

**METAL SEMICONDUCTOR FIELD  
EFFECT TRANSISTORS**

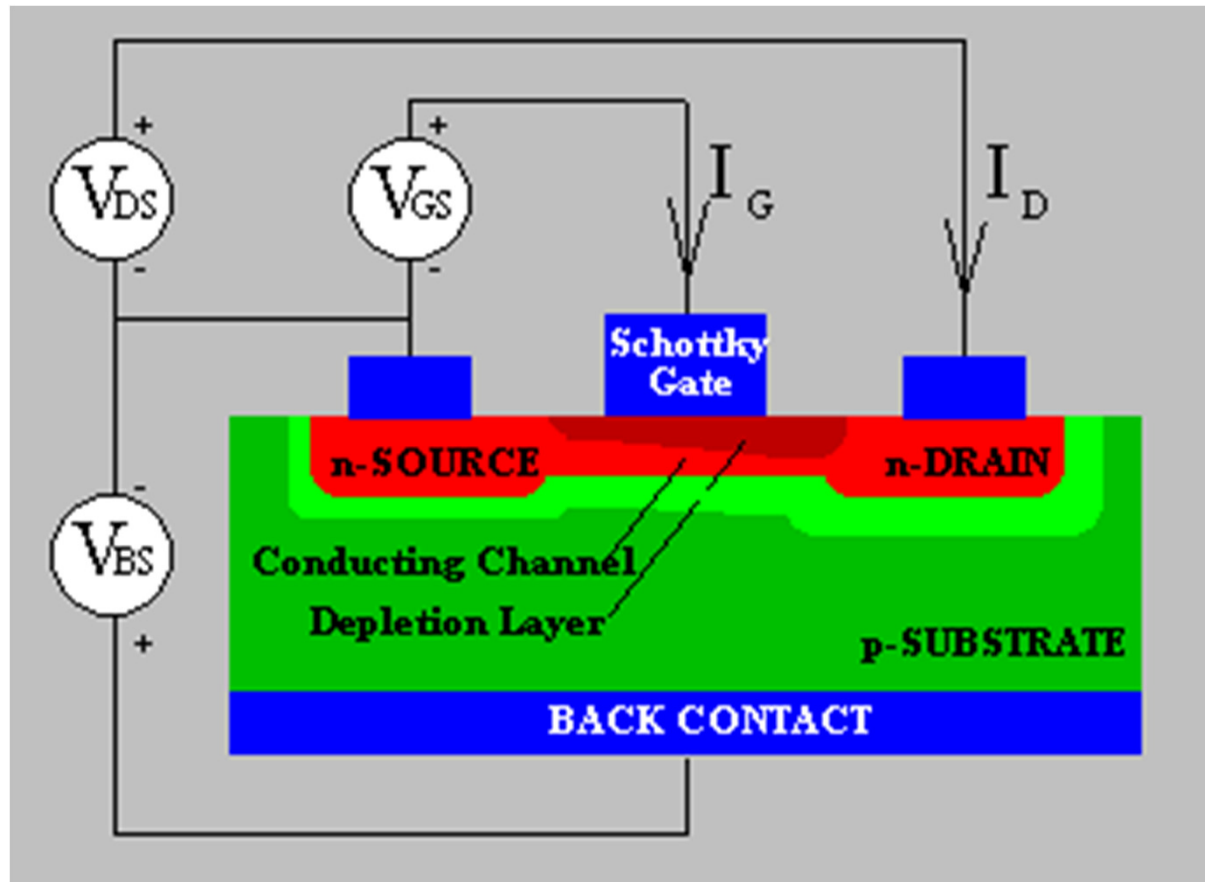
**MESFET**

# MESFET



- MESFET = Metal Semiconductor Field Effect Transistor = **Schottky gate FET**.
- The MESFET consists of a conducting channel positioned between a source and drain contact region.
- The carrier flow from source to drain is controlled by a **Schottky metal gate**.
- The control of the channel is obtained by varying the depletion layer width underneath the metal contact which modulates the thickness of the conducting channel and thereby the current.

