TE 364

LECTURE 3:

Introduction to Microwave Active Devices

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Abdul-Rahman Ahmed

Introduction

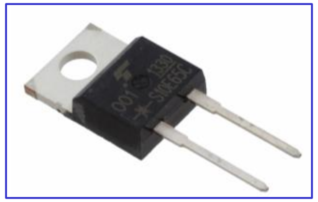
- Prior to 1970, most of microwave semiconductor devices were largely
  - 2-terminal diodes and
  - 3-terminal Si BJTs (Bipolar Junction Transistor)
- Frequently used microwave diodes include
  - Gunn,
  - IMPATT (**IMP**act **I**onization **A**valanche **T**ransit-**T**ime diode)
  - Varactor (variable capacitor, oscillator application)
  - PIN, and
  - Schottky diodes.

Gunn Diode

IMPATT

Veractor

PIN



Shottkey

Introduction

- Application of Veractor Diodes
  - When a reverse-biased voltage is applied to a *p-n* junction diode,
    - a depletion capacitance appears in the *p-n* junction.
    - Since this depletion capacitance varies according to the reverse-biased voltage,
  - varactor diode is a ***variable capacitor*** exploiting this property and
  - is often used in adjusting the frequency of ***oscillators***.

Introduction

- In addition, a varactor diode can be used to
  - amplify a weak signal as ***parametric amplifier***
    - the operation of which resembles that of a ***mixer***.
  - Such parametric amplifier played an important role as a low noise amplifier in the past

Introduction

Application of PIN diode

- PIN diode formed by creating an intrinsic-region (I-region) in the *p-n* jun ction
  - The resistance of this I-region in PIN diode varies depending on the DC voltage.
- ***electronic switches*** in the microwave region were implemented based o n this property
- Furthermore, by combining the PIN diodes with the appropriate lengths of transmission lines,
  - it can also be utilized as a ***digital phase shifter***.
- A PIN diode can also function as an ***analog type variable attenuator***.

Introduction

- Application of Shottky diode
  - Schottky diode has for a long time been used in ***detectors*** and ***mixers***
- Due to its property of rectification
  - this diode uses majority carrier diffusion unlike *p-n* diode.
  - Consequently, it has no diffusion capacitance, which is associated with minority carriers which
  - provides various benefits when applied in mixers at high frequencies.

Introduction

- Application of IMPATT diode
  - IMPATT diode were mostly used as active components in ***oscillators*** and ***amplifiers***
  - The DC characteristics of these diodes show negative resistance when DC biased for the optimum operating point.
  - With negative resistance, it was much easier to design ***oscillators***
  - the reflection coefficient of devices with negative resistance is greater than 1
  - thefore can be configured as reflection amplifiers in combination with a circulator

Introduction

- Disadvantages of these diodes as active devices
  - they have poor efficiency,
  - problem of heat dissipation must always be considered.
    - Therefore, they were used in constructing circuits which use waveguides that easily adapt to thermal design.
  - Such heat problems become important limiting factor in circuit integration.

Introduction

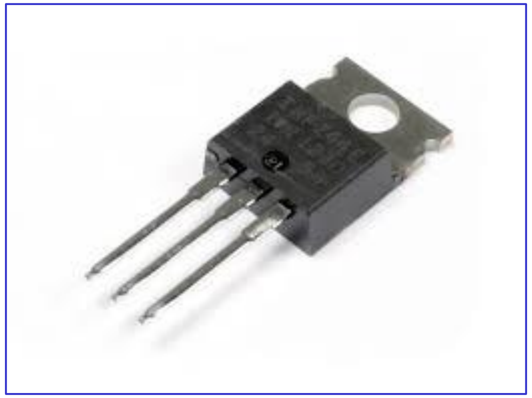
- Another disadvantage of these diodes is that,
  - because they cannot be integrated with other devices in a single process,
  - it is intrinsically difficult to build up complex functioning integrated circuits that need other devices.

Introduction…

- Major types of transistors are
  - BJT (**B**ipolar **J**unction **T**ransistor) and
  - FET(**F**ield **E**ffect **T**ransistor)

FET

BJT



Introduction

- BJTs
  - use the two carriers, holes and electrons, and
  - use a diffusion mechanism in current flow.
  - controls current flow by raising or lowering barrier height formed at junctions.
  - Number of diffusing carriers depends on barrier height
    - which is attained by altering the DC voltage across the junction
  - Could not be used at frequencies beyond 4 GHz.

Introduction

- On the contrary, FETs
  - use one majority carrier, electron, and
  - a drift mechanism in current flow.
  - form a channel through which electrons can flow.
    - The number of electrons flowing can be controlled by narrowing or widening the thickness of the channel,
    - which is achieved by controlling the gate voltage.
  - FETs are classified according to their channel formation;
    - ***enhancement type*** and ***depletion type***

Introduction

- In the early 1970s,
  - with the advance of GaAs compound semiconductor process technology,
  - GaAs MESFET (Metal Semiconductor FET) or simply GaAs FET was developed
  - The electron mobility in GaAs is 6 times faster than in Si.
  - With this electron mobility advantage, GaAs FET shows far more excellent performance than Si transistors.
  - With the advent of GaAs FET, Gunn diodes, became no longer used in amplifiers

Introduction

- Further improvement of the characteristics of GaAs FET led to the emergence of
  - HEMT (High Electron Mobility Transistor) and
  - pHEMT (pseudo-morphic HEMT).
- It became possible
  - to construct integrated circuit up to a frequency of 200 GHz with these FETs.

