# 7.1 Microwave Transistors, Amplifiers

## Module:7 Microwave Active Circuits

### Course: BECE305L – Antenna and Microwave Engineering

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# Module:7 Microwave Active Circuits 4 hours

- Microwave transistors, Microwave amplifiers: Two port power gains, stability of the amplifier, Microwave oscillators

- Source of the contents: Pozar

# 1.1 Microwave transistors: Advantages

- Previously: klystron, TWT, tunnel diodes and varactor diodes in microwave amplifiers
- After magnetrons, reflex klystrons, Gunn and IMPATT diodes, microwave transistors are mostly used in solid-state sources over a wide frequency range with medium power.

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- **Microwave transistors in amplifier design**
  - are rugged,
  - low-cost,
  - reliable, and
  - can be easily integrated in MICs.
  - up to about 100 GHz with low-noise figure,
  - broad bandwidth and
  - medium power output.

# 1.2 Limitations of ordinary transistors

- **Ordinary transistors are npn or pnp junction transistors**—bipolar and unipolar FET.
- High **frequency operation of these devices is limited** by
  (1) **diffusion capacitance** at base-emitter junction,
  (2) **space charge capacitances** at base-emitter and base-collection junction,
  (3)

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# 1.3 Microwave transistors

- **Microwave transistors are miniaturized designs**
  a) **to reduce device and package parasitic capacitances** and **inductances**
  b) to **overcome the finite transit time of the charge carriers** in the semiconductor materials.
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- The most commonly used semiconductors are Si and GaAs.
- Transit times are dependent on the electron mobility and saturation velocity in the semiconductor material.
- **GaAs is better than Si** for high frequency devices because of its **higher electron mobility and saturation velocity** compared with Si.
- **Si-bipolar has advantage over GaAs** due to inexpensive, durable, higher gain and moderate noise characteristics.
- By means of **molecular beam epitaxy techniques**, the **High Electron Mobility Transistors (HEMT)** are developed presently which can operate at frequencies of the order of 100 GHz.

# 1.4 Categories of Microwave Transistors:

(1) **low-noise transistor** which is employed at the front end, since this is the **major determinant of the overall system noise**,

(2) **low-level transistor** which is used to drive power stage, and

(3) **power transistor** which amplifies final power output.

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Microwave transistor amplifiers are constructed either as

a) **hybrid Microwave Integrated Circuits (MIC)** where the **transmission lines** and **matching networks** are realized by microstrip circuit elements and **the discrete components** such as chip capacitors, resistors, and transistors are soldered in place, or as

b) **Monolithic Microwave Integrated Circuits (MMIC)** where all active devices and passive circuit elements are fabricated on a single semiconductor (GaAs) crystal

# 1.5 Construction of microwave transistors

- **Bipolar** is a three-semiconductor n-p-n region junction structure where **charge carriers of both negative (electrons) and positive (holes) polarities** are involved in transistor operation.
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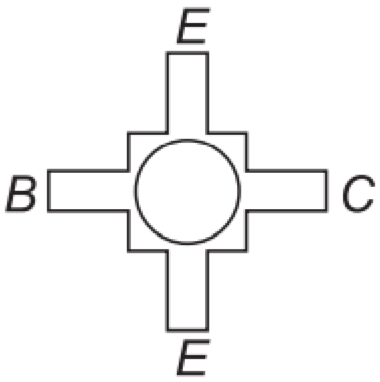
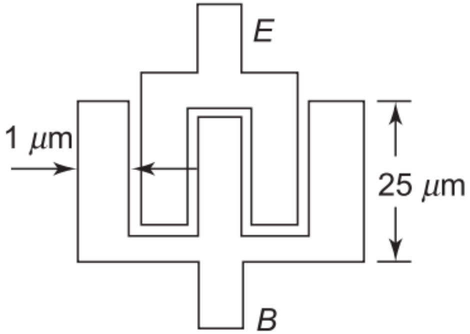
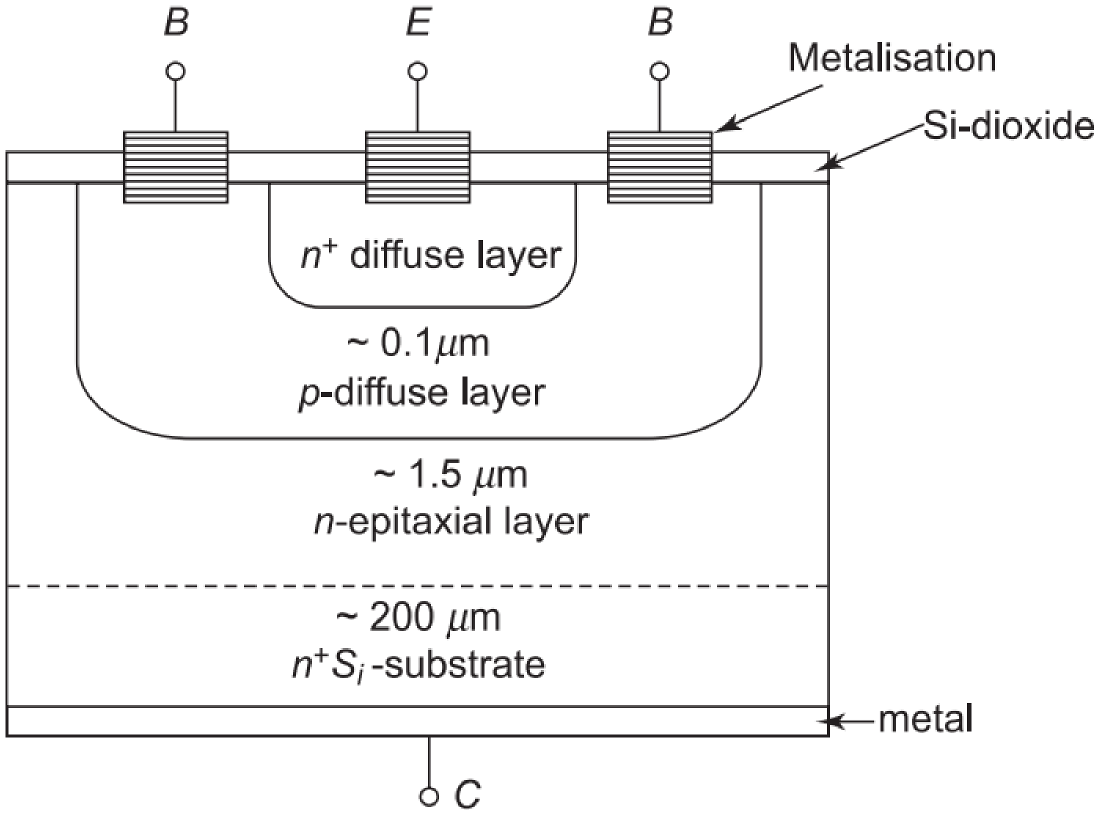
- **Unipolar** transistors are junction gate and insulated gate field-effect transistors (FETs)
- These are **one or two semiconductor region structures** where **dominant carriers are of single polarity** (electrons or holes)
- Si-bipolar for UHF-S band, and Si bipolar/ GaAs FET

# 2.1 Microwave Bipolar (junction) transistor (BJT)

- planar in form and mostly Si n-p-n type operating up to 5 GHz.
- GaAs also is used for **performance improvements in the operating frequency**, **<u>in high temperatures</u>**, and in **<u>high radiation field</u>**.