# MESFET



# MESFET



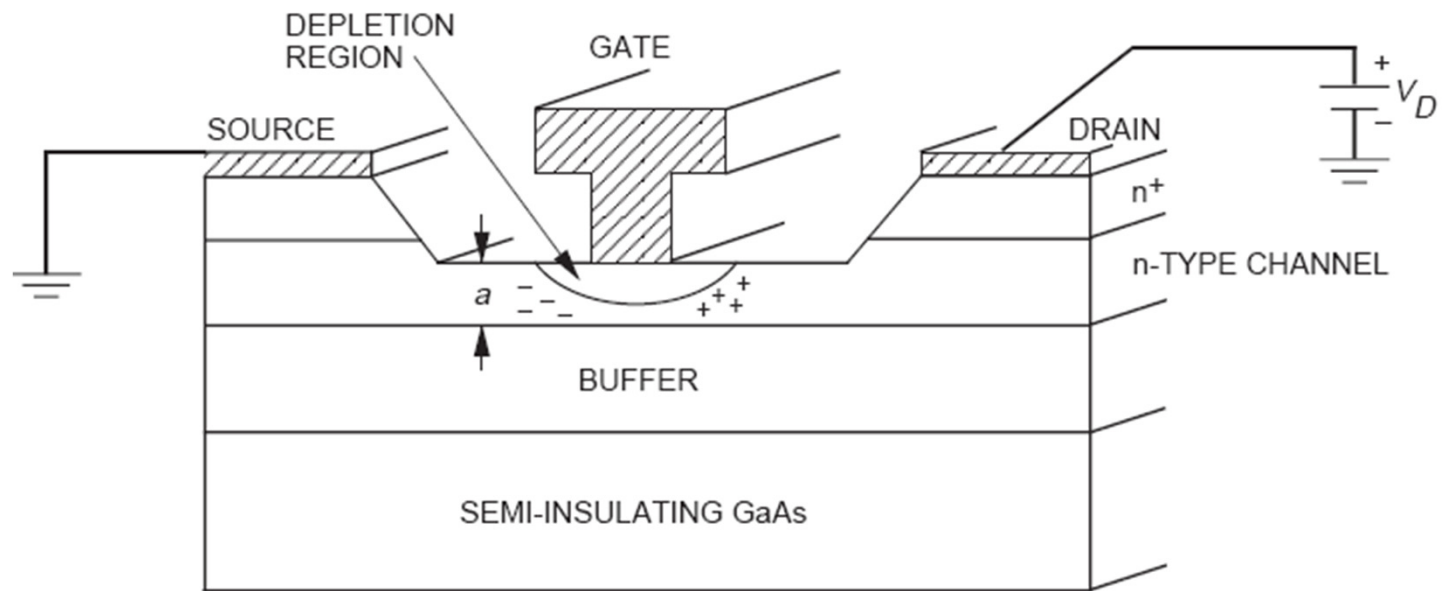
- The key advantage of the MESFET is the higher mobility of the carriers in the channel as compared to the MOSFET.
- The disadvantage of the MESFET structure is the presence of the Schottky metal gate.
- It limits the forward bias voltage on the gate to the turn-on voltage of the Schottky diode.
- This turn-on voltage is typically 0.7 V for GaAs Schottky diodes.
- The threshold voltage therefore must be lower than this turn-on voltage.
- As a result it is more difficult to fabricate circuits containing a large number of enhancement-mode MESFET.