GaAs MESFET

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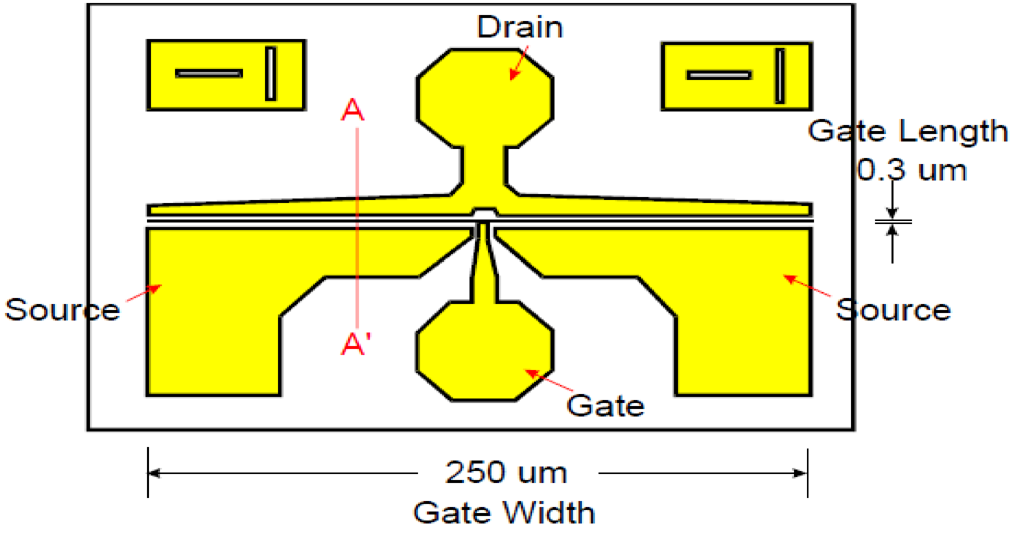
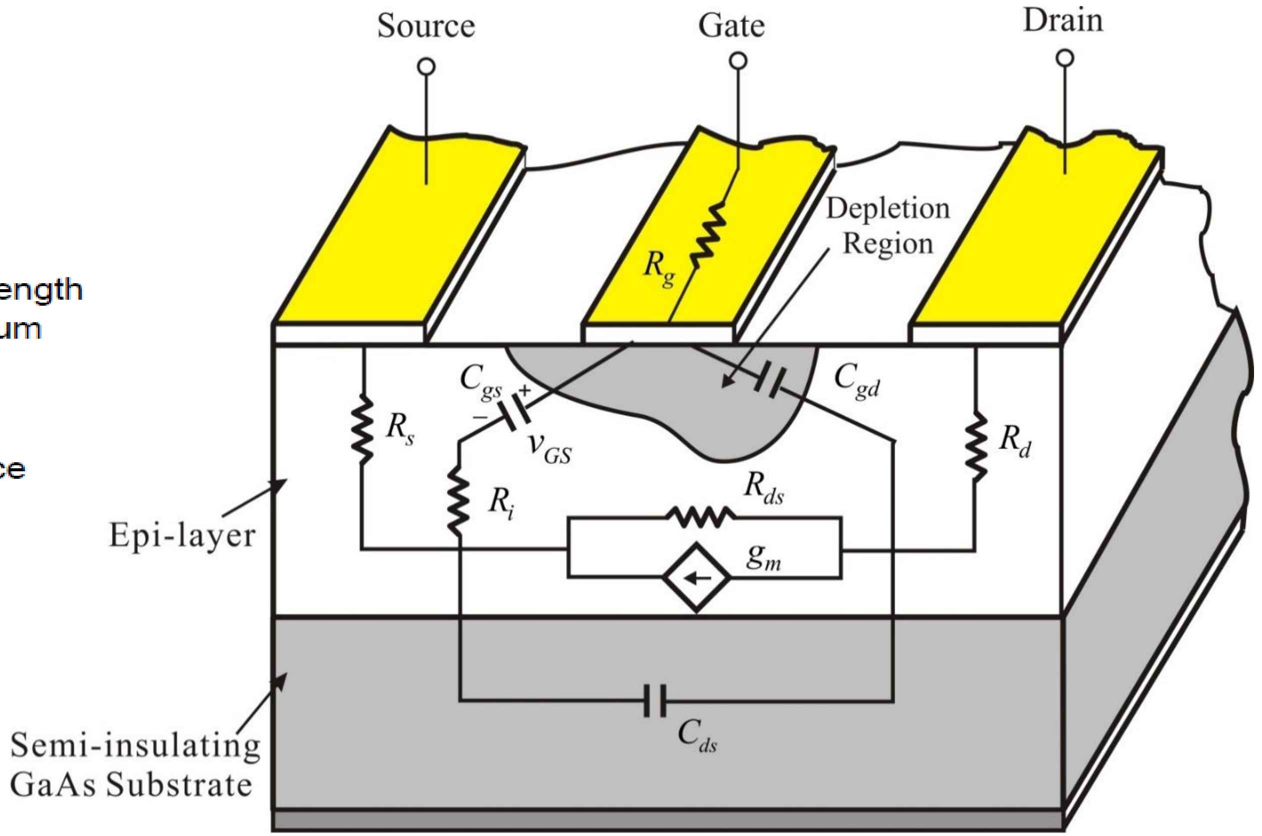
❖Structure of GaAs MESFET





