EE4011

RF IC Design

GaAs MESFETs

MESFETs made from compound semiconductor materials have traditionally been used for RF design because of their high cut-off frequencies, low noise characteristics and good power-handling capabilities.

Some Properties of Si and GaAs (all at 300 K)

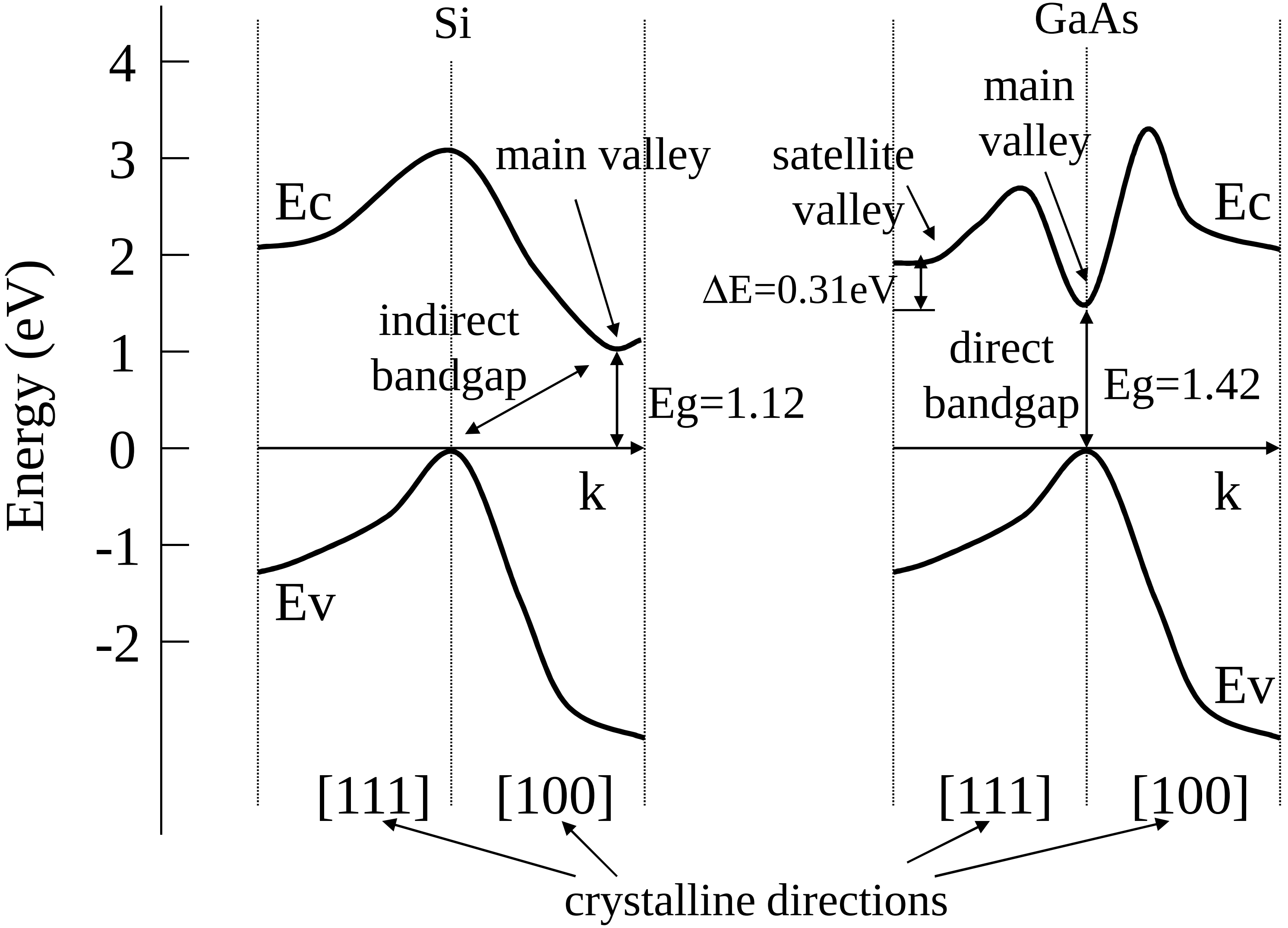
Property	Silicon	Gallium Arsenide
Bandgap (eV)	1.12	1.424
Dielectric Constant	11.9	13.1
Intrinsic carrier concentration (cm^{-3})	1.45×10^{10}	1.79×10^{6}
Mobility (cm^2/Vs) Electrons Holes	 1500 450	 8500 400
Intrinsic resistivity (Ω-cm)	2.3×10^{5}	10^{8}

Resistivity of glass is > 10^{10} Ω-cm, resistivity of copper is < 10^{-5} Ω-cm

The resistivity of intrinsic GaAs is high enough to be considered “semi-insulating”.

Data taken from “Physics of Semiconductor Devices” and “Semiconductor Devices Physics and Technology” by S.M. Sze.

Simplified E-k Diagrams for Si (Silicon) and GaAs (Gallium Arsenide)



Some details on the E-k relationship

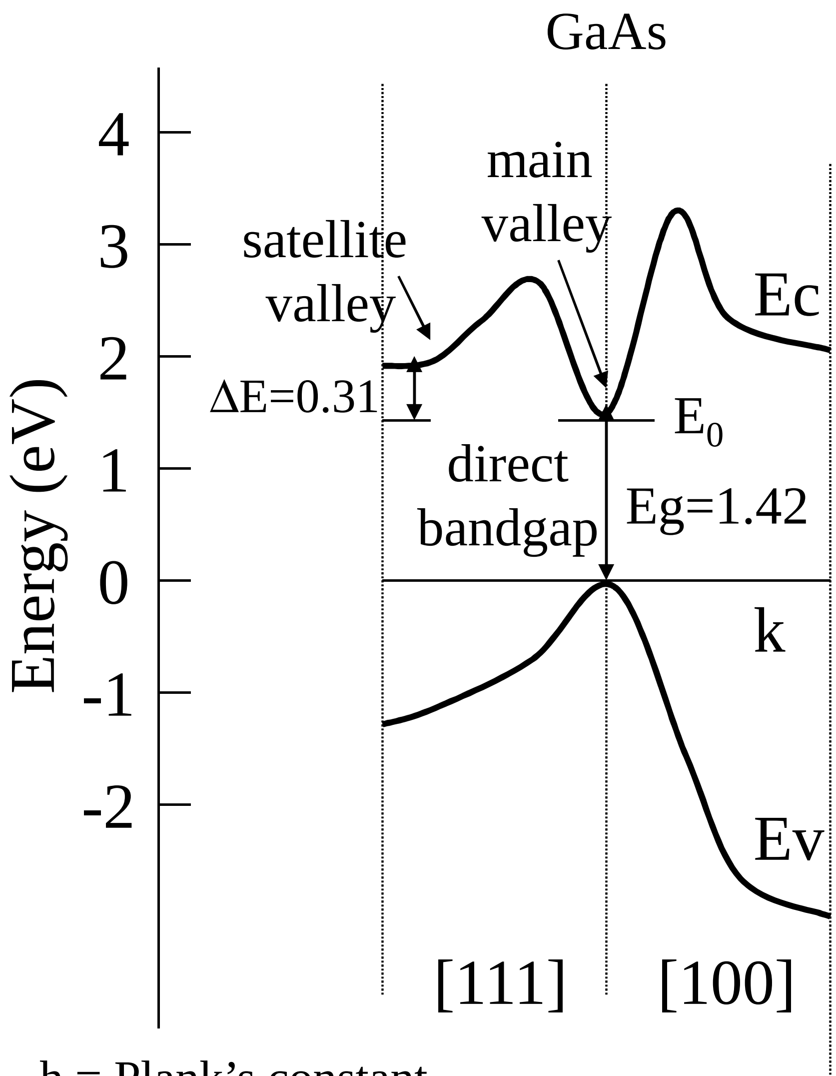
Energy-momentum (E-k) plots for Si and GaAs display characteristic peaks and troughs which depend on the crystal structure along the direction in which momentum is being plotted. The distance between the highest peak of the valence band and the lowest trough of the conduction band is known as the "bandgap" (Eg) and is the minimum energy which must be acquired or released by an electron in transferring from the valence band to the conduction band or vice-versa.

In Si the valence band energy has a maximum at $k = 0$ but the conduction band minimum occurs for $k \neq 0$. Therefore for an electron to move from the conduction to the valence band or vice versa with a minimum energy change, it will have to experience a momentum change as well. Thus Si is an "indirect bandgap" semiconductor.

In GaAs the valence band maximum and conduction band minimum both occur at $k=0$. Therefore no momentum change is necessary for an electron to move from the conduction to the valence band or vice versa. Thus GaAs is a "direct bandgap" semiconductor.

The trough in the conduction band corresponding to the minimum energy level is usually called the "main valley". In GaAs there is another trough in the conduction band only 0.31eV above the minimum level. This is called the "satellite valley" and energetic electrons can transfer into this valley.

Relationship Between Mobility and E-k Diagrams



h = Plank's constant,

τ = relaxation time or average time between collisions.