# Basic Structure



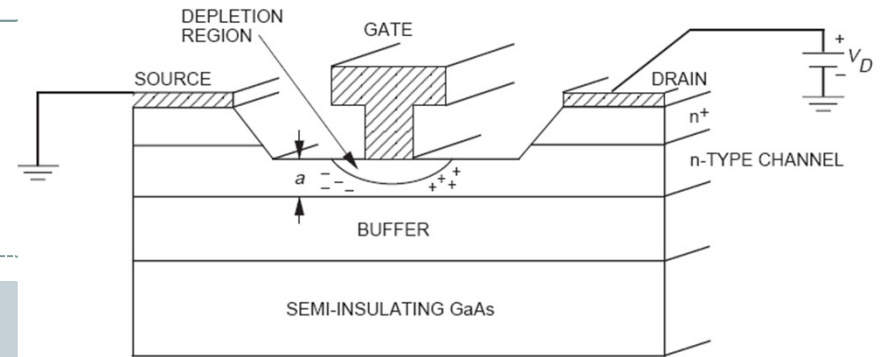
- GaAs MESFETs are the most commonly used and important active devices in microwave circuits.
- In fact, until the late 1980s, almost all microwave integrated circuits used GaAs MESFETs.
- Although more complicated devices with better performance for some applications have been introduced, the MESFET is still the dominant active device for **power amplifiers and switching circuits in the microwave spectrum.**

# Basic Structure



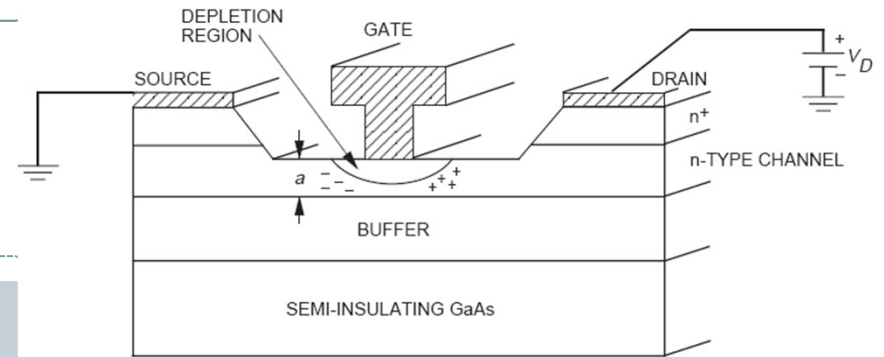
Schematic and cross section of a MESFET

# Basic Structure



- The base material on which the transistor is fabricated is a GaAs substrate.
- A buffer layer is epitaxially grown over the GaAs substrate to isolate defects in the substrate from the transistor.
- The channel or the conducting layer is a thin, lightly doped (n) conducting layer of semiconducting material epitaxially grown over the buffer layer.
- Since the electron mobility is approximately 20 times greater than the hole mobility for GaAs, the conducting channel is always n-type for microwave transistors.

# Basic Structure

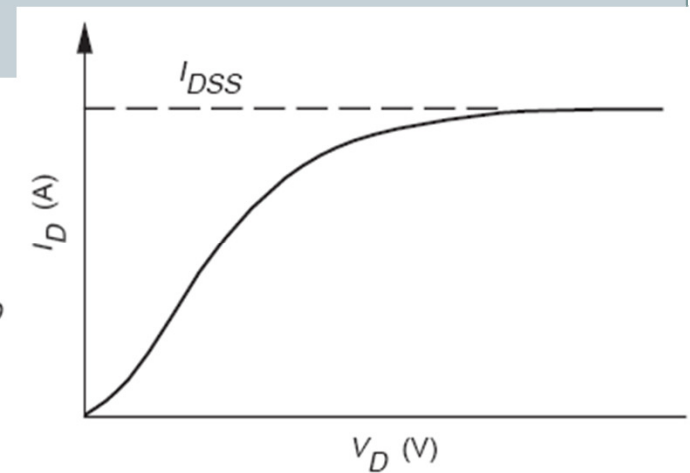
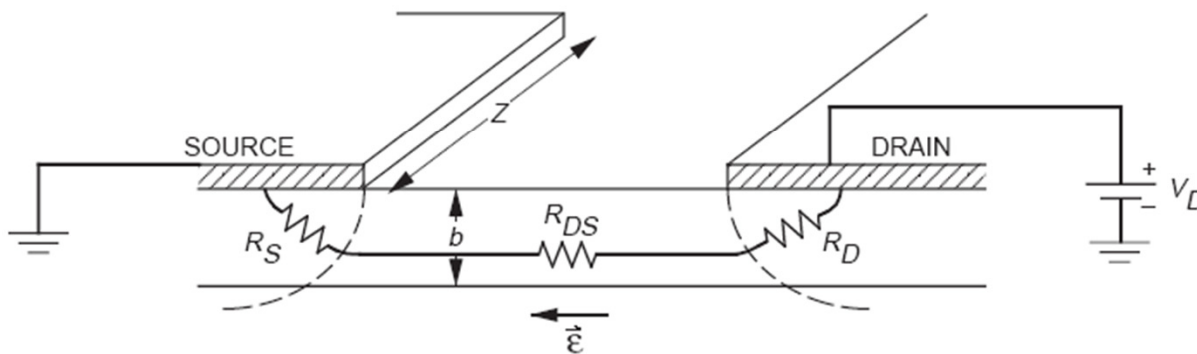