GaAs MESFET

- Electron-rich n-type epitaxial layer (epi-layer) is grown on semi-insulating GaAs substrate
  - drain and source terminals are formed as ohmic contacts
  - gate terminals are formed as Schottky contact

GaAs MESFET

- When a negative voltage is applied to the gate,
  - the diode between the gate and the epitaxial layer is reverse-biased
    - no current flows
  - Due to this reverse voltage, a depletion region with no carriers occurs in the epitaxial layer.
- When the negative voltage applied to the gate is increased,
  - the depletion region will be further widened, which
    - results in narrowing of the channel where electrons can flow.
  - This causes the drain-source current to be further reduced.

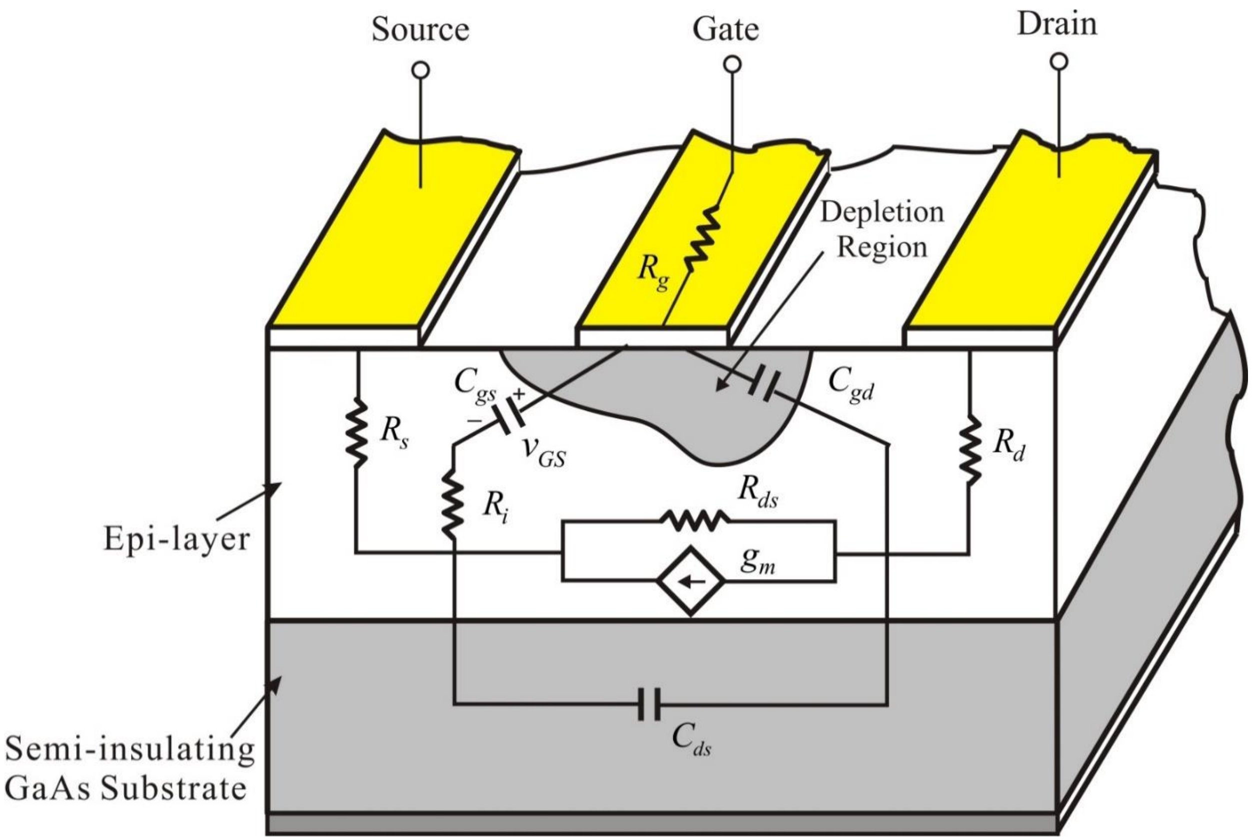
GaAs MESFET

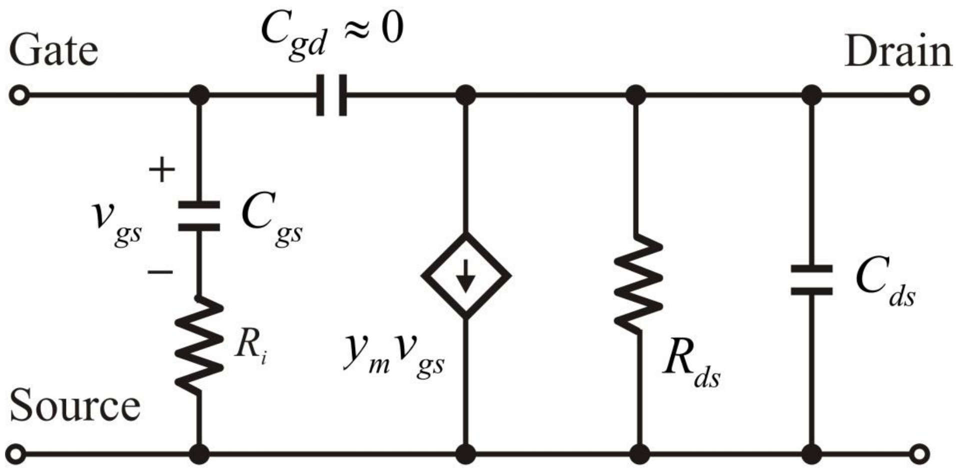
- Therefore
  - the current flowing in the drain-source in this device is controlled through the gate voltage.

GaAs MESFET

- Simplified Equivalent Circuit

$$S_{21} = -2g_m Z_o = 2g_m Z_o \angle 180°$$





$$y_m = g_m e^{-j\omega\tau}$$

$$S_{12} = 2j\omega C_{gd} Z_o = 2\omega C_{gd} Z_o \angle 90°$$

GaAs MESFET

- Resistors R_s and R_d
  - represent the ohmic resistance from source and drain ohmic contacts
- Resistor R_g represents the gate metallization resistance.
- trans-conductance g_m