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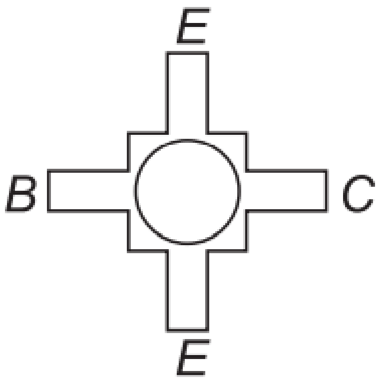
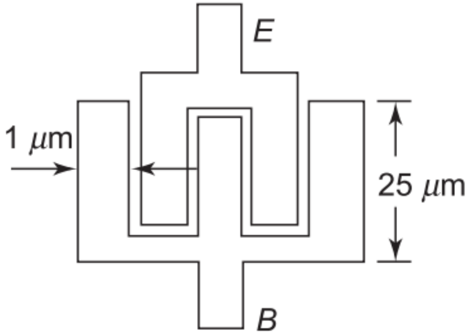
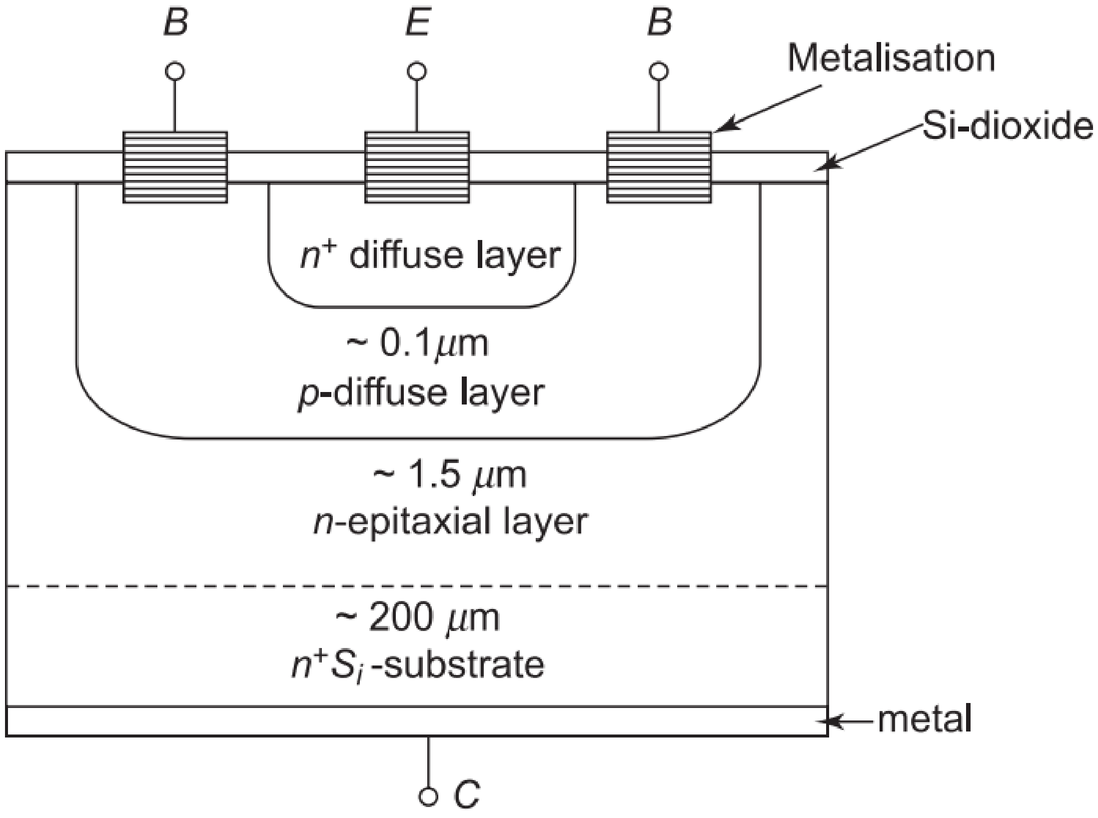
  **Geometries of these devices** are
  (a) inter-digitated,
  (b) overlay, and
  (c) matrix forms with wide emitter area to overcome transit time limitations.