- Finally, a highly doped (n<sup>+</sup>) layer is grown on the surface to aid in the fabrication of low-resistance **ohmic contacts** to the transistor.
- This layer is etched away in the channel region.
- Alternatively, ion implantation may be used to create the n channel and the highly doped ohmic contact regions directly in the semi-insulating substrate.
- Two ohmic contacts, the **source** and **drain**, are fabricated on the highly doped layer to provide access to the external circuit.
- Between the two ohmic contacts, a rectifying or **Schottky contact** is fabricated.
- Typically, the ohmic contacts are Au–Ge based and the Schottky contact is Ti–Pt–Au.

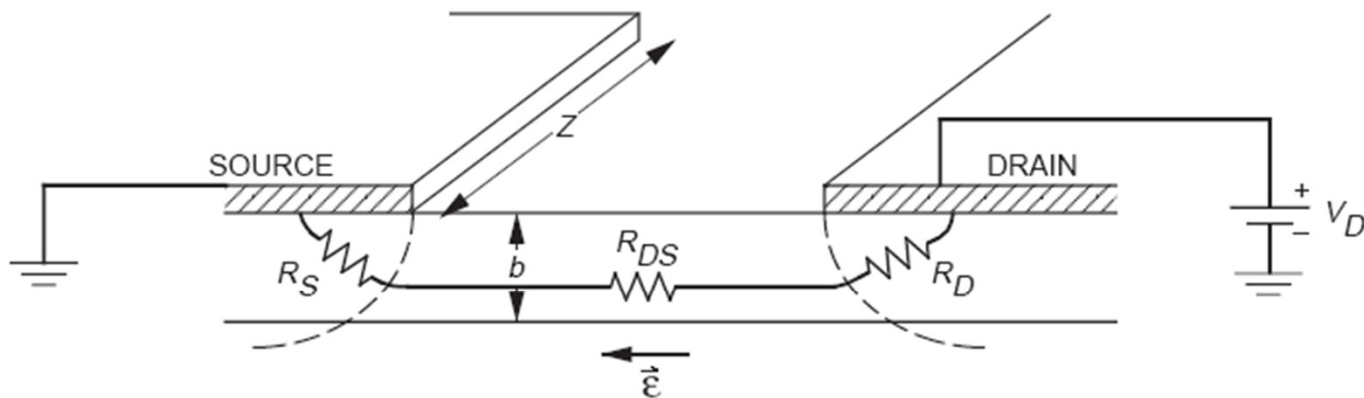