  - represents dependence of drain current on the gate voltage
- resistance R_{ds}
  - represents dependence of drain current on v_{DS}
- Resistor R_i is channel resistance

GaAs MESFET

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- Capacitors C_{gs} and C_{gd}
  - represent the capacitances caused by the depletion region
    - between the gate and source terminals C_{gs}, and
    - between the gate and drain terminals C_{gd} respectively.
- Capacitor Cds
  - represents the capacitance occurring between the terminals of the source-drain.

GaAs pHEMT

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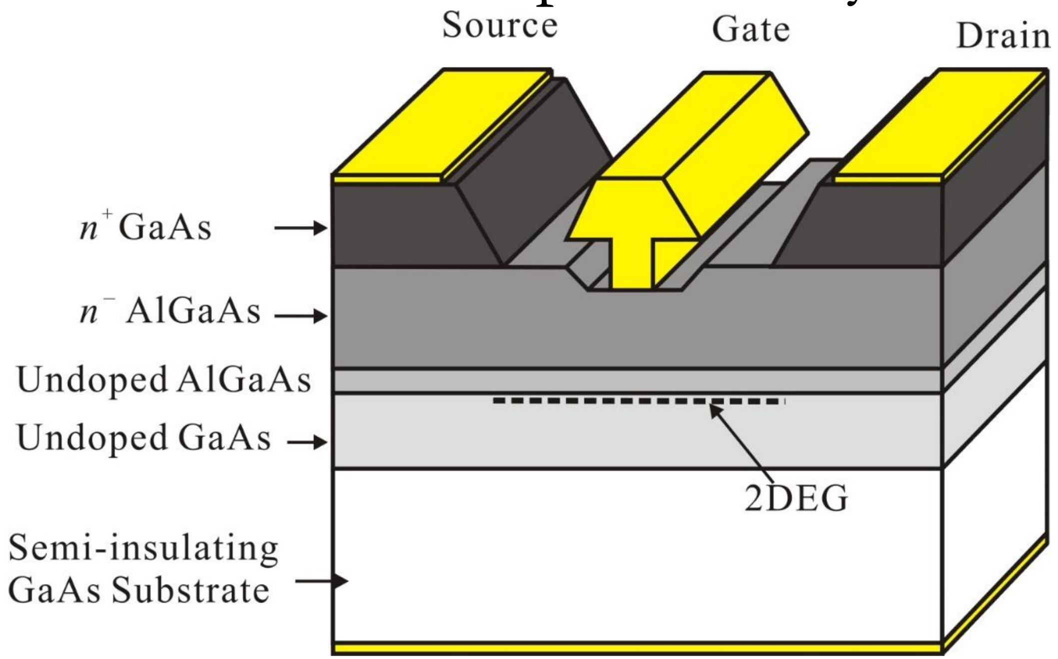
- In MESFET velocity of electrons, limited by the impurity doping which is done to generate electrons (impurity scattering)
  - Problem solved in GaAs pHEMT by Use of ***Electron well***



2-Dimensional Electron Gas (2DEG)

GaAs pHEMT

- Note:
  - the lattice constants of the AlGaAs and GaAs differ significantly
  - and so it is difficult to grow a stable AlGaAs layer on the GaAs.
- Stable crystal growth is done using pseudo-morphic techniques
  - i.e. inserting extremely thin undoped InGaAs layer between undoped GaAs and undoped AlGaAs layer.
- The device is thus called
  - GaAs **p**seudomorphic **H**igh **E**lectron **M**obility **T**ransistor (***GaAs pHEMT***)

Bipolar Junction Transistor (BJT)