Near the peaks and troughs the E-k relationship is approximately parabolic e.g. near the conduction band minima:

$$E - E_0 = Ck^2$$

where C is a constant representing the curvature of the E-k plot. This gives

$$\frac{d^2E}{dk^2} = 2C$$

The effective mass of the electron is given by

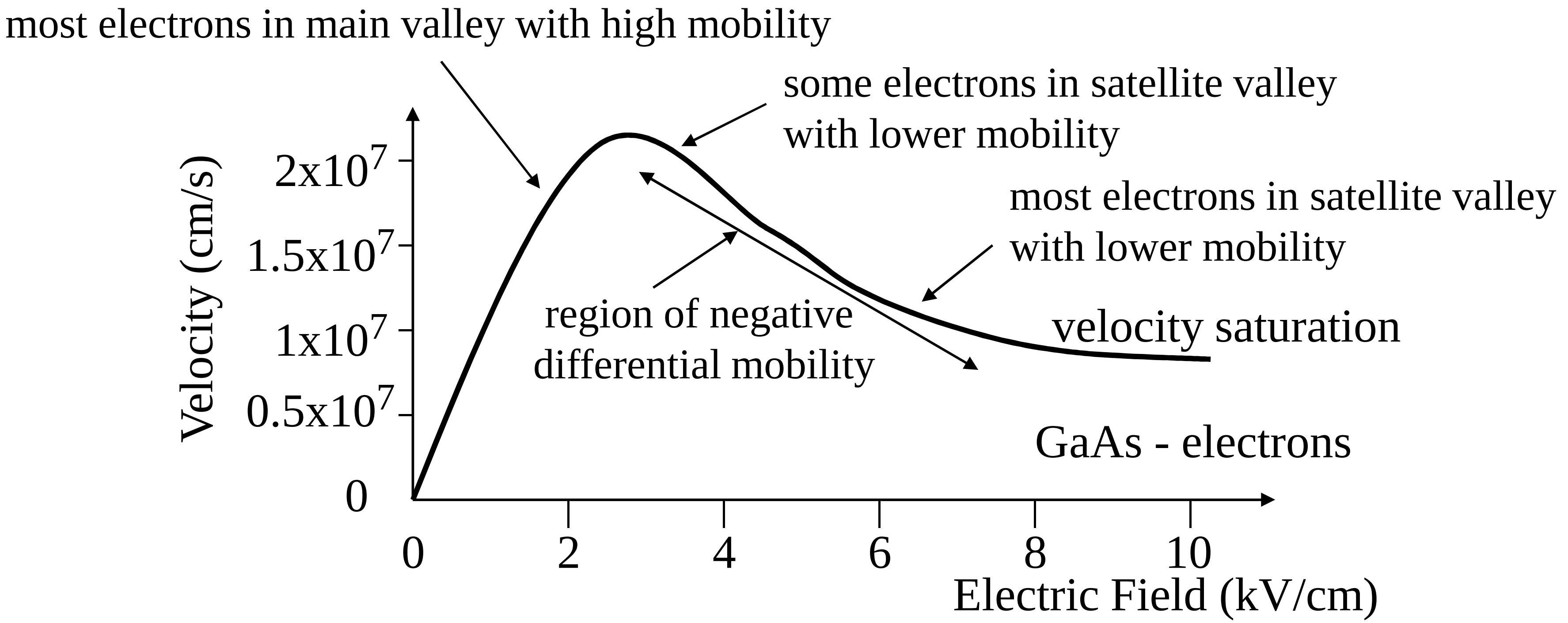
$$m^* = \frac{\hbar^2}{d^2E/dk^2} = \frac{\hbar^2}{2C} \qquad \hbar = \frac{h}{2\pi}$$

The mobility of the electrons is

$$\mu = \frac{q\tau}{m^*} = \frac{2q\tau}{\hbar^2}C$$

i.e. mobility is proportional to curvature of E-k relationship.

Velocity-Field Relationships for GaAs



The velocity-field relationship in GaAs is more complicated than silicon because of the close satellite valley only 0.31eV higher than the bottom of the main valley. Like silicon, the low-field velocity shows a linear dependence on electric field but saturates at high fields. The transition region between the low-field and high-field regimes is more complicated that silicon and shows an overshoot behaviour and a region of negative differential mobility due to the movement of electrons between the main valley and the satellite valley of the conduction band.

Some details on the v-E relationship

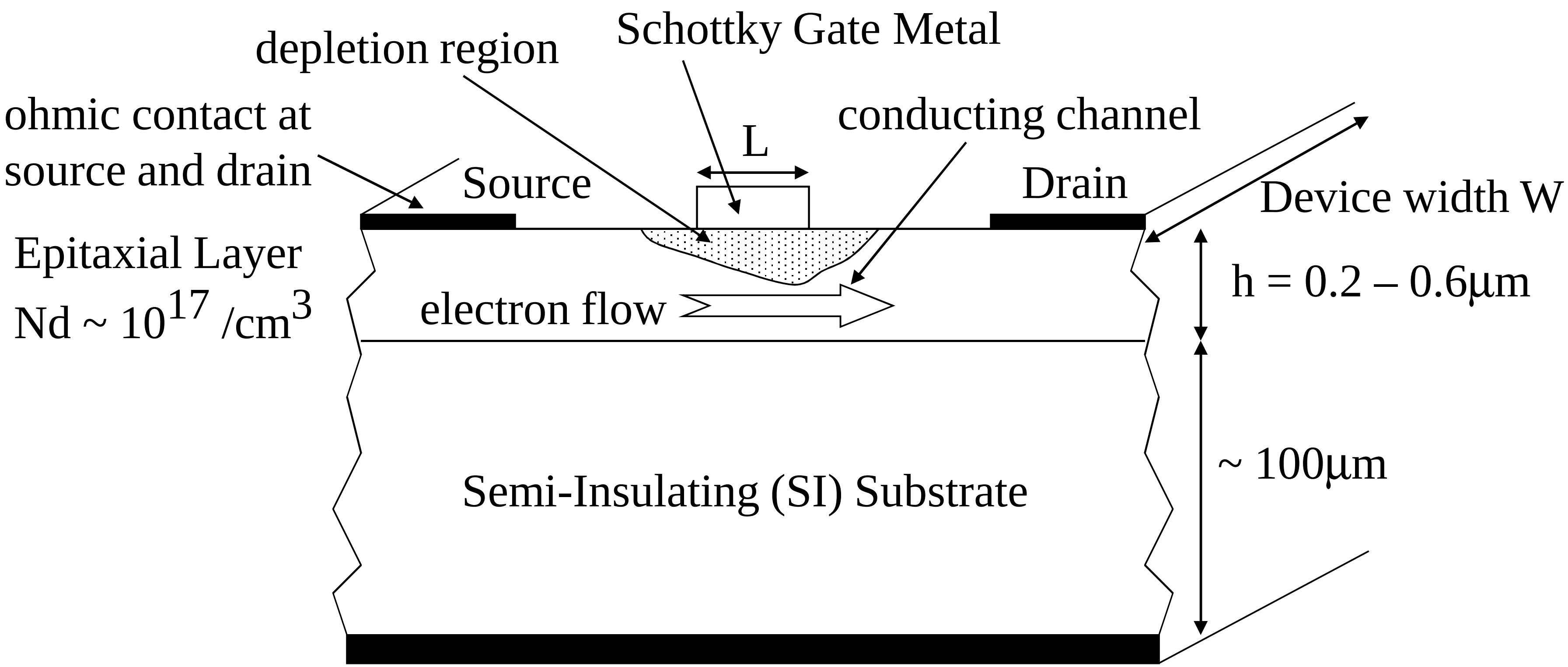
The main valley in GaAs has a higher curvature than the main valley in Si. This results in a lower effective mass and thus a higher mobility for GaAs. The satellite valley in GaAs has a lower curvature than the main valley. Thus, electrons in the satellite valley have a higher effective mass and lower mobility than in the main valley.

For both low fields and high fields, the behaviour of GaAs is similar to that of silicon except that the mobility at low fields is much higher than Si. The high-field saturation velocity is approximately the same for Si and GaAs. For intermediate fields (2-10kV/cm) GaAs behaves much different to Si due to the satellite valley.

As the field increases from about 2kV/cm to 8kV/cm, an increasing proportion of electrons in the main valley gain sufficient energy to transfer into the satellite valley. These electrons have a lower mobility than the main valley electrons so the average mobility decreases giving a decrease in average velocity. This results in a range of electric fields where GaAs exhibits negative differential mobility.

Some devices have been specially designed to make use of the negative differential mobility characteristic such as Gunn diodes which are used to make microwave oscillators.