# Basic operation of MESFET

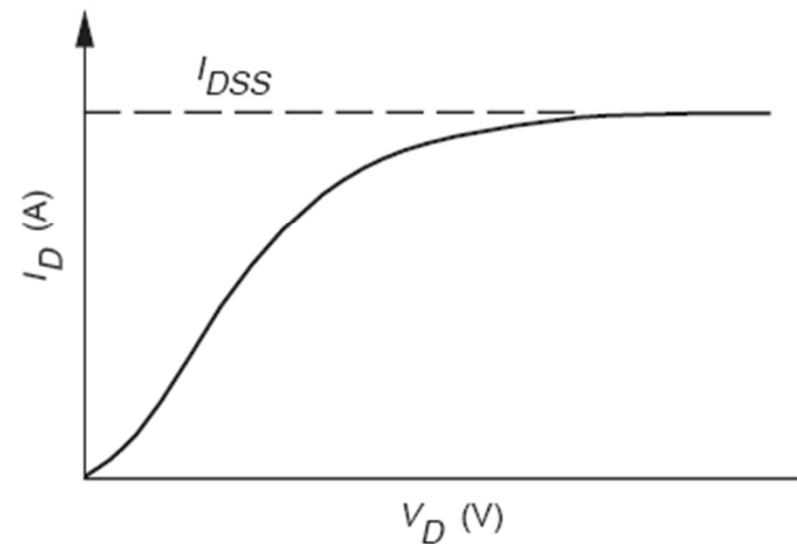
- The basic operation of the MESFET is easily understood by first considering the I–V characteristics of the device without the gate contact, as shown in figure below.
- If a small voltage is applied between the source and drain, a current will flow between the two contacts.
- As the voltage is increased, the current increases linearly with an associated resistance that is the sum of the two ohmic resistances,  $R_S$  and  $R_D$ , and the channel resistance,  $R_{DS}$ .



# Basic operation of MESFET



$$I_D = \frac{V_D}{R_D + R_S + R_{DS}}$$

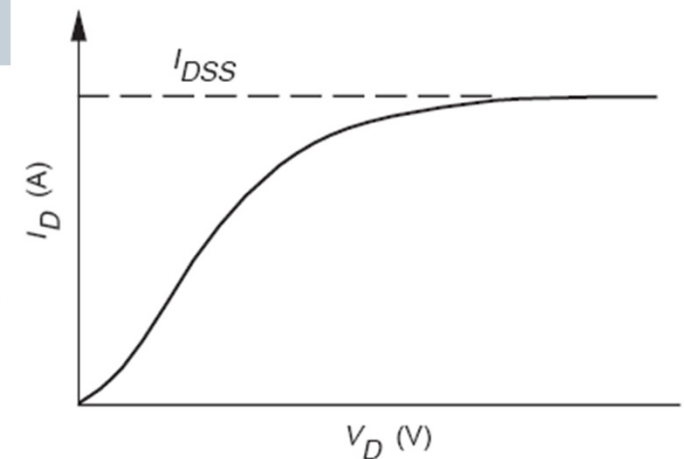
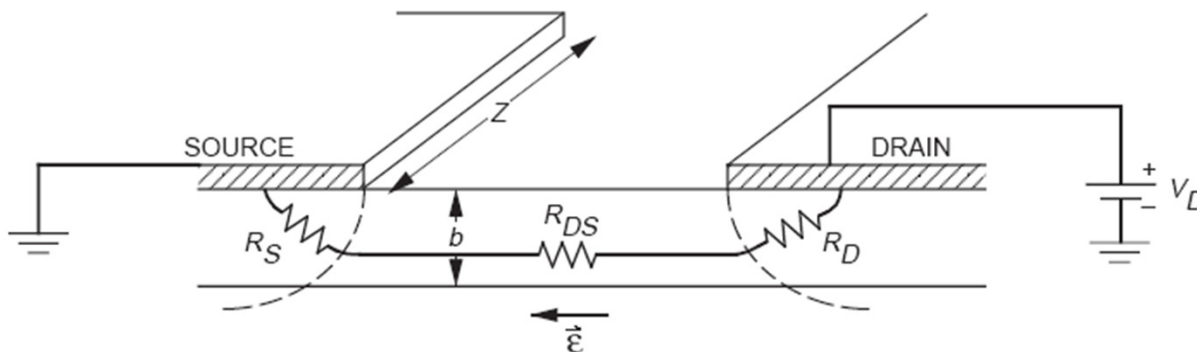