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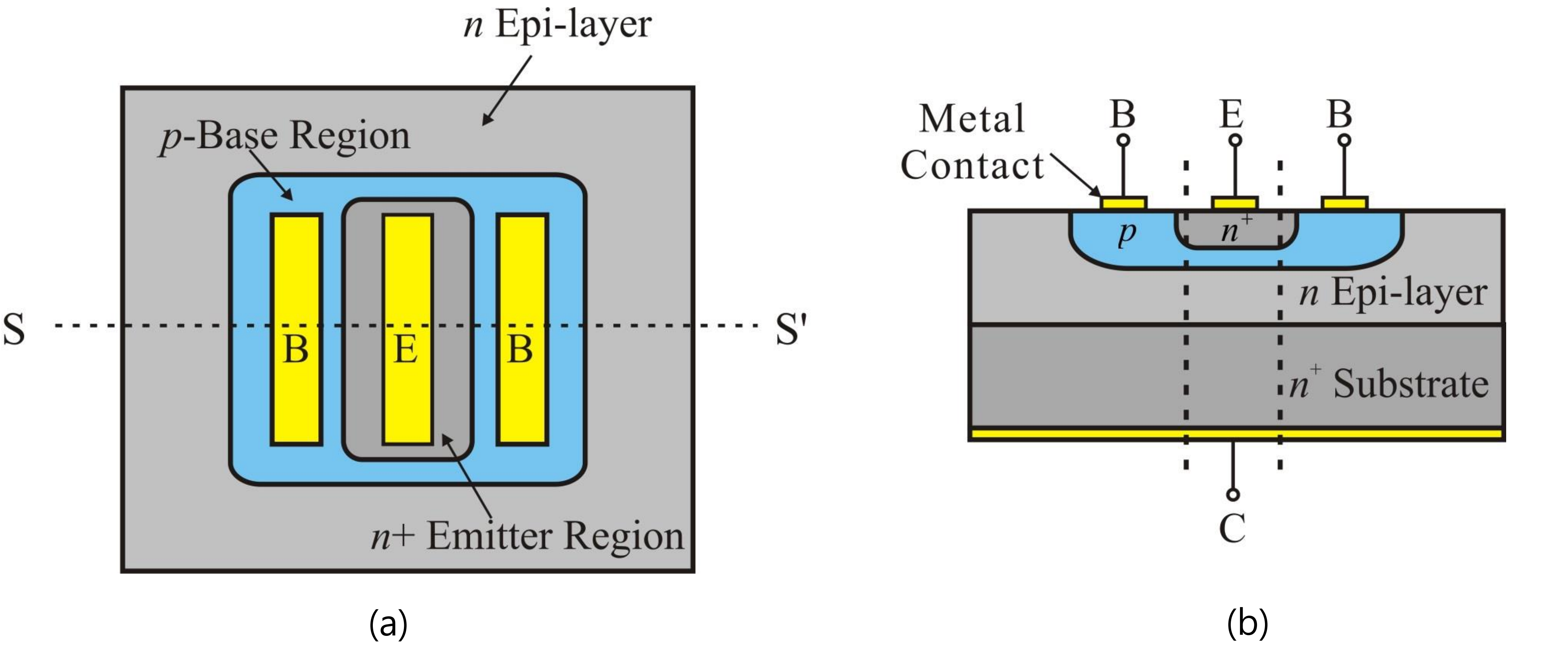
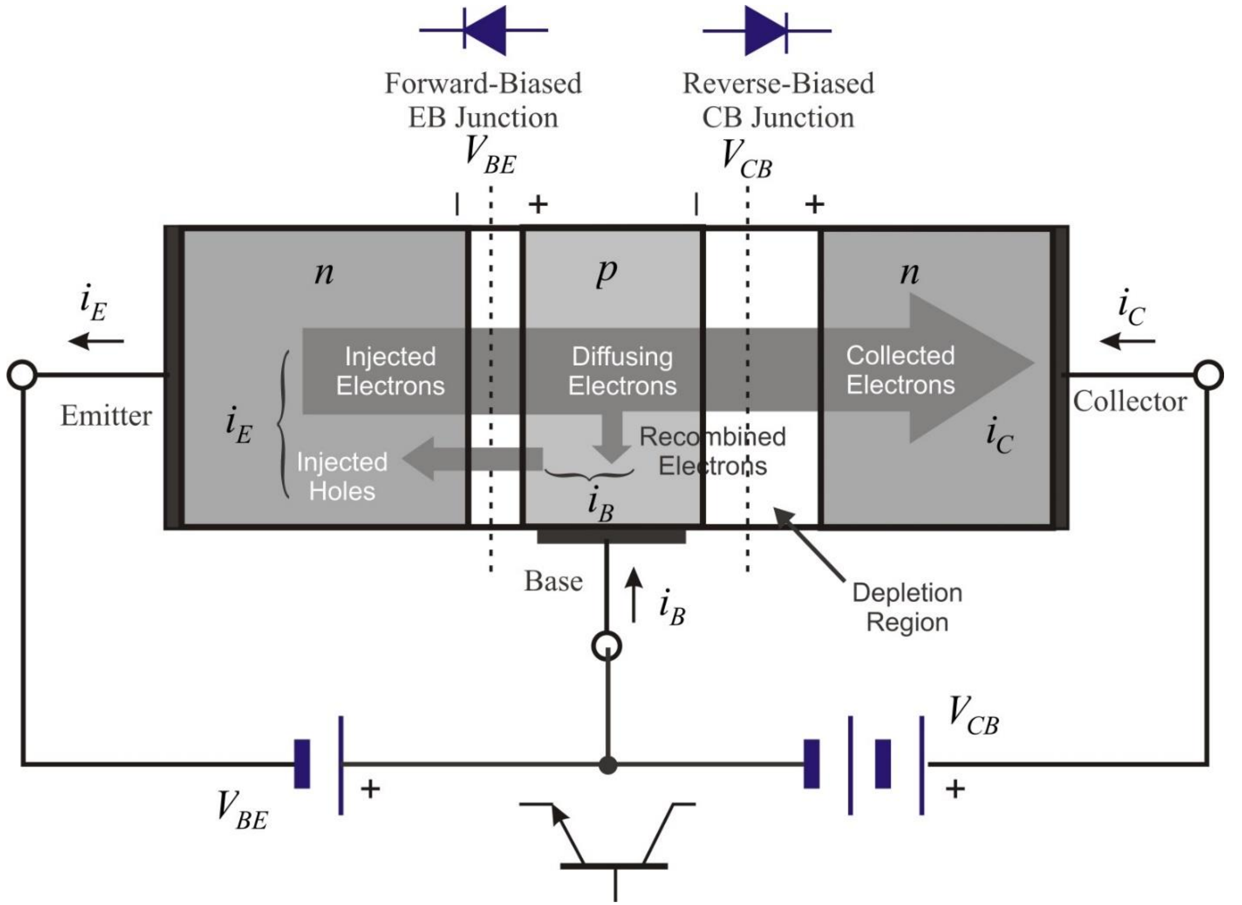