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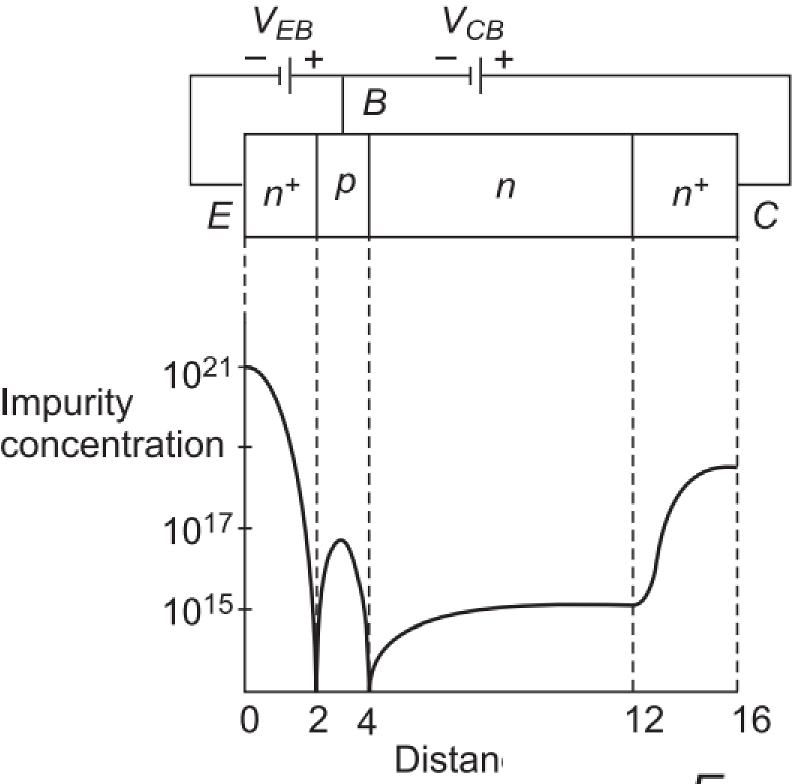
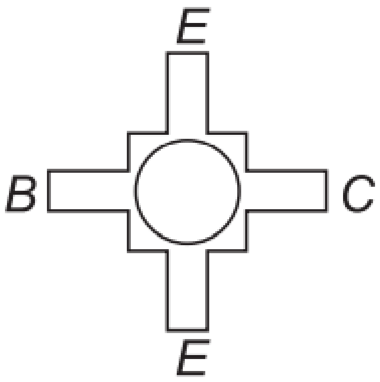
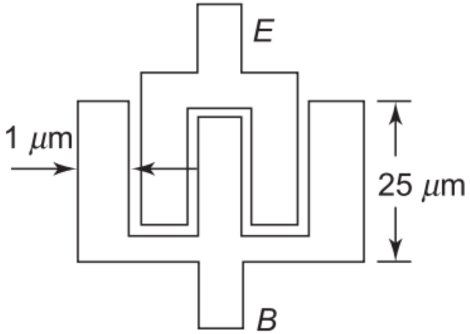
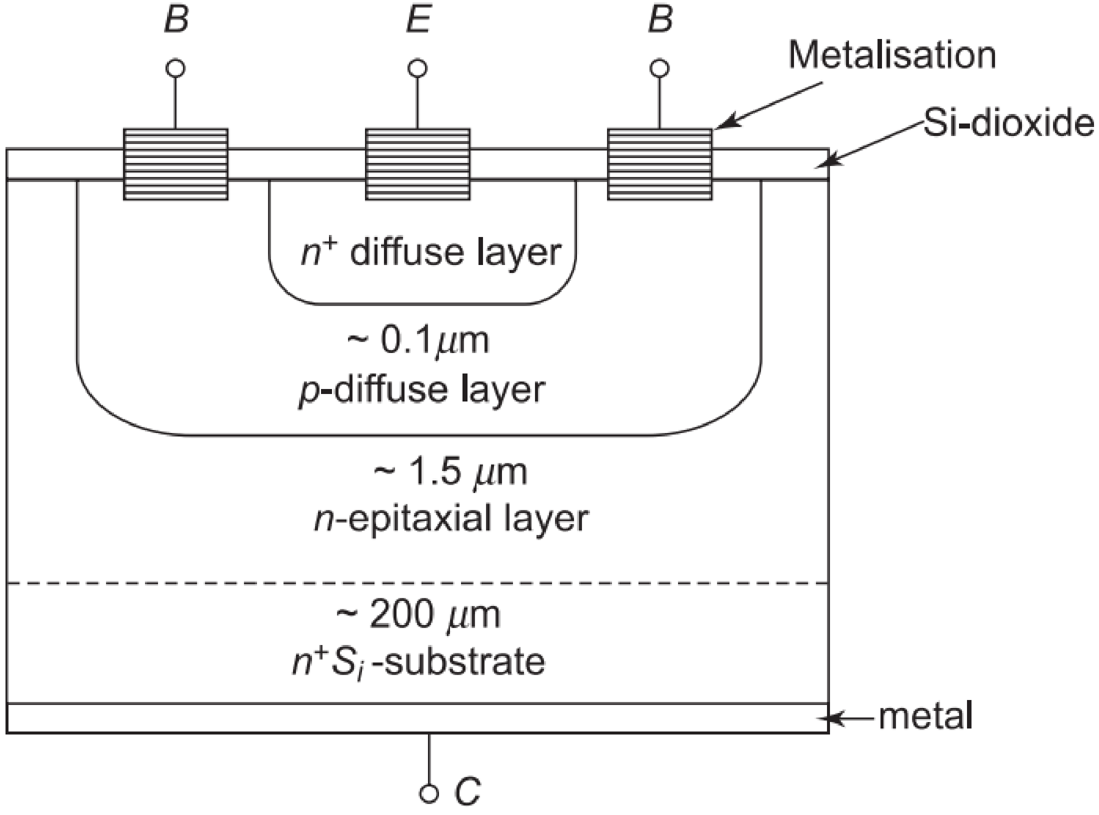