**Schematic and I-V characteristics for an ungated MESFET.**

# Basic operation of MESFET

- If the voltage is increased further, the applied electric field will become greater than the electric field required for saturation of electron velocity.
- Under large bias conditions, an alternative expression for  $I_D$  is useful; this expression relates the current directly to the channel parameters:

$$I_D = Q(x)v(x) = Zb(x)qn(x)v(x)$$



# Basic operation of MESFET



- This expression omits the parasitic resistances,  $R_S$  and  $R_D$ .
- The parameters in equation above are  $Z$ , the width of the channel;  $b(x)$ , the effective channel depth;  $q$ , the electron charge;  $n(x)$ , the electron density; and  $v(x)$ , the electron velocity, which is related to the electric field across the channel.
- Note that if  $v(x)$  saturates,  $I_D$  will also saturate.
- This saturation current is called  $I_{DSS}$ .

# Basic operation of MESFET



- Now consider the effect of the gate electrode placed over the channel but without any gate bias,  $V_G = 0$ .
- A depletion region formed under the gate electrode reduces the effective channel depth,  $b(x)$ , and therefore increases the resistance to current flow under the gate.
- The depletion region depth is dependent on the voltage drop across the Schottky junction.
- Since the current flowing through the channel is equivalent to a current flow through a distributed resistor, there is a larger voltage drop across the drain end of the channel than at the source end.
- This results in the depletion region depth being greater on the drain side of the channel.

# Basic operation of MESFET



- The nonuniform channel depth has **two effects** on the device operation.
- First, there is an **accumulation** of electrons on the source side and a **depletion** of electrons on the drain side of the depletion region.
- This dipole of charge creates a **feedback capacitance** between the drain and the channel; this capacitance is typically called  $C_{DC}$ .
- The second effect is that the electric field due to the dipole adds to the applied electric field causing the **saturation conditions** to occur at a lower  $V_D$ .

# Basic operation of MESFET



- By applying a bias to the gate junction, the depletion depth and therefore the resistance of the current flow between the source and drain and the saturation current can be controlled.
- If a large enough negative gate bias is applied, **the depletion region depth will equal the channel depth, or the channel will be pinched off.**
- This gate bias is called the pinch-off voltage and is given by

$$V_P = \left( \frac{qN_d}{2\epsilon_0\epsilon_r} \right) a^2$$

# Basic operation of MESFET



- Under pinch-off conditions, the drain current drops to a very small value.
- Therefore, the transistor can act as a voltage-controlled resistor or **a switch**.



# Basic operation of MESFET



- The most important feature of MESFET is that they may be used to increase the power level of a microwave signal, or that they provide gain.
- Because the drain current can be made to vary greatly by introducing small variations in the gate potential, the MESFET can be modeled as a voltage-controlled current source.
- The transconductance of the MESFET is defined as

$$g_m = \left. \frac{\partial I_D}{\partial V_{GS}} \right|_{V_{DS} \text{ constant}}$$

# Basic operation of MESFET



- Using short-channel approximations, it can be shown that the transconductance may be written as

$$g_m = \frac{I_S}{2V_P} \left( \frac{I_S}{I_S - I_D} \right)$$

- where  $I_S$  is the maximum current that can flow if the channel were fully undepleted under saturated velocity conditions.
- Since  $I_S$  is proportional to the channel depth,  $a$ , and  $V_P$  is proportional to the square of the channel depth,  $g_m$  is inversely proportional to the channel depth.
- In addition, note that for large  $I_S$  and  $g_m$ , the parasitic resistances  $R_S$  and  $R_D$  must be minimized.