Structure of BJT: (a) Top view and (b) cross-section through line S-S'

The Operation Principle of *n-p-n* Transistor



Current flow of *npn* transistor biased to operate in the active mode.

The Operation Principle of *n-p-n* Transistor

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- To operate the BJT in the active region,
  - the BE junction is forward-biased
  - while the CB junction is reverse-biased
    - Thus the barrier height of the BE junction is lowered while
    - That of the CB junction is raised.
  - Due to the lowered BE junction barrier height,
    - electrons in the emitter region can diffuse into the base region while
    - the holes in the base region diffuse into the emitter region.

The Operation Principle of *n-p-n* Transistor

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- On the other hand, because the CB junction is reverse-biased,
  - No diffusion occurs between the collector and base due to increased barrier height.
  - Normally, the emitter region is more heavily doped than the base region.
  - Thus, more electrons will diffuse from the emitter to the base than holes from the base to the emitter.
  - Consequently, the current contribution from the diffusion of holes can be neglected.
  - Small number of the diffused electrons from the emitter recombines and there by disappears in the base region while
  - most of the electrons reach and are collected in the collector region.

The Operation Principle of *n-p-n* Transistor

- Note that
  - the emitter current i_E depends on the BE junction barrier height,
  - which in turn is controlled by a small voltage applied to the BE junction, V_{BE} .
  - large emitter current flow of BJT can be controlled by a small voltage V_{BE}, thereby acting as amplifier.

High-frequency BJTs

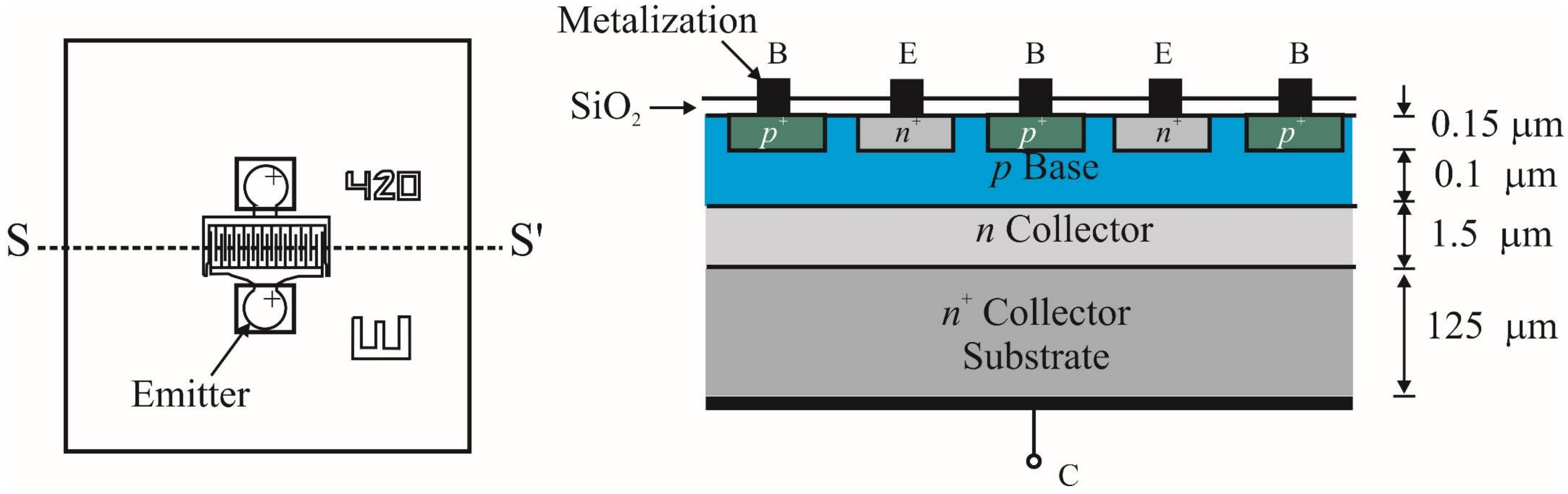
- high frequency performance
  - is strongly related to the base width.
  - The electrons injected from the emitter should transit the base region to reach the collector.
  - The transit time is related to the base width.
- Thus, the base width should be as narrow as possible.