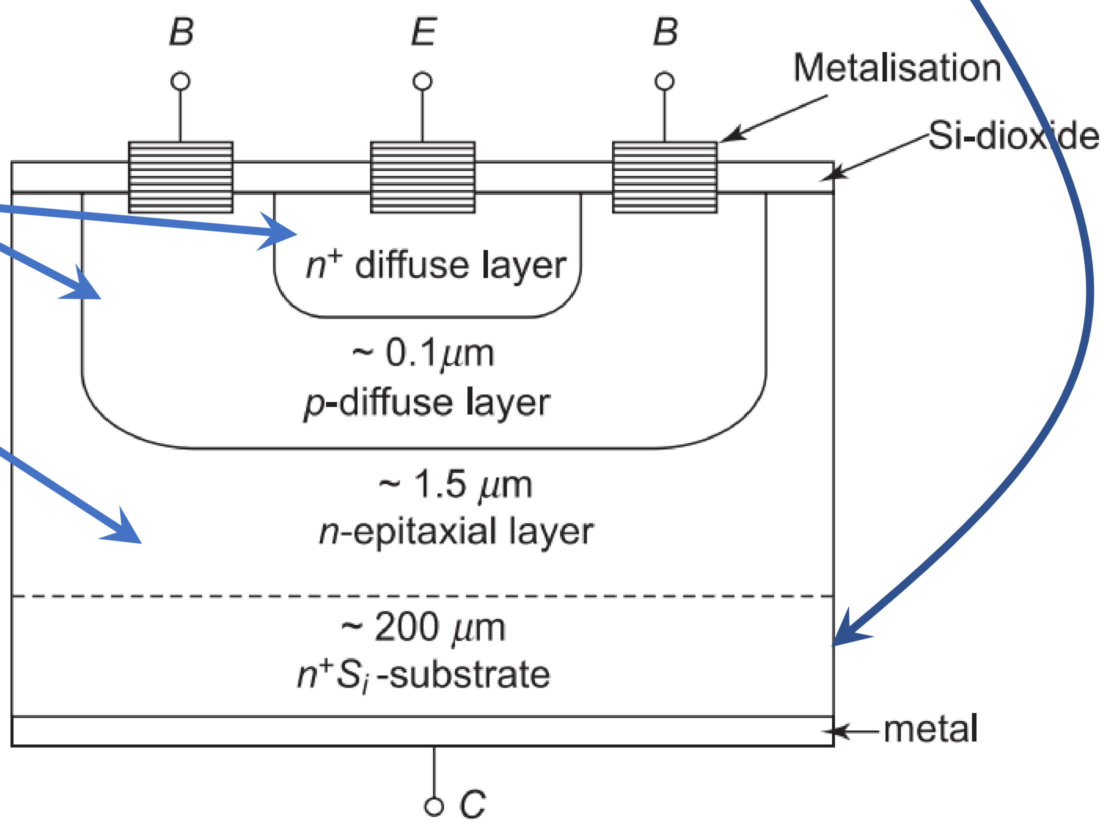



# 2.1 Microwave Bipolar (junction) transistor (BJT)

- Epitaxial n layer is formed by **condensing a single crystal film of semiconductor material** upon a **low resistivity Si wafer** of substrate n+ .
- Above this, a **p-type diffused base** and **n+ -type diffused emitter** are formed.



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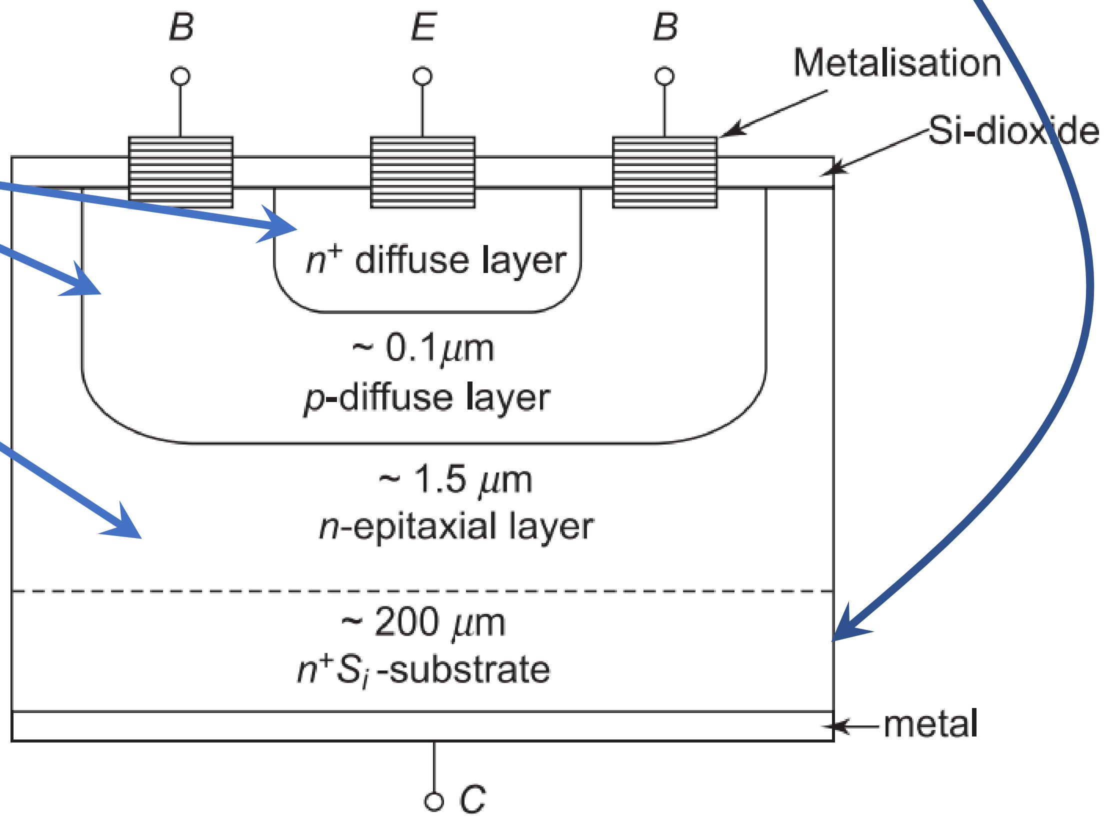
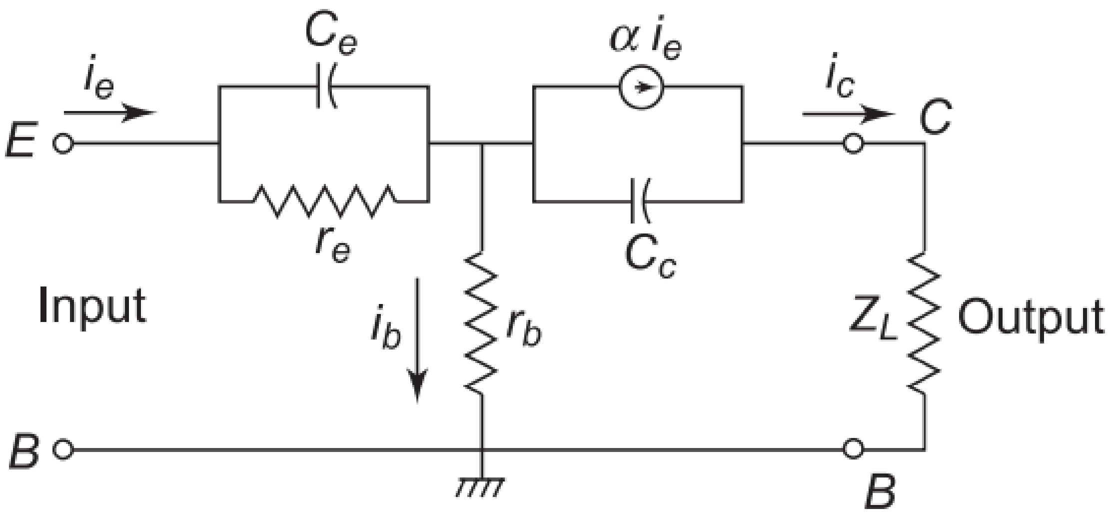
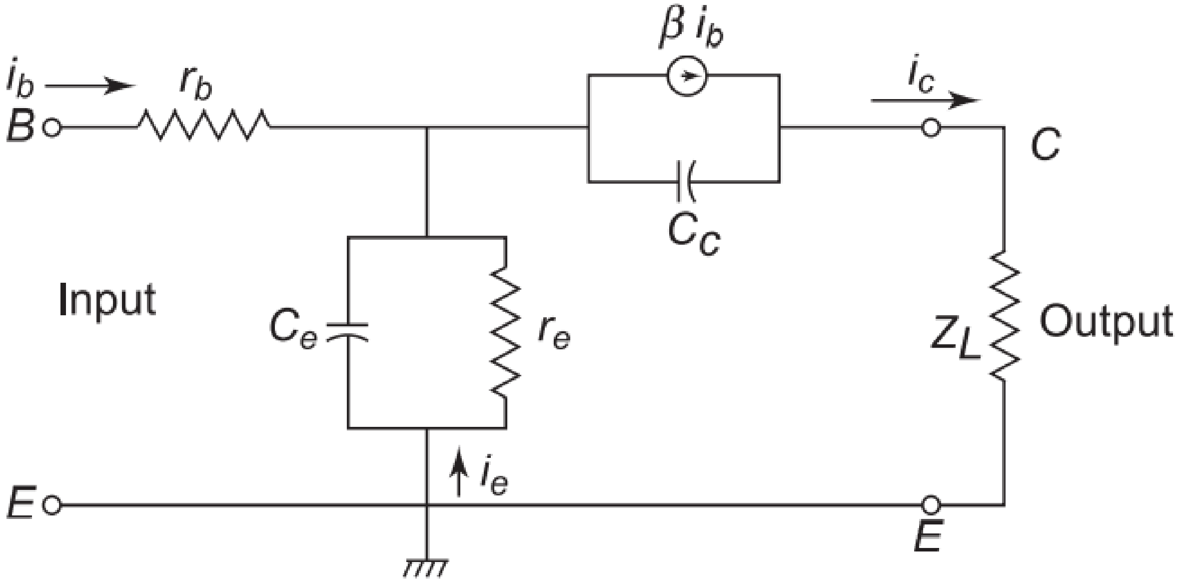
- Typically the emitter width W is 1 micron, base thickness is 2 microns and emitter length is 25 microns.
- The packaging is done with minimum beam leads to reduce inductance.