# Basic operation of MESFET



- The most commonly used figures of merit for microwave transistors are the gain bandwidth product, the maximum frequency of oscillation,  $f_{max}$ , and the frequency where the unilateral power gain of the device is equal to one,  $f_t$ .
- If short gate length approximations are made,  $f_t$  can be related to the transit time of the electrons through the channel,  $t$ , by the expression

$$f_t = \frac{1}{2\pi\tau} = \frac{v_{sat}}{2\pi L}$$

- Since  $v_{sat}$  is approximately  $6 \times 10^{10}$   $\mu\text{m/s}$  for GaAs with doping levels typically used in the channel, the gate length must be less than  $1 \mu\text{m}$  for  $f_t$  to be greater than 10 GHz.

# Basic operation of MESFET



- The parameter  $f_{max}$  may be approximated by

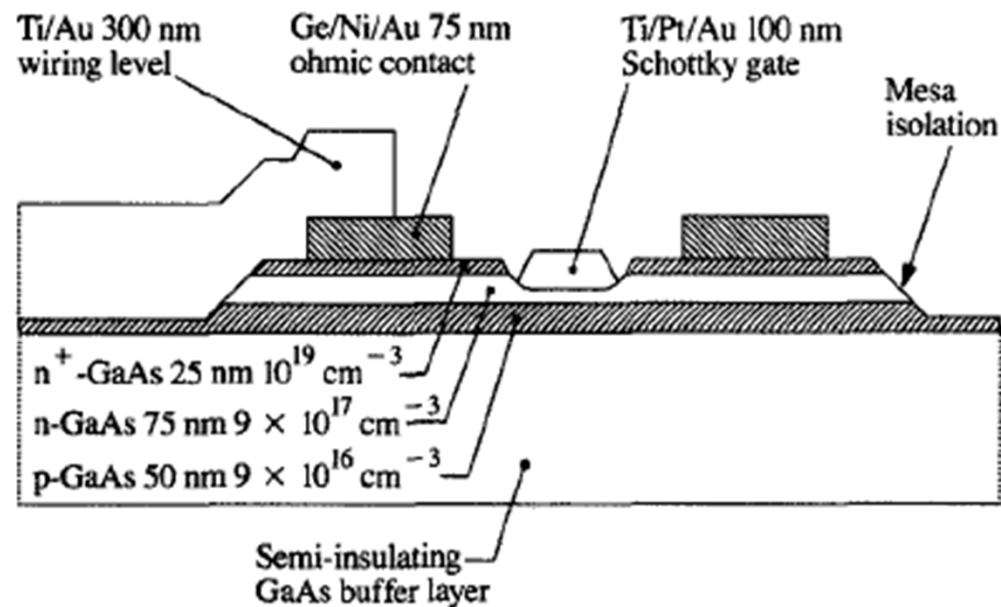
$$f_{max} = \frac{f_t}{2} \sqrt{\frac{R_{DS}}{R_G}}$$

- where  $R_G$  is the gate resistance.
- From the above two expressions for  $f_t$  and  $f_{max}$ , it is apparent that the gate length should be made as small as possible.
- Both the limits of fabrication and the need to keep the electric field under the channel less than the critical field strength required for avalanche breakdown set the lower limit on  $L$  at approximately  $0.1 \mu\text{m}$ .