High-frequency BJTs

- Secondly a base spreading resistance occurs
  - due to the distance between the true base region and the actual base terminals
  - thus, high frequency gain is reduced.
- The base spreading resistance can be reduced
  - by increasing the base region doping.
  - However, this increases the number of holes and consequently
  - holes diffusing from the base to the emitter increases.
  - As a result, the base current increases, which is not useful.

High-frequency BJTs

- As a way of reducing the base spreading resistance, base and emitter is implemented using the inter-digital structure

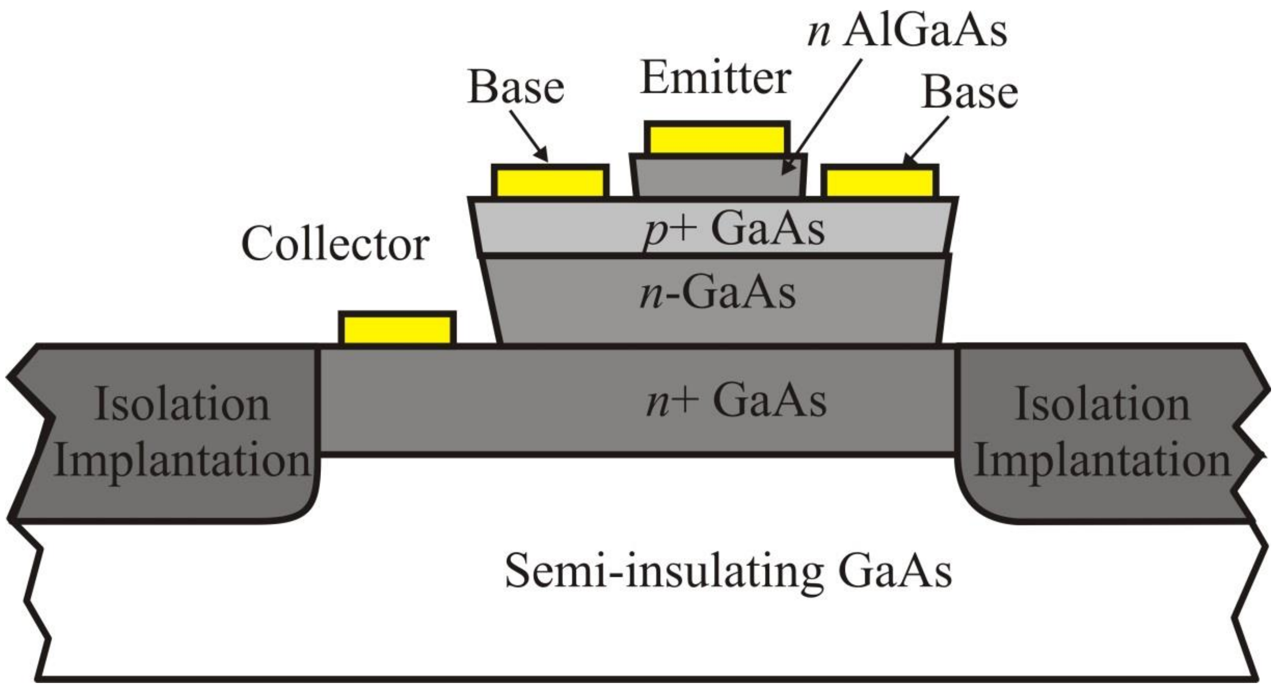


(a) (b)

High-frequency BJT's (a) top and (b) cross-sectional views

GaAs/AlGaAs HBT

- GaAs HBT improves the performance of Si BJT



  - diffusion constant of electrons in GaAs, *Dn* is 4x bigger than in Si

Active Devices For Power Amplifiers

- pHEMT and HBT
  - were noted to have excellent high-frequency characteristics.
  - However, their structure must be modified to handle large output power
  - This is done by
    - expanding the gate width in the case of the pHEMT and
    - the emitter area in the case of HBT.
  - the breakdown voltage of these devices is basically low
    - this limits their application as high power devices

Active Devices For Power Amplifiers

- High power active devices include,
  - GaN HEMTs and
  - LDMOSFET (Laterally Diffused MOSFET),
    - simply referred to as LDMOS

Active Devices For Power Amplifiers

- The important parameters of semiconductor material for a high-power application are
  - electron mobility,
  - energy band-gap (band-gap), and
  - thermal conductivity.

Active Devices For Power Amplifiers

- The higher the electron mobility,
  - The higher the frequency it can be applied to and
  - the higher the gain.
- The higher the thermal conductivity,
  - the greater the advantage in heat dissipation

Active Devices For Power Amplifiers

- The higher the band-gap is,
  - the higher the breakdown voltage.
  - Thus higher band-gap semiconductor is advantageous in constructing high power devices.
- The energy band-gap is defined as
  - the difference in energy between the conduction band and the valence band.