# 2.2 Microwave (BJT): Modes of operation



*CB*-mode



*CE*-mode

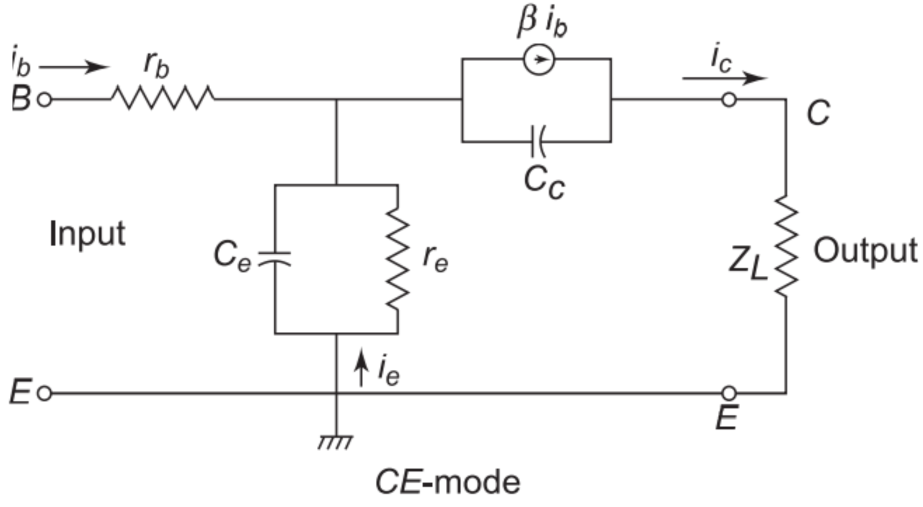
# 2.2 Microwave (BJT): Modes of operation

$T_{jeb}$ = Emitter-base junction capacitance charging time

$T_b$ = Base region transit time

$T_{bc}$ = Base collector-region depletion-layer transit time

$T_{jbc}$ = Base collector junction capacitance charging time

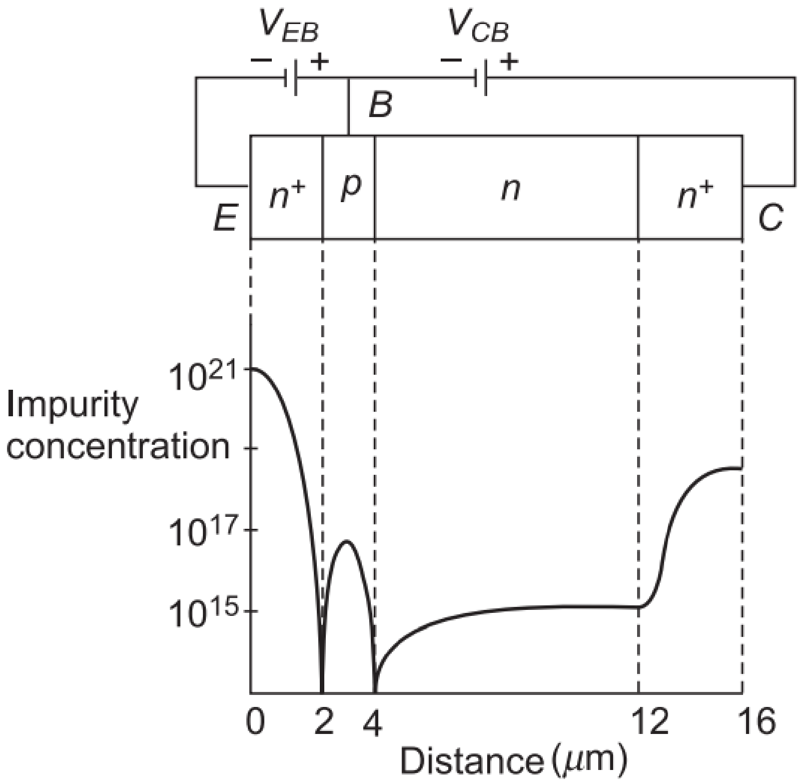


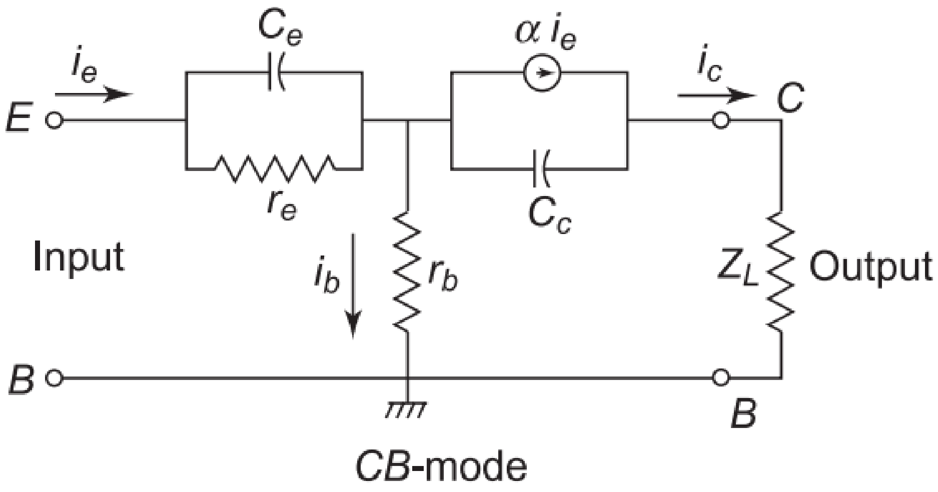

- Upper frequency limit

current gain ≈ 1

$$f_T = 1/(2\pi T)$$

$$T = T_{jeb} + T_b + T_{bc} + T_{jbc}$$
$$\approx T_b + T_{bc}$$



# 2.3 Microwave (BJT): Power limitation

- for a given device impedance, **the power capacity of the transistor decreases with increase in the device cut-off frequency**

$$(P_m X_c)^{1/2} f_T = E_m v_s / 2\pi$$

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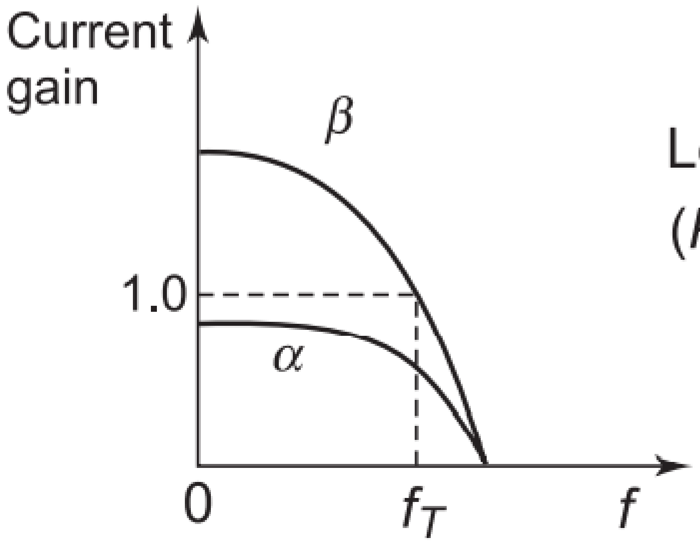
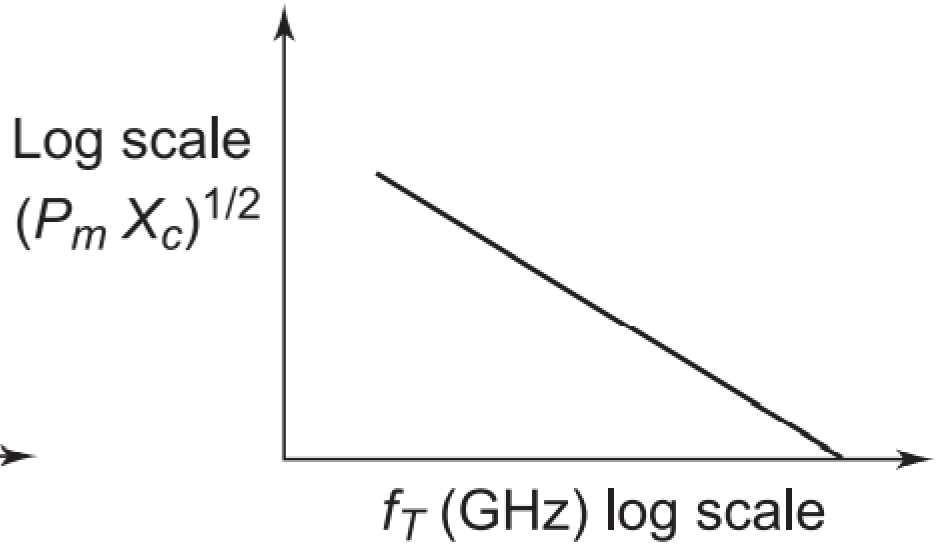
- Where $P_m$: Maximum power
  $f_T$: Device Cutoff frequency
  $E_m$: Maximum E field that can be sustained in a semiconductor without having dielectric breakdown
  $v_s$: Maximum saturated drift velocity of carriers in semiconductor



2.4 Example: An Si microwave transistor has reactance of 1 ohm, transit time cut-off frequency of 4 GHz, maximum E-field $1.6 \times 10^5$ V/m and saturation drift velocity $4 \times 10^5$ m/s. Determine the maximum allowable power.

- $P_m = 6.48\, watts$

$$(P_m X_c)^{1/2} f_T = E_m v_s / 2\pi$$

# 3.1 Microwave Unipolar Transistors

- Field-effect transistors manufactured from semiconductors incorporating gallium or indium which have better high-frequency performance due to the higher electron mobility compared to Si.
- Two very commonly used transistors are Metal–Semiconductor Field Effect Transistor (**MESFET**) and High-Electron-Mobility Transistor (**HEMT**)

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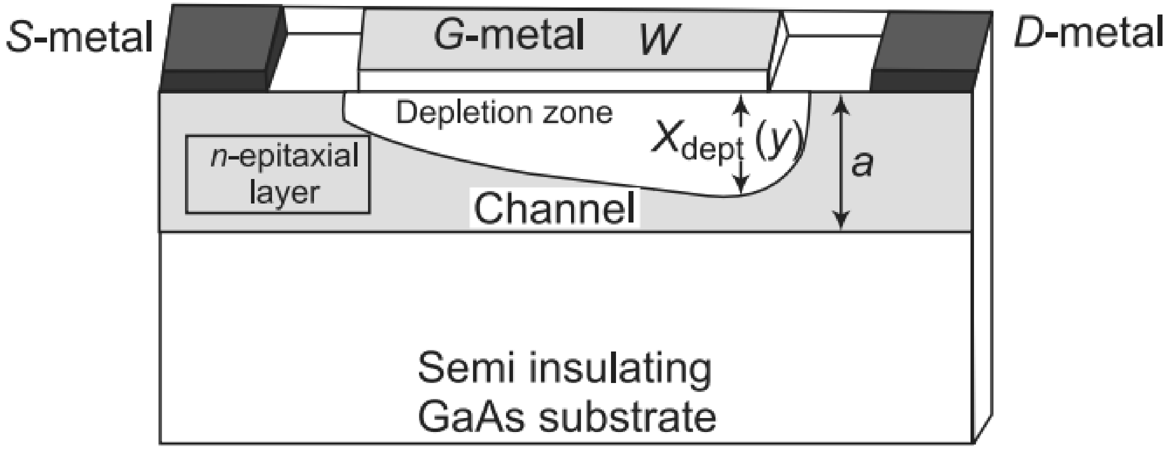
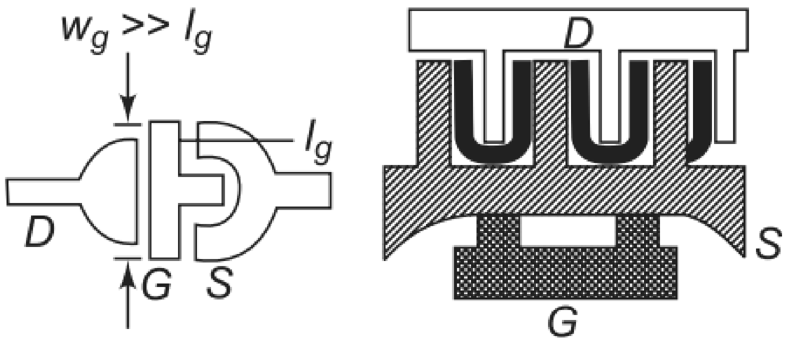
- Two very commonly used transistors are Metal–Semiconductor Field Effect Transistor (**MESFET**) and High-Electron-Mobility Transistor (**HEMT**)
- Since **only one type of carriers (n or p electrons) are responsible for the operation of the device**, these devices are called **unipolar**.
- MESFET: 2–20 GHz range and give a single gain of 10-15 dB at 2 GHz with noise figure less than 1 dB

# 3.2 MESFET (Metal-Semiconductor Field Effect Transistor)

- three terminals—source(S), gate (G), and drain (D)

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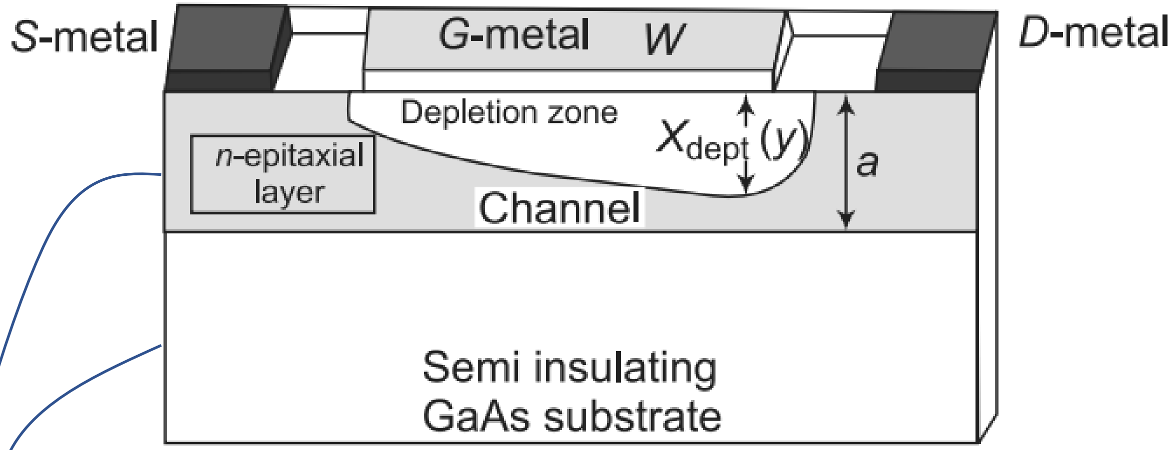


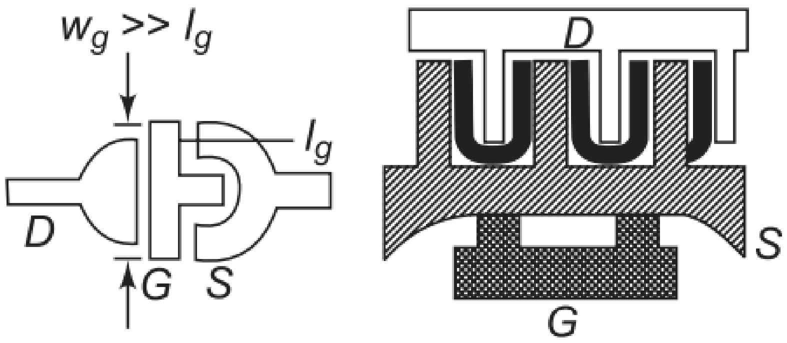


- A Schottky (metal-semiconductor) junction is used for a gate instead of normal p-n junction.
- **constructed using GaAs and InP semiconductors**.
- **conducting n-type semiconductor channel** positioned between a source and drain contact region

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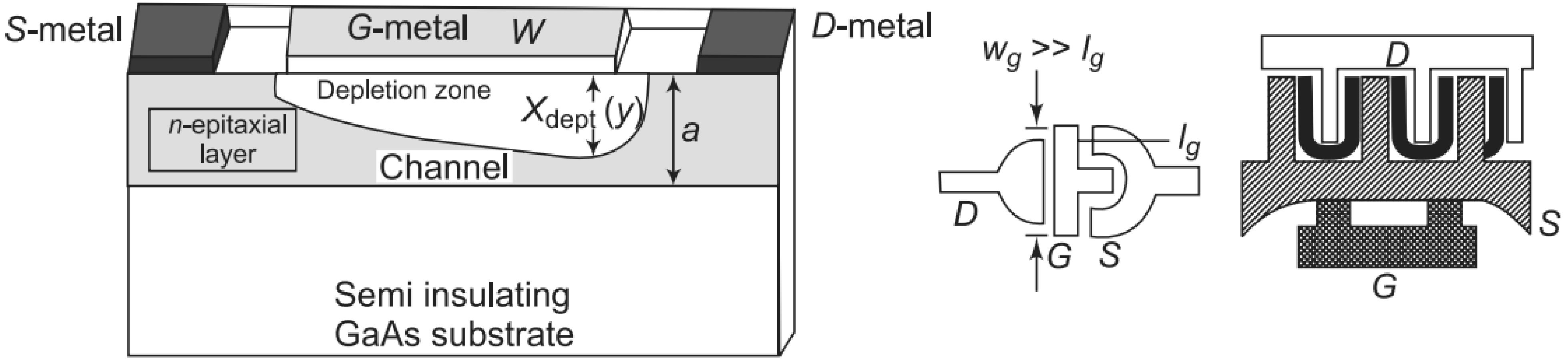


- substrate is a semi-insulating material (GaAs doped with chromium) with resistivity about $10^8$ ohm-cm

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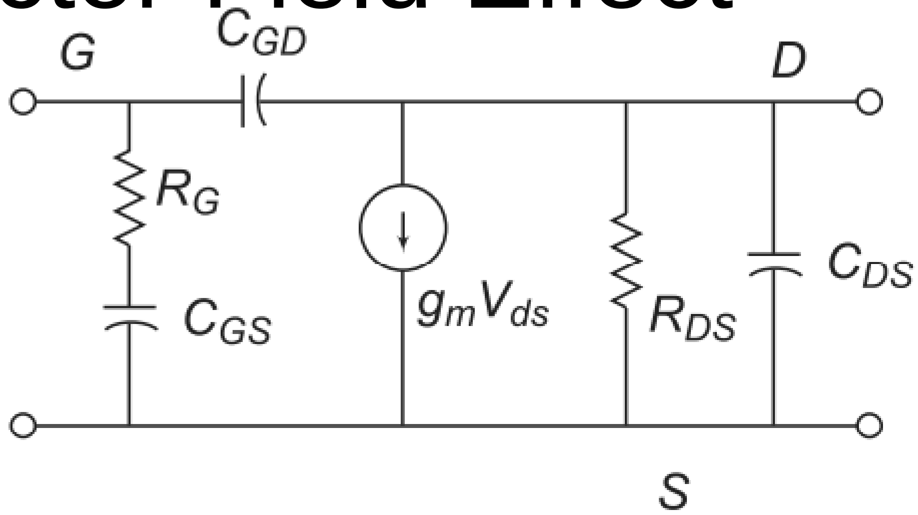


- over the gate length L, $v_d$ is the saturation drift velocity in the channel

$$\text{Transit time } \tau = \frac{L}{v_d}$$

$$R_{DS} = \text{Drain to source resistance}$$

$$g_m = \text{Transconductance of the MESFET}$$

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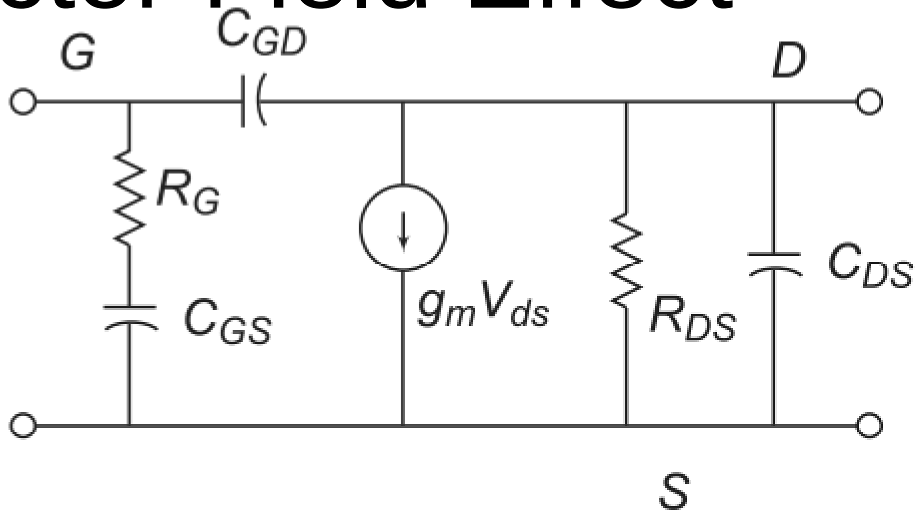


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- The **cut-off frequency of operation**: the frequency $\boldsymbol{f_c}$ at which the current through $C_{GS}$ is equal to that of the equivalent current generator $g_m V_{ds}$ in the intrinsic FET, given by

$$f_c = \frac{g_m}{2\pi C_{GS}} = \frac{1}{2\pi\tau} = \frac{v_d}{2\pi L}$$

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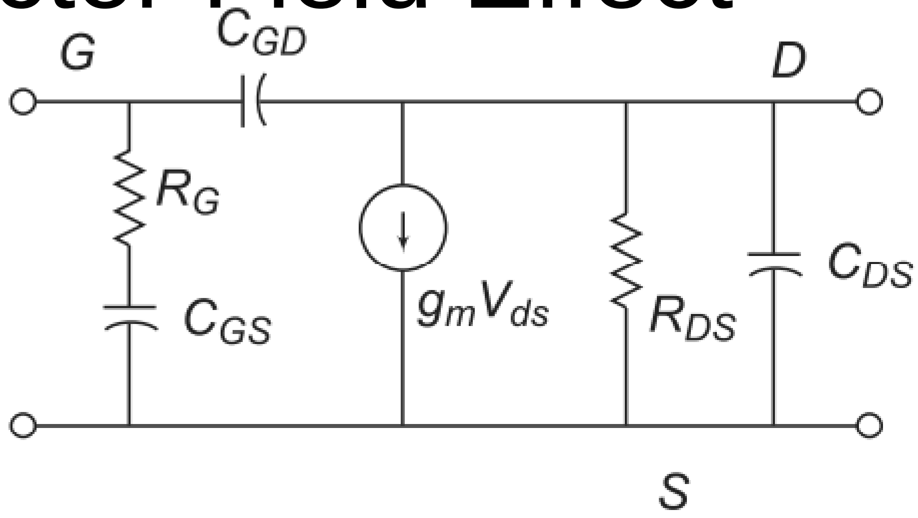


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- The maximum frequency of oscillation for maximum power gain with matched terminated circuit is

$$f_{\max} = \frac{f_c}{2}(R_{DS})$$

# 3.2.1 MESFET: Advantage

- The basic advantage of GaAs MOSFETs are
  (i) high power,
  (ii) low noise,
  (iii) broadband performance, and
  (iv) compatibility to MICs.
  The carrier (electron) flow from source to drain is controlled by a Schottky metal gate.

# 3.2.2 MESFET: Disadvantage

- The disadvantage of the MESFET structure is the presence of the Schottky metal gate. **It limits the forward bias voltage on the gate to the turn-on voltage of the Schottky diode**.
- The threshold voltage, therefore, must be lower than this turn-on voltage.
- more difficult to fabricate circuits containing a large number of enhancement-mode MESFET.