, lower noise, and higher speed. Table 6-3-1 compares HEMT data with other semiconductor electronic devices.

Example 6-3-1: Current of a HEMT

A HEMT has the following parameters:

Gate width:	$W = 150\ \mu\text{m}$
Electron velocity:	$v(z) = 2 \times 10^5$ m/s
Two-dimensional electron-gas density:	$n(z) = 5.21 \times 10^{15}\ \text{m}^{-2}$

Determine the drain current of the HEMT.

Solution From Eq. (6-3-1), the drain current is

$$\begin{aligned} I_{ds} &= qn(z)Wv(z) \\ &= 1.6 \times 10^{-19} \times 5.21 \times 10^{15} \times 150 \times 10^{-6} \times 2 \times 10^5 \\ &= 25\ \text{mA} \end{aligned}$$

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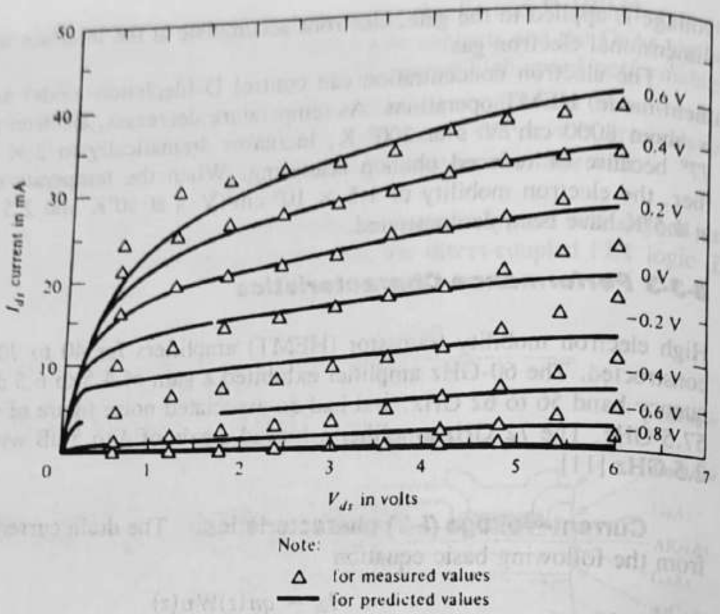

Figure 6-3-4 *I-V* characteristics of a HEMT.

TABLE 6-3-1 HEMT PERFORMANCE COMPARED WITH OTHER DEVICES

Device	Frequency (GHz)	Noise	Power	Speed
HEMT	Up to 70	Very Good	Very Good	Excellent
GaAs MESFET	40	Good	Good	Good
GaAs–AlGaAs HBT*	20	Good	Good	Excellent
Si MOSFET	10	Poor	Very good	Very poor
Si bipolar transistor	1	Poor	Poor	Good

*HBT = heterojunction bipolar transistor

Equivalent circuit. In order to predict or calculate the values for a small- or large-signal HEMT amplifier, the following high-frequency equivalent circuit, shown in Fig. 6-3-5, may be useful.

It is difficult to compare the optimized performance of most major semiconductor devices. The switching delay time of GaAs MESFETs is two or three times longer than that of HEMTs. The GaAs–AlGaAs heterojunction bipolar transistor (HBT) can achieve the same high-speed performance as the HEMT. The ultimate speed capability, limited by cutoff frequency f_T, is more than 100 GHz, and the HBT also has the merit of flexible fan-out loading capability. The silicon MOSFET and the bipolar transistor have excellent performance in threshold voltage uniformity and controllability with no material problems, and they are easy to fabricate despite complex processing steps. HEMTs are very promising devices for high-speed, very large-scale integration (VLSI) with low-power dissipation, but they require new

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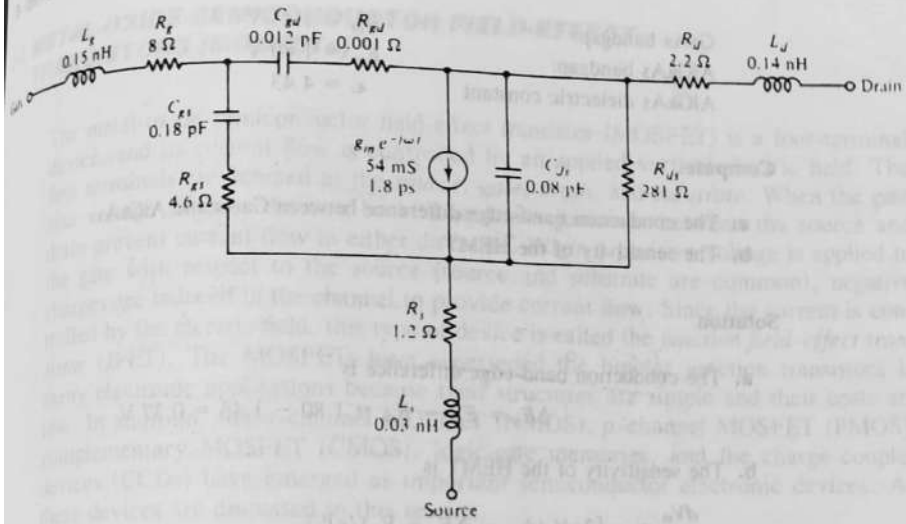