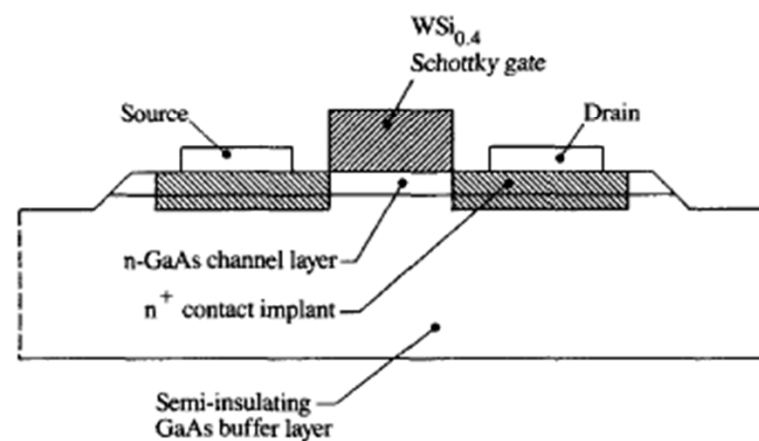
# Basic operation of MESFET



- For the gate to have effective control of the channel current, the gate length  $L$  must be larger than the channel depth,  $a$ , or  $L/a > 1$ .
- This requires a channel depth on the order of 0.05 to 0.3  $\mu\text{m}$  for most GaAs MESFETs.
- The small channel depth requires that the carrier concentration in the channel be as high as possible to maintain a high current.

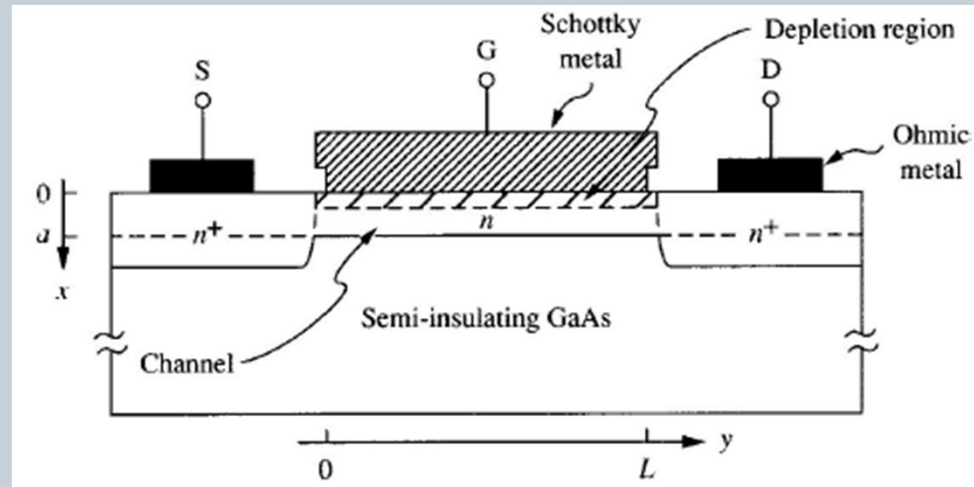


GaAs MESFET cross section.



Self-aligned GaAs MESFET cross section.

# MESFET - Summary



- The operation is very similar to that of a JFET.
- The p-n junction gate is replaced by a Schottky barrier, and the lower contact and p-n junction are eliminated because the lightly doped p-type substrate is replaced by a semi-insulating substrate.

# Applications



- The higher transit frequency of the MESFET makes it particularly of interest for **microwave circuits**.
- While the advantage of the MESFET provides a superior microwave amplifier or circuit, the limitation by the diode turn-on is easily tolerated.
- Typically depletion-mode devices are used since they provide a larger current and larger transconductance and the circuits contain only a few transistors, so that threshold control is not a limiting factor.
- The buried channel also yields a better noise performance as trapping and release of carriers into and from surface states and defects is eliminated.



# Applications



- The use of **GaAs rather than Si** MESFETs provides two more significant advantages:
  - First of all the room temperature mobility is more than 5 times larger, while the saturation velocity is about twice that in silicon.
  - Second it is possible to fabricate semi-insulating (SI) GaAs substrates which eliminates the problem of absorbing microwave power in the substrate due to free carrier absorption.

# Applications



## MESFET applications- Summary:

- High frequency devices, cellular phones, satellite receivers, radar, microwave devices.
- GaAs is a primary material for MESFETs.
- GaAs has high electron mobility.
- Generally,
  - if  $f > 2$  GHz: GaAs transistors are usually used.
  - If  $f < 2$  GHz: Si transistors are usually used.