GaAs MESFET
MEtal Semiconductor Field Effect Transistor



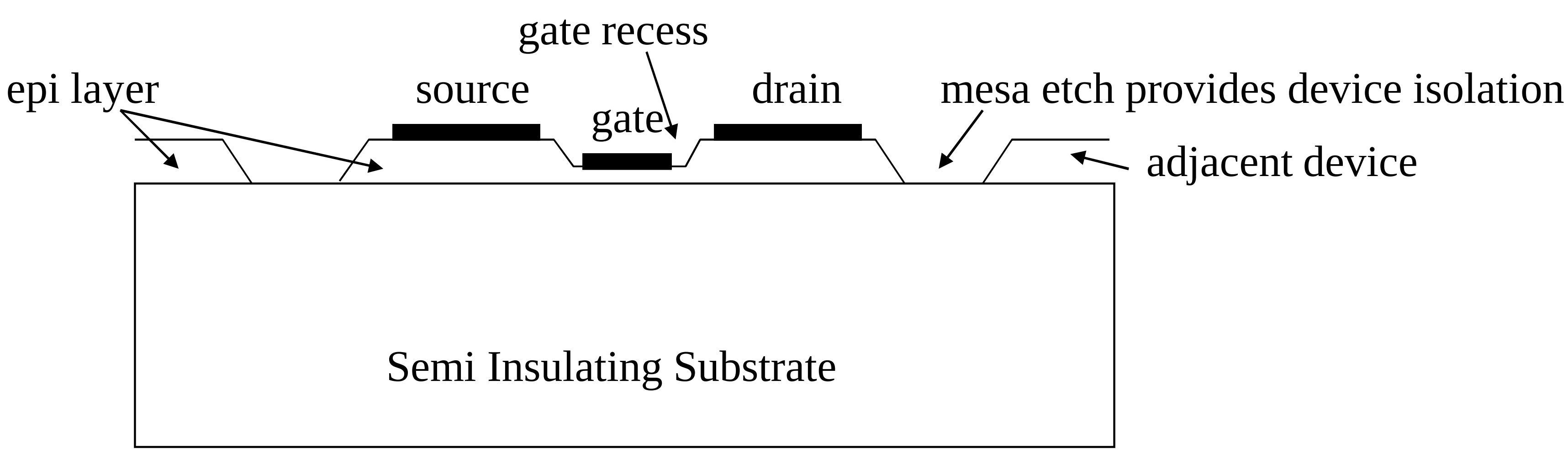
The back of semiconductor slice usually mounted on the ground plane of the microwave circuit

Some details on the MESFET structure

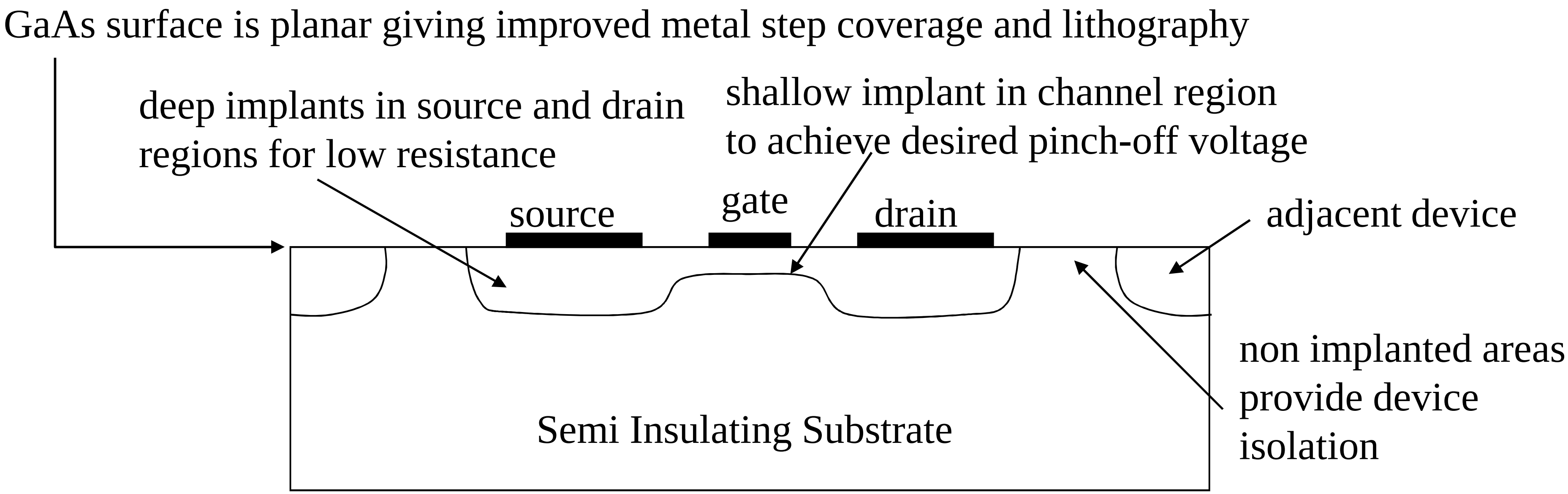
The basic structure of a MESFET is a highly doped thin epitaxial layer of GaAs grown on top of a semi-insulating (SI) substrate. Two ohmic contacts known as source and drain are formed onto the epi layer and allow easy current flow. A gate electrode is formed between the source and drain by means of a Schottky contact. This creates a depletion region under the gate, the width of which is controlled by the gate voltage.
The depletion width under the gate controls the size of the conducting channel in the epi layer giving a JFET-like operation to the MESFET. The resistivity of intrinsic GaAs is very high ($10^8 \Omega$-cm) and so current flow is confined to the highly doped epitaxial layer. The SI substrate provides good device isolation and is a low-loss material for microwave interconnects.

MESA-Isolated MESFET

A thin epitaxial layer is grown on a semi-insulating substrate. This epi layer is completely etched away except where devices are to be sited. Each device is thus in the form of a “mesa” and is completely isolated from the other devices. The epi layer has to be thick enough to give low parasitic source and drain resistances but the channel region has to be thin enough to give the desired pinch off voltage. Therefore, the gate region is usually etched to achieve the required pinch-off voltage before the Schottky contact is made so that the gate is formed in a recess area. The overall mesa/gate recess structure is non-planar which can give problems with metal step coverage and lithography depth of focus so more modern processes use ion-implantation.



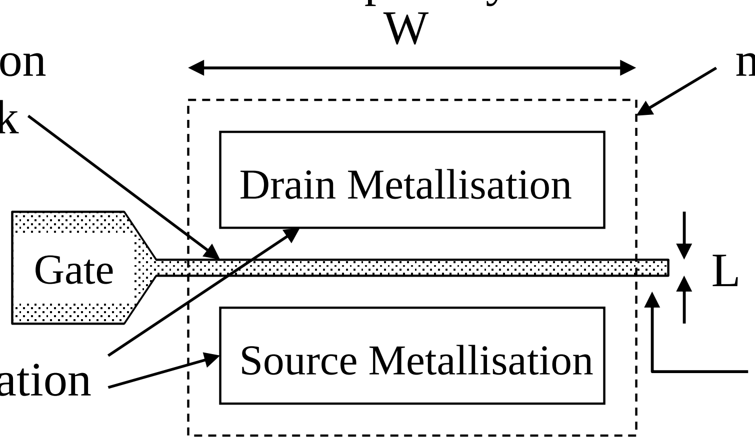
Ion-Implanted MESFET



For ion-implanted MESFETs the implantation is only performed where the devices are desired. Different devices are automatically isolated by means of the semi-insulating substrate. Ion-implantation can be controlled very precisely so the implant depth in the channel region can be tailored to suit the desired turn-off voltage. This is especially useful when fabricating enhancement mode devices (which aren’t used much nowadays).

Common Layout Styles for MESFETs

Simple Layout



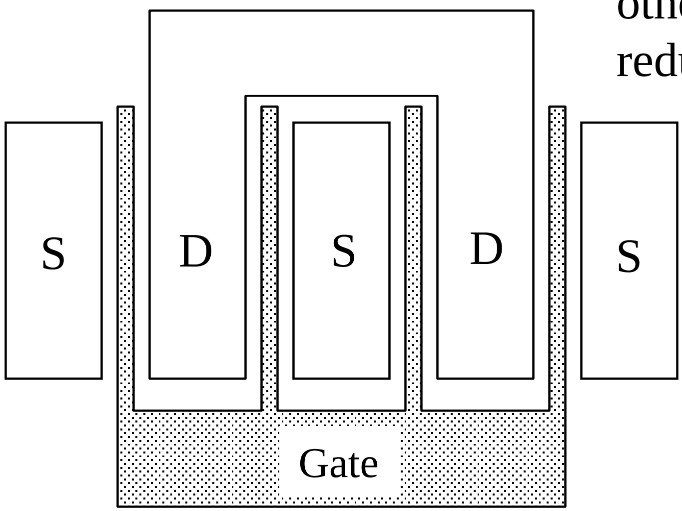
Schottky metallisation and gate recess mask

mesa isolation mask

ohmic metallisation masks

The gate mask extends beyond the mesa mask to ensure that the final gate will cover the full channel area even if some misalignment occurs.

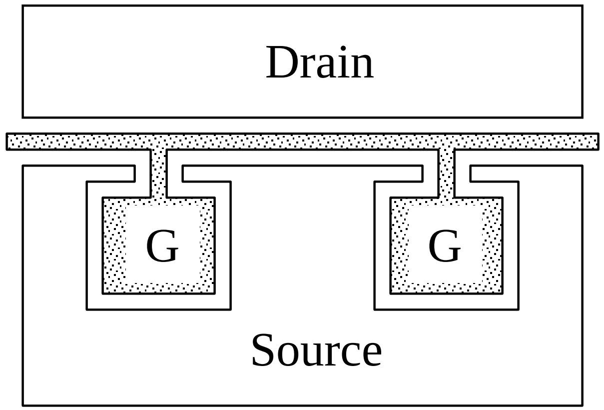
Interdigitated



other layout styles to reduce gate resistance

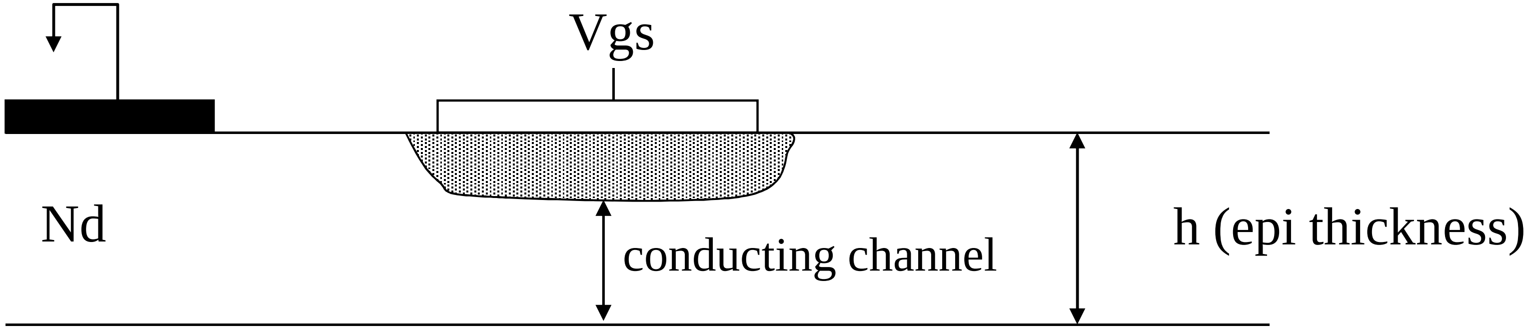
Here, the source fingers are interconnected by bond wires, vias or another metal layer