Figure 6-3-5 Equivalent circuit of a HEMT.

technological breakthroughs to achieve the large-scale integration (LSI) quality of GaAs–AlGaAs material. Such technologies include molecular-beam epitaxy (MBE), organic metal-vapor phase epitaxy (OMPVE), and self-alignment device fabrications. The excellent controllability of MBE growth can regulate the ratio of standard deviation of threshold voltage to the logic voltage swing.

The vertical threshold sensitivity is defined by the differential threshold voltage to the thickness of the $Al_xGa_{1-x}As$ layer and is expressed as

$$\frac{dV_{th}}{d\ell} = -[2qN_d(\psi_{ms} - \Delta E_c - V_{th})/\epsilon]^{1/2} \qquad (6\text{-}3\text{-}2)$$

where V_{th} = threshold voltage in volts
ℓ = AlGaAs layer thickness in meters
q = electron charge
N_d = donor concentration
ψ_{ms} = metal-semicondcutor Schottky barrier potential between Al and GaAs
E_c = conduction bandedge difference between GaAs and AlGaAs
$\epsilon = \epsilon_o\epsilon_r$ is the permittivity of AlGaAs
ϵ_r = dielectric constant of AlGaAs

Example 6-3-2: Sensitivity of HEMT

A HEMT has the following parameters:

Threshold voltage:	$V_{th} = 0.13$ V
Donor concentration:	$N_d = 2 \times 10^{24}$ m^{-3}
Metal-semiconductor Schottky barrier potential:	$\psi_{ms} = 0.8$ V

GaAs bandgap: $E_{gg} = 1.43$ V
AlGaAs bandgap: $E_{ga} = 1.80$ V
AlGaAs dielectric constant $\epsilon_r = 4.43$

Compute:

a. The conduction band-edge difference between GaAs and AlGaAs
b. The sensitivity of the HEMT

Solution

a. The conduction band-edge difference is

$$\Delta E_c = E_{ga} - E_{gg} = 1.80 - 1.43 = 0.37 \text{ V}$$

b. The sensitivity of the HEMT is

$$\begin{aligned}\frac{dV_{th}}{d\ell} &= -[2qN_d(\psi_{ms} - \Delta E_c - V_{th})/\epsilon]^{1/2}\\ &= -[2 \times 1.6 \times 10^{-19} \times 2 \times 10^{24}(0.80 - 0.37\\ &\qquad\qquad - 0.13)/(8.854 \times 10^{-12} \times 4.43)]^{1/2}\\ &= -\left[\frac{0.49 \times 10^{4}}{10^{-12}}\right]^{1/2} = -70 \text{ mV/nm}\end{aligned}$$

$$\left|\frac{dV_{th}}{d}\right| = 70 \text{ mV/nm}$$

6-3-4 Electronic Applications

The switching speed of a HEMT is about three times as fast as that of a GaAs MESFET. The largest-scale logic integrated circuit (IC) with HEMT technology has achieved the highest speed ever reported among 8 × 8 bit multipliers. The switching delay time of a HEMT is below 10 picosecond with a power dissipation reported at about 100 μW. Therefore, HEMTs are promising devices for very large-scale integration, especially in very high-speed supercomputers, star wars, and space communications.

Information processing in the 1990s will require ultrahigh-speed computers, having high-speed large-scale integration circuits with logic delays in the subhundred-picosecond range. A 4K × 1 bit static random-access memory (SRAM) device consists of a memory cell of 55 μm × 39 μm. Its normal read-write operation was confirmed both at 300° K and 77° K. The minimum address access time obtained was 2.0 nanosecond with a chip dissipation power of 1.6 W and a supply voltage of 1.54 V. The HEMT SRAMs have demonstrated better performance than the SiMOS, BJT, and GaAs MESFET SRAMs.