Active Devices For Power Amplifiers

- Thus, a higher energy band-gap means
  - valence band electrons can seldom move into the conduction band
    - because they require energy sufficiently higher than the energy band-gap to move into the conduction band.
- On the other hand, when the energy band-gap is low,
  - the valence band electrons can easily move into the conduction band
    - as they can easily attain the required energy.
  - The energy band-gap is thus an important measure in the estimation of the ***breakdown voltage*** of an active device

Active Devices For Power Amplifiers

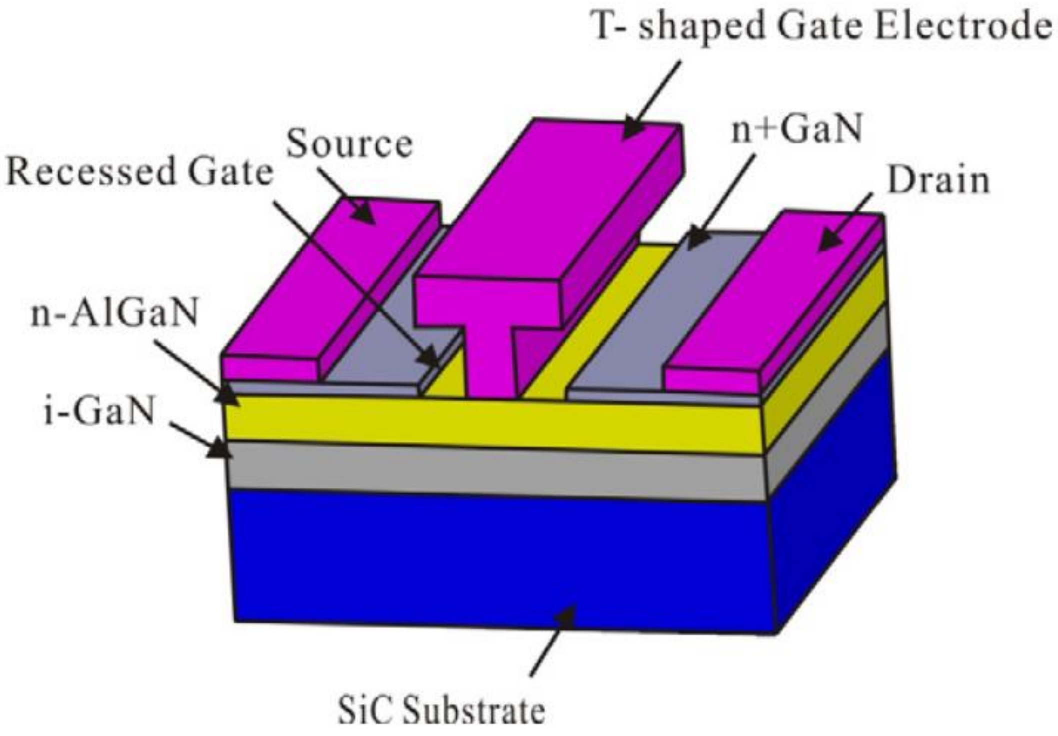
- Comparison of the properties of various semiconductors

Property	Si	GaAs	SiC	GaN
Energy-gap [eV]	1.11	1.43	3.2	3.4
Break down voltage [V/cm]	6.0×10^5	6.5×10^5	3.5×10^6	3.5×10^6
Saturation velocity [cm / sec]	1.0×10^7	2.0×10^7	2.0×10^7	2.5×10^7
Electron mobility [cm^2/ V·s]	1350	6000	800	1600*
Thermal conductivity [W/cm°K]	1.5	0.46	3.5	1.7
Hetero-junction structure	SiGe/Si	AlGaAs/GaAs InGaP/GaAs AlGaAs/InGaAs	None	AlGaN/GaN InGaN/GaN

* The electron mobility of GaN is the electron mobility of AlGaN/GaN at the hetero-junction.

GaN HEMT

- GaN process suitable for active device for high frequency power amplifier



T-shaped gate terminal on the n–GaN layer is to minimize the resistance of the gate terminal and

to decrease the gate length for improved frequency characteristics.

GaN HEMT

- HEMT structure
  - is primarily related to the electron mobility of GaN, i.e.
- maximum electron mobility
  - can be obtained by employing a HEMT structure
- V_{DS} can be applied up to 100V, and
  - this device does not show breakdown in spite of higher DC voltage.
- Reaches maximum power gain at about 20 GHz

LDMOSFET

- LDMOSFET (Laterally Diffused MOSFET)
  - is a high power active device fabricated using Si process technology,
  - and has a structure designed to improve the breakdown voltage of MOSFET.
  - channel electrons attain sufficient energy at a high drain voltage V_{DS}
  - The electrons collide with the atoms in the drain region with high impurity doping for ohmic contact.
  - More electrons are generated due to the collision, and
    - these electrons gain the energy sufficient for them to move into the conduction band.

LDMOSFET

- More electrons are generated due to the collision, and
  - these electrons gain the energy sufficient for them to move into the conduct -ion band
- Thus, there is a sudden increase in the drain current.
- As a result, LDMOSFET shows a lower breakdown voltage

LDMOSFET

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