π-gate



Here, the two gate fingers are bonded to the same terminal

The MESFET pinch-off voltage



For low drain voltages the depletion width associated with the Schottky gate is uniform and given by

$$X_{dep} = \sqrt{\frac{2\varepsilon(V_{bi} - V_{gs})}{qN_d}}$$

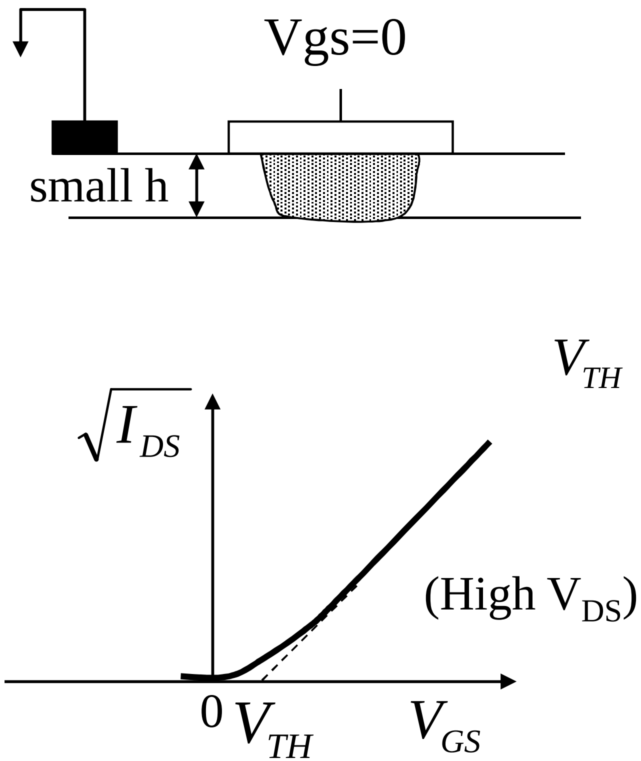
As Vgs is made more negative the depletion region will eventually extend over the full channel depth and no current will flow from source to drain. The gate voltage at which this occurs is known as the threshold bias $Vgs=V_{TH}$ i.e.

$$h = \sqrt{\frac{2\varepsilon(V_{bi} - V_{TH})}{qN_d}} \Rightarrow V_{TH} = V_{bi} - \frac{qN_d h^2}{2\varepsilon} \quad \text{i.e.} \quad V_{TH} = V_{bi} - V_p \text{ where } V_p = \frac{qN_d h^2}{2\varepsilon}$$

V_p is known as the pinch-off voltage (or intrinsic pinch-off voltage).
V_{bi} is the built-in potential of the Schottky gate.

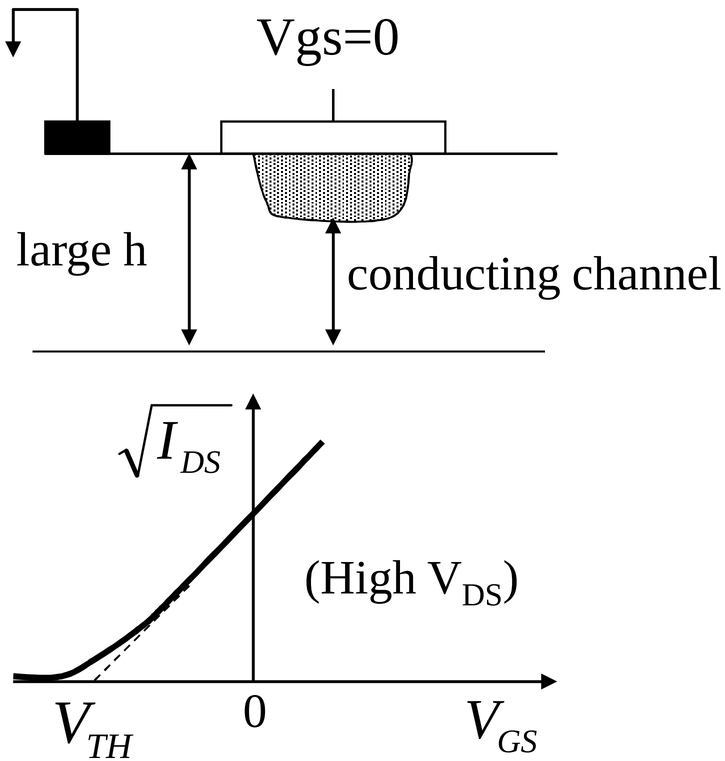
Enhancement and Depletion Mode Devices

Enhancement Mode Device



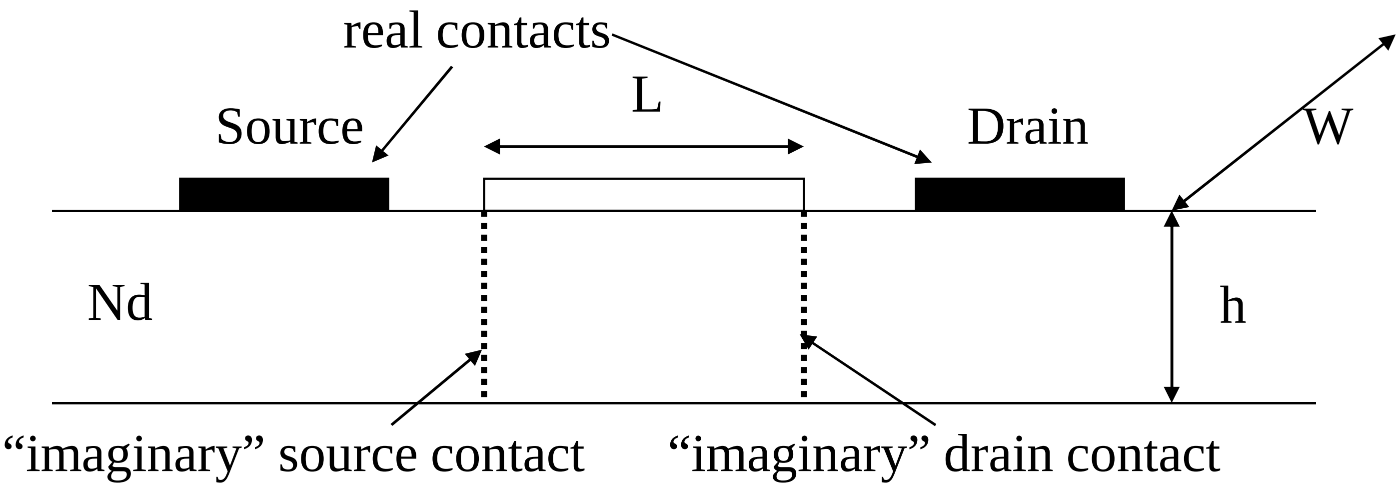
$$V_{TH} = V_{bi} - \frac{qN_d h^2}{2\varepsilon}$$

Depletion Mode Device



If the channel thickness is small then the full channel may be depleted at V_{GS}=0 due to the inbuilt potential of the Schottky gate. In this case, a positive V_{GS} is needed to reduce the depletion region thickness and open up a channel to allow current flow. This is an enhancement mode device and is most suitable for digital circuits. Most microwave MESFETs are depletion mode devices. Here, most of the channel is “open” at V_{GS}=0 and a negative V_{GS} is needed to turn the device off.

Maximum Channel Conductance



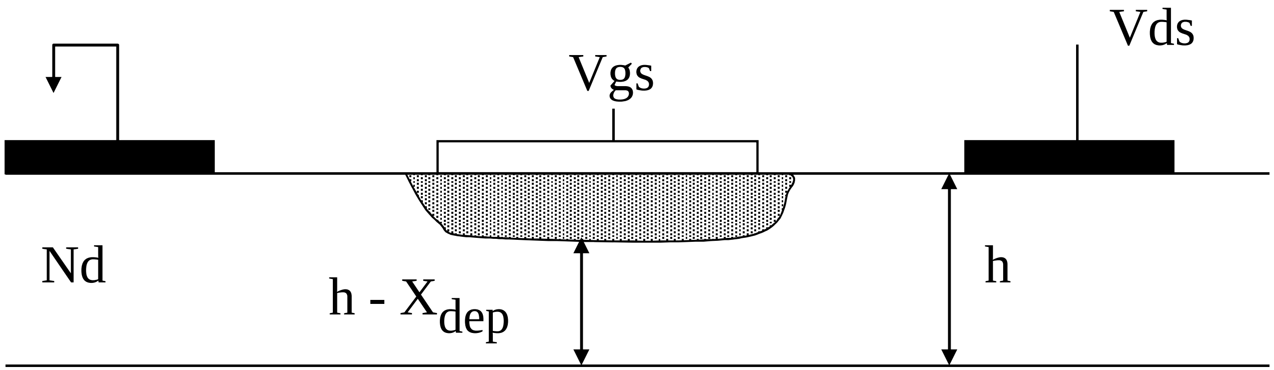
If we imagine contacts extending the full depth of the epitaxial layer and zero depletion width then the conductance of the epitaxial region under the gate is given by

g_0 = (conductivity x Width x Height)/Length

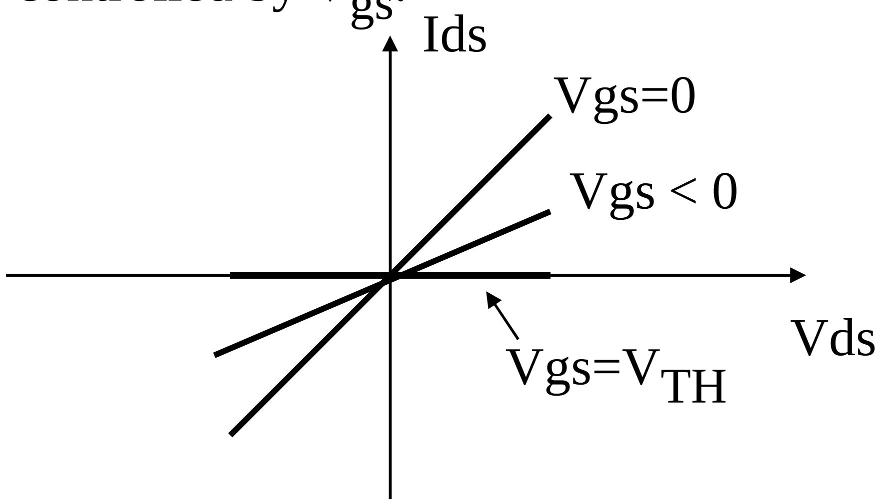
$$g_0 = \frac{q\mu_n N_d W h}{L}$$

q = electron charge
μ_n = electron mobility
N_d = donor concentration
W = device width
L = device length
h = epitaxial layer thickness

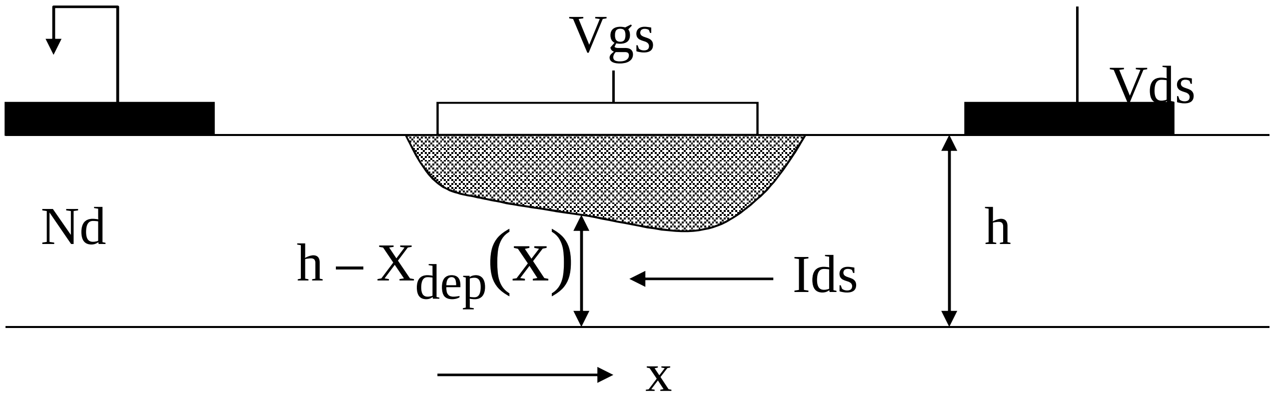
Linear Region Operation for Low Vds



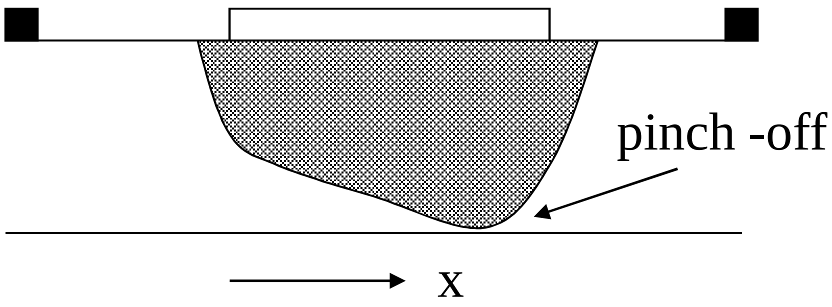
If Vds is small the conducting channel under the gate is fairly uniform with a thickness h-X_{dep}. Thus it behaves like a resistor between source and drain whose value is controlled by V_{gs}.



Operation for higher Vds and Saturation



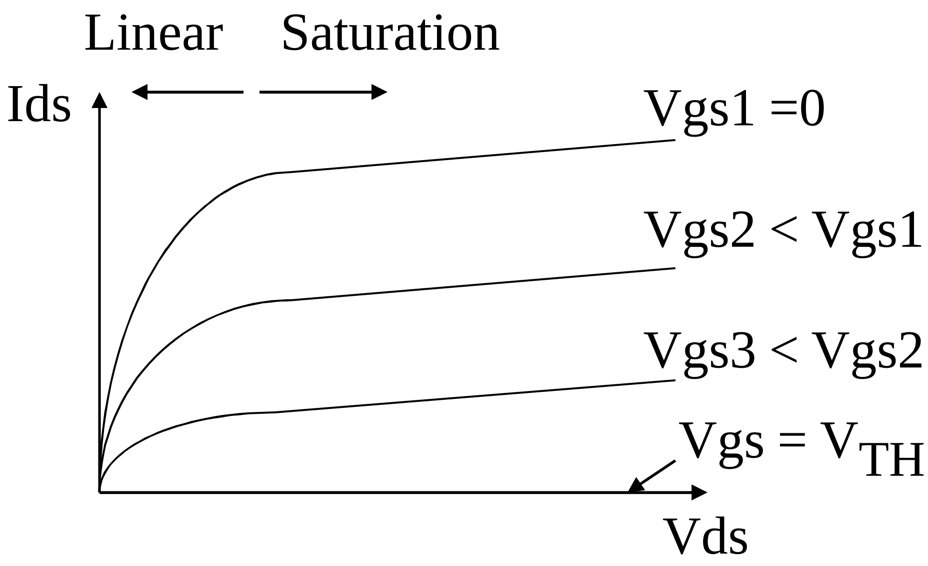
As Vds increases (Vds>0) there is more reverse bias across the Schottky contact at the drain side of the channel and the depletion region is wider here. Thus Xdep is a function of x, the distance along the channel and the "average channel resistance" increases with Vds. Thus the current does not continue to increase linearly with increasing Vds. At some critical value of Vds the channel pinches off and the current saturates.



Just like a MOSFET, the drain voltage at which pinch off occurs can be shown to be given by:

$$V_{DSAT} = V_{GS} - V_{TH}$$

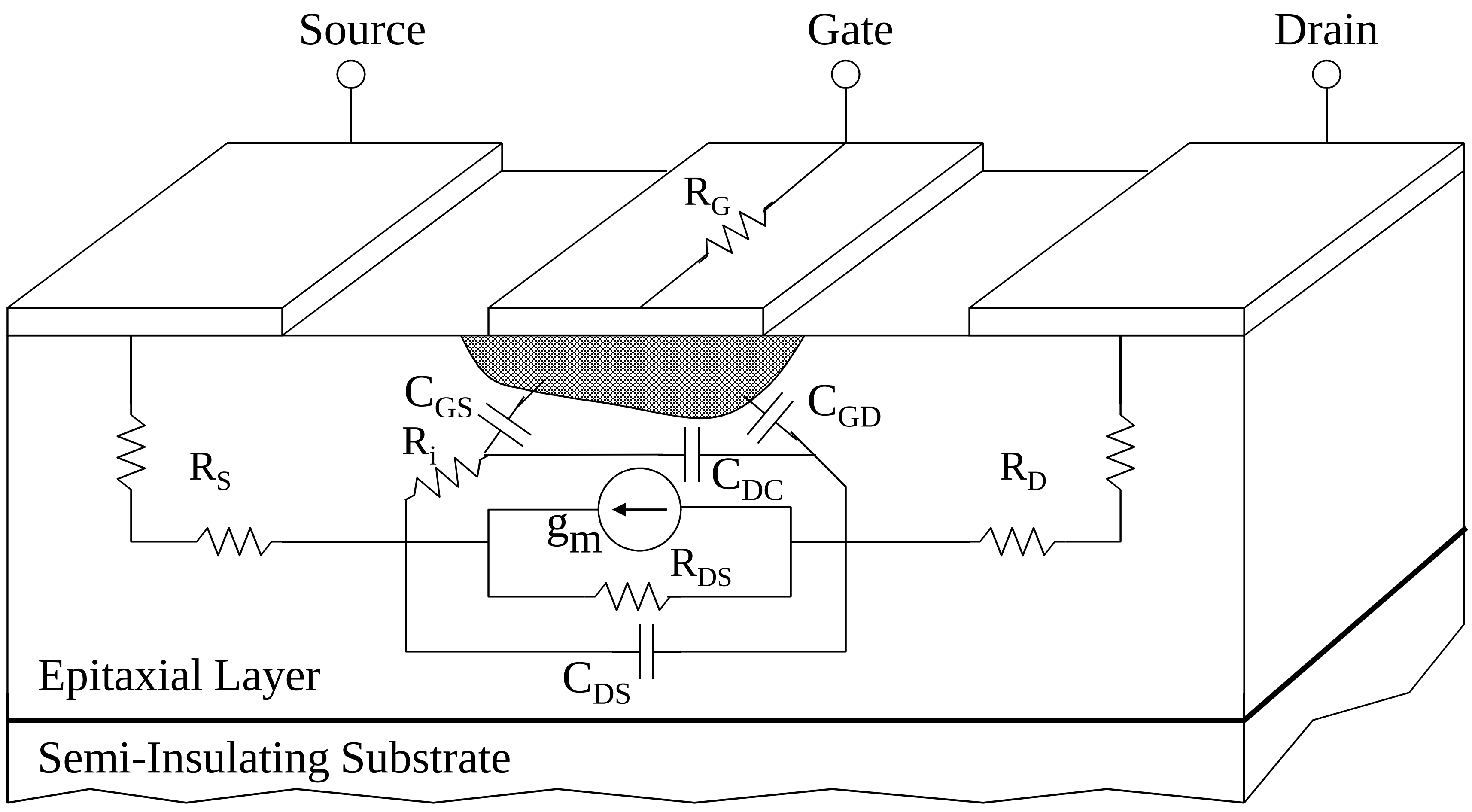
I-V Characteristics



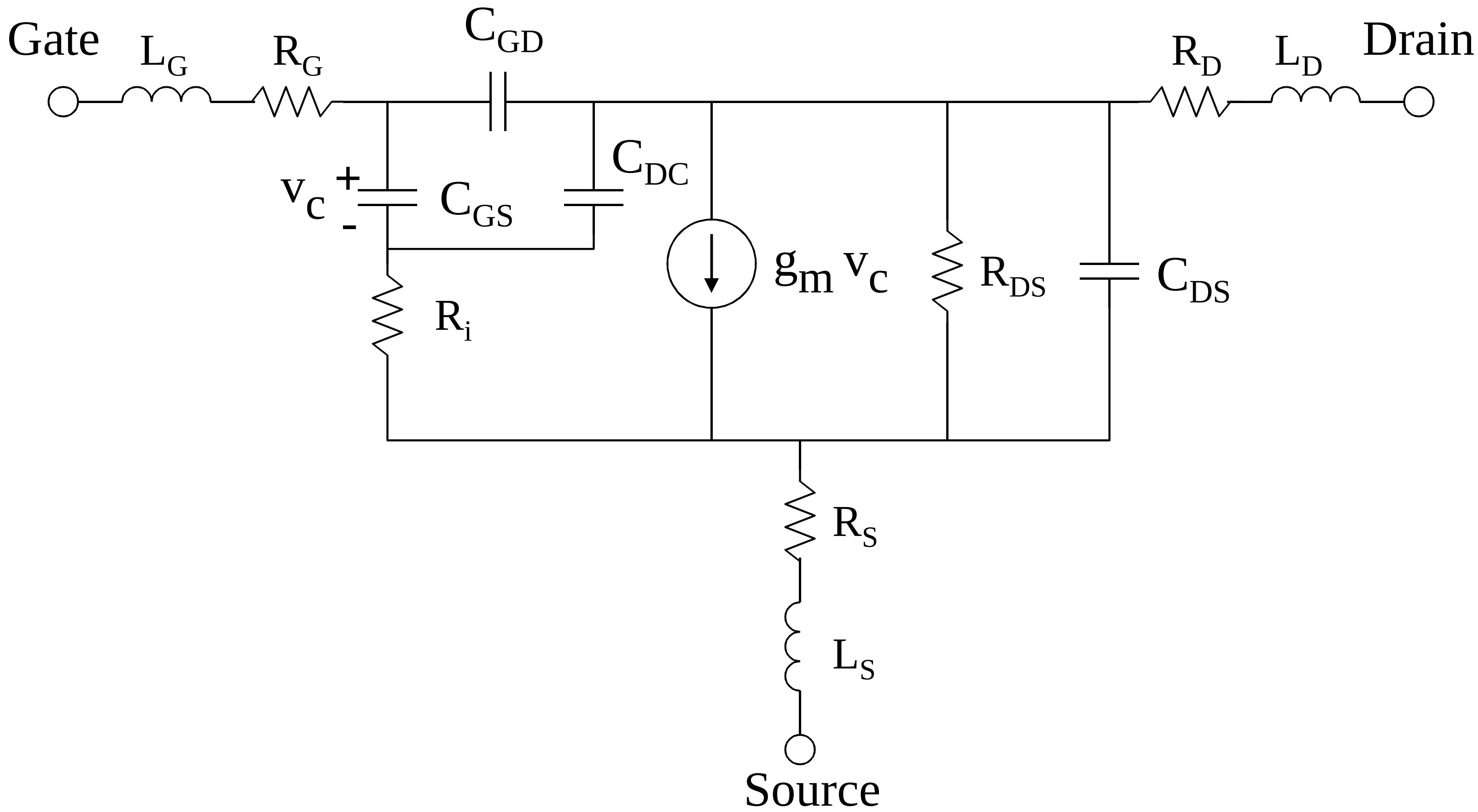
For highest transconductance when used for amplification, the MESFET is biased in the saturation region. MESFETs are often used to make RF switches. In this case, they are biased in the linear region for low resistance between source and drain.

Because MESFETs are so like JFETs, expressions for the I-V behaviour can be derived in a similar fashion to JFETs and the resulting expressions are very similar (but these derivations are not covered here).

Origin of Small-Signal Circuit Elements



MESFET Small-Signal Equivalent Circuit for Common Source Configuration

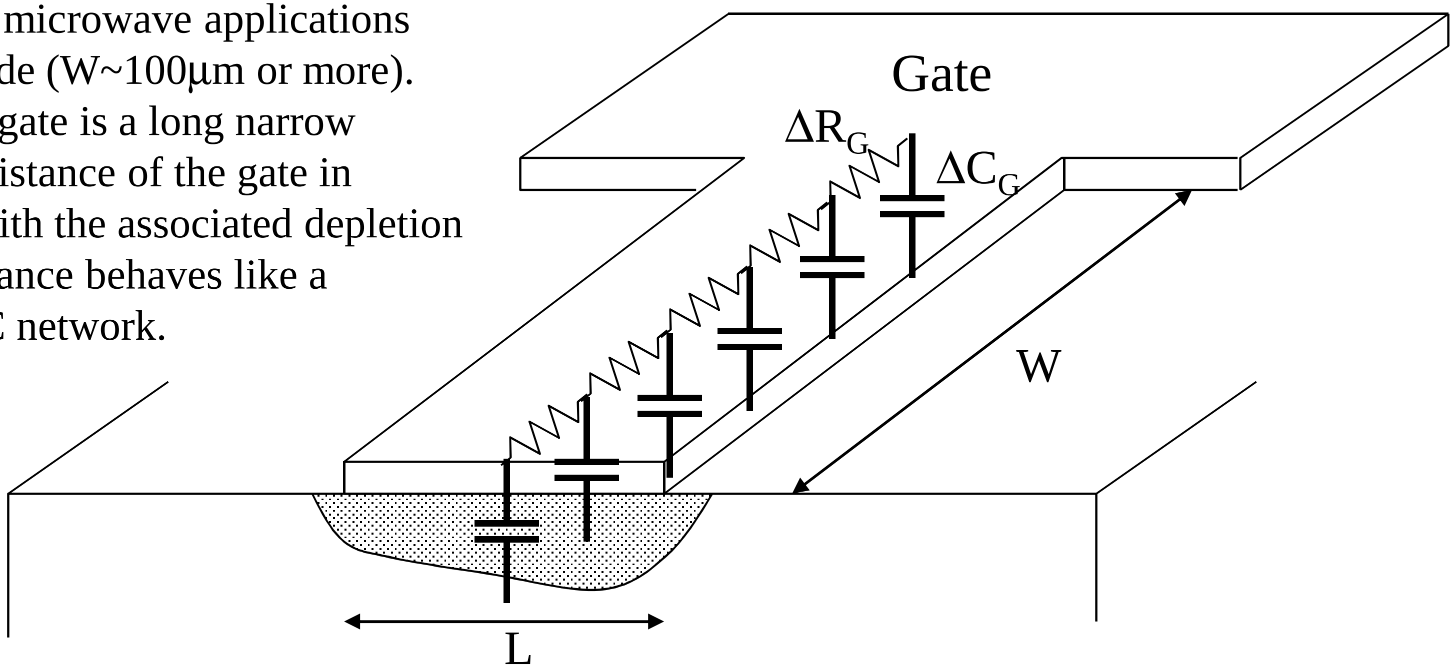


The inductances are only included for the case of discrete devices contacted using bond wires. They are not usually necessary for integrated devices.

For maximum gain, MESFETs like (MOSFETs and JFETs) are biased in the saturation region.
There have been many equivalent circuit topologies proposed for MESFETs. The one shown here is intermediate in complexity. More complex equivalent circuit topologies may include an extra RC network to model the charge dipole near the pinch-off region and include other parasitics. The origins of the main small-signal elements are as follows:
Transconductance: This can be derived from the DC I-V behaviour using $g_m=dI_{DS}/dV_{GS}$ for V_{DS} constant. In some models g_m is multiplied by a factor $\exp(-j\omega\tau)$ where ω is the angular frequency being considered and τ is the electron transit time across the device. This does not change the magnitude of the transconductance but it introduces a phase lag into the small signal current to reflect the finite electron transit time across the channel.
Output Resistance: This is again derived from the DC I-V characteristics and represents the small-signal quantity Rds=1/gds where gds= dI_{DS}/dV_{DS} for V_{GS} constant.
R_D and R_S represent the epi-layer or implanted layer resistances from the edge of the channel region to the metal contacts.
R_G represents the distributed gate resistance.
C_{GS} represents the gate-source capacitance. In saturation, the charge in the depletion region under the gate is mainly controlled by the gate-source voltage. Then C_{GS} is the derivative of this charge w.r.t. V_{GS} .
In the linear region the depletion region charge is also a function of V_{DS} and C_{GD} represents the derivative of this charge w.r.t. V_{GD}. Some portion of the depletion charge is controlled by the drain in saturation and this contributes to C_{GD} in saturation. Fringing capacitances associated with the metallizations also contribute to C_{GD} . C_{DS} represents the capacitive coupling between drain and source caused by the substrate.
The intrinsic resistance R_i represents a portion of the channel resistance which is is series with C_{GS} and thus effects its charging and discharging. In saturation, there is a charge dipole at the pinch-off point and the effect of this is represented by C_{DC}.

Gate Resistance

MESFETs for microwave applications are usually wide (W~100μm or more). Therefore the gate is a long narrow stripe. The resistance of the gate in conjunction with the associated depletion region capacitance behaves like a distributed RC network.



The equivalent lumped gate resistance of a single finger MESFET of width W has been shown to be

$$R_G = \frac{1}{3} W R_m$$

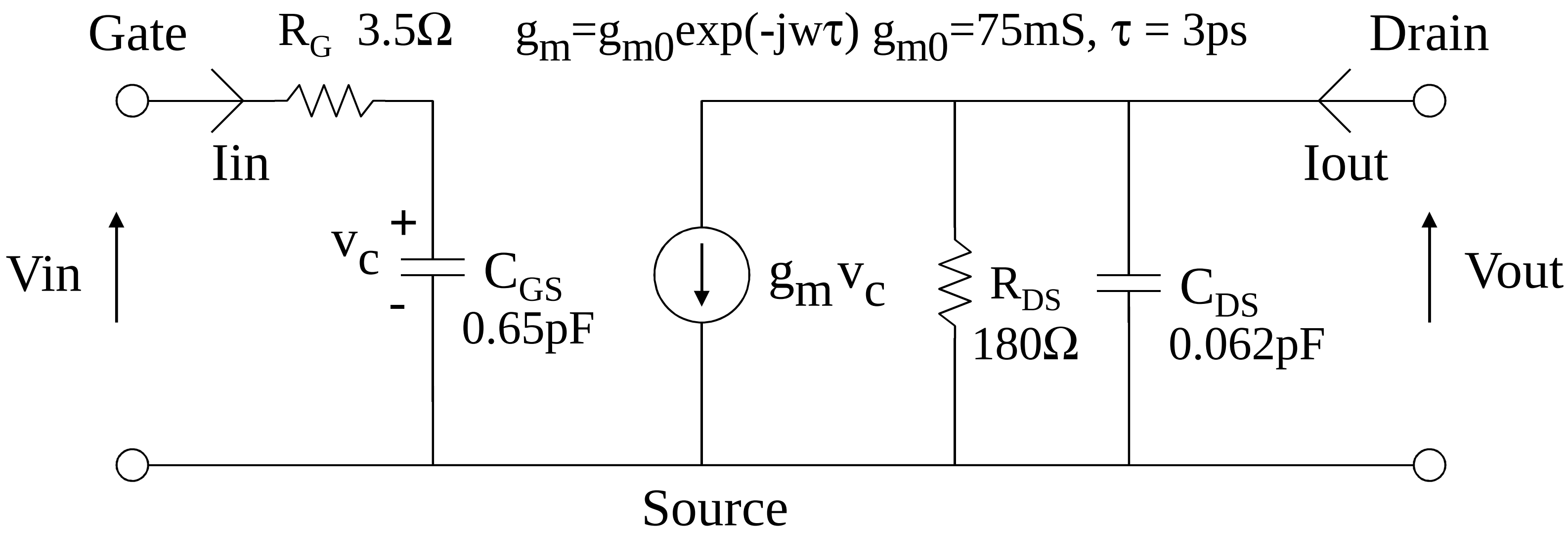
where R_m is the resistance per mm (Ω/mm) of the gate stripe

If a device of total width W is made instead using N parallel fingers the resistance drops to

$$R_G = \frac{1}{N^2} \frac{1}{3} W R_m$$

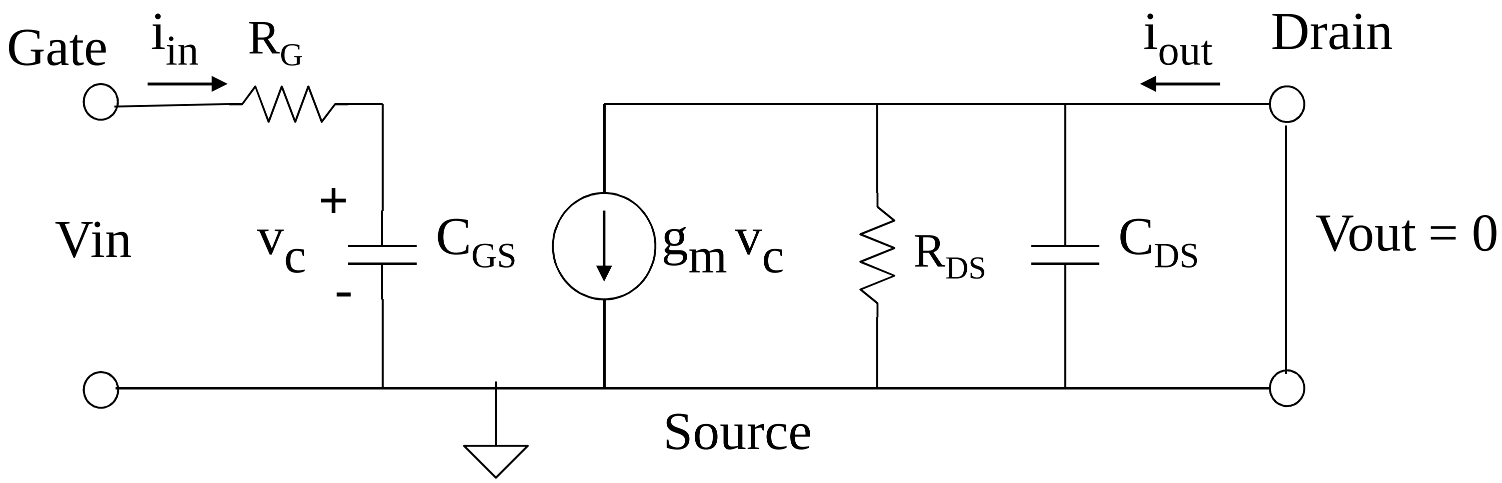
Simpler MESFET Small-Signal Circuit for Common Source Configuration

Values taken from a datasheet for a GaAs MESFET with W=500μm, L=0.3μm, I_{DS}=50mA



In this simplified circuit, C_{GD} has been removed so there is no possible feedback (in the intrinsic device) from output to input. This is typically referred to as a unilateral configuration.

MESFET Cut-off Frequency (1)

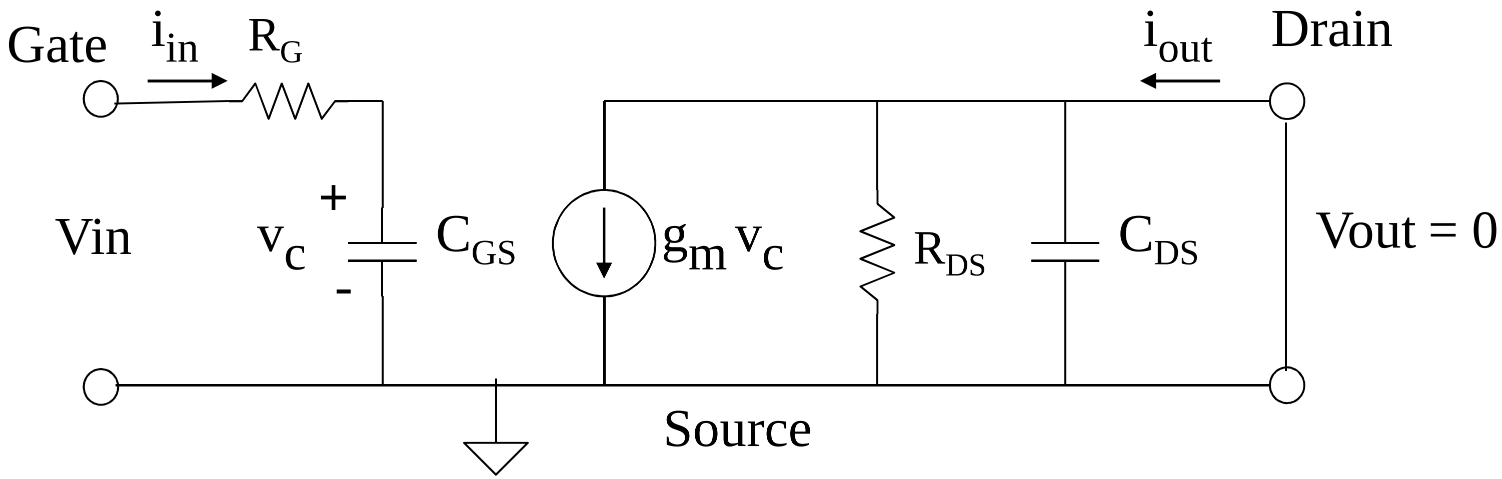


Again this is calculated as the frequency at which the output short-circuited current gain drops to unity. Because the o/p is short-circuited there is no current flowing in R_{DS} or C_{DS} so the only contribution to o/p current is the transconductance term. Note that it is the voltage across the input capacitance that controls this current.

$$i_{in} = \frac{v_{in}}{R_G + 1/j\omega C_{GS}} = v_{in}\frac{j\omega C_{GS}}{1 + j\omega R_G C_{GS}}$$

$$v_c = v_{in}\frac{1/j\omega C_{GS}}{R_G + 1/j\omega C_{GS}} = v_{in}\frac{1}{1 + j\omega R_G C_{GS}} \Rightarrow i_{out} = g_m v_c = v_{in}\frac{g_m}{1 + j\omega R_G C_{GS}}$$

MESFET Cut-off Frequency (2)



$$i_{in} = \frac{v_{in}}{R_G + 1/\,j\omega C_{GS}} = v_{in}\,\frac{j\omega C_{GS}}{1 + j\omega R_G C_{GS}}$$

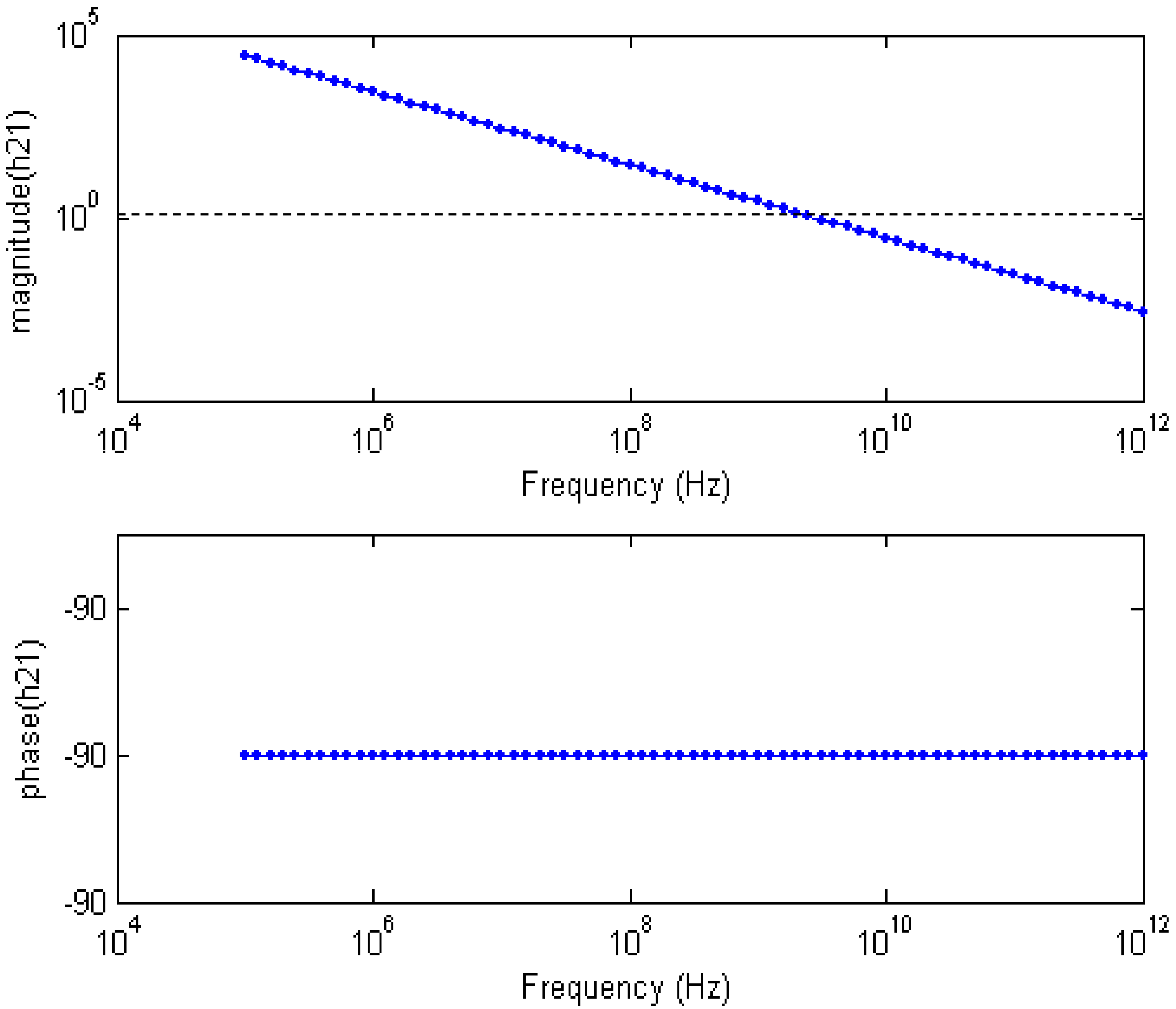
$$i_{out} = g_m v_c = v_{in}\,\frac{g_m}{1 + j\omega R_G C_{GS}}$$

$$\Rightarrow h_{21} = \frac{i_{out}}{i_{in}} = \frac{g_m}{j\omega C_{GS}} \Rightarrow \left|h_{21}\right| = \frac{g_m}{2\pi f\, C_{GS}}$$

$$\text{at f} = \text{f}_{\text{T}}\,,\ \left|\text{h}_{21}\right| = 1 \Rightarrow\ f_T = \frac{g_m}{2\pi C_{GS}}$$

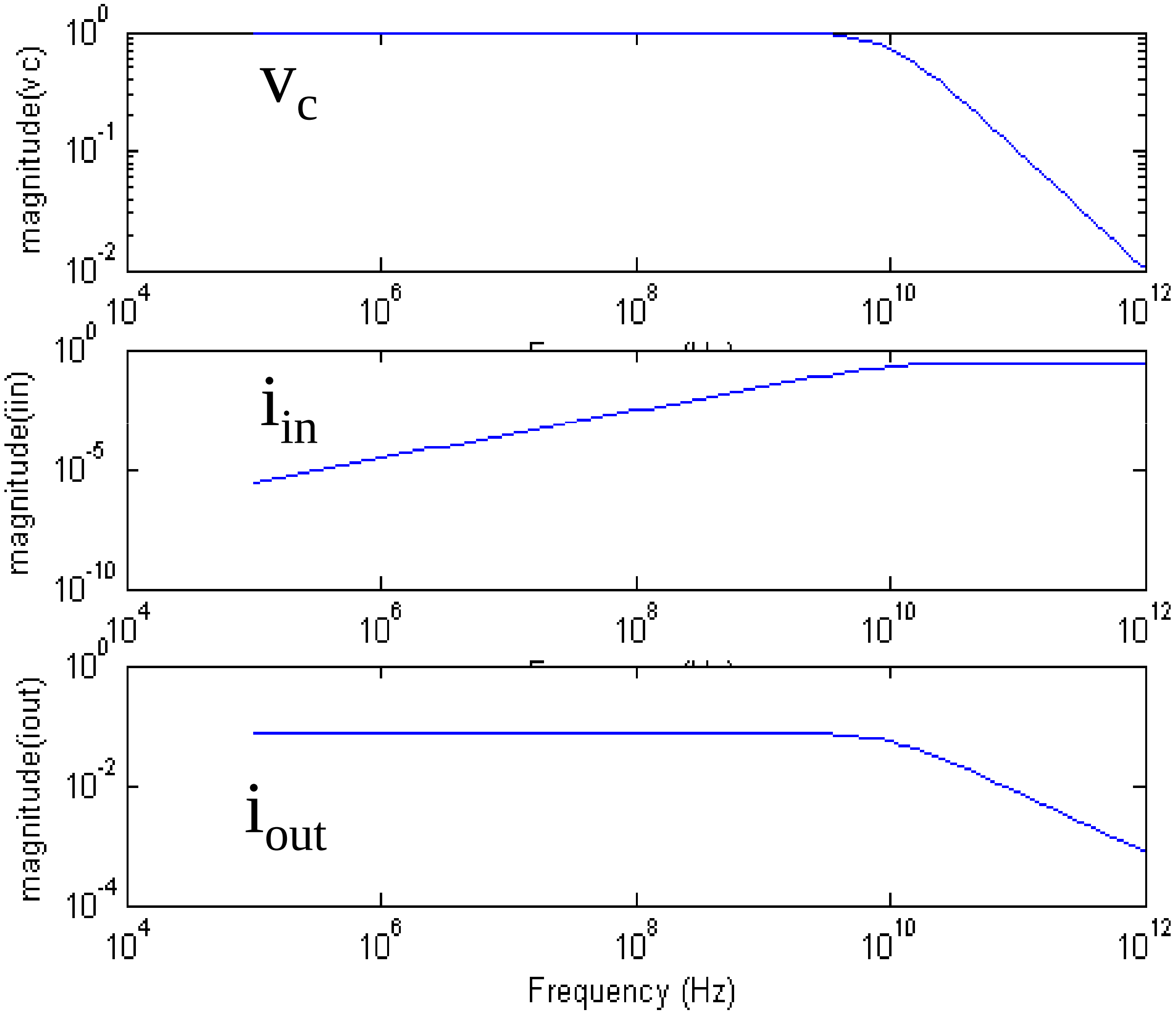
looks familiar!

h_{21} vs. frequency for typical component values



special case
where $\tau = 0$

v_c etc. vs. frequency for typical component values



At the cut-off frequency:

v_c begins to drop

i_{in} begins to saturate at a value determined by r_g alone

i_{out} begins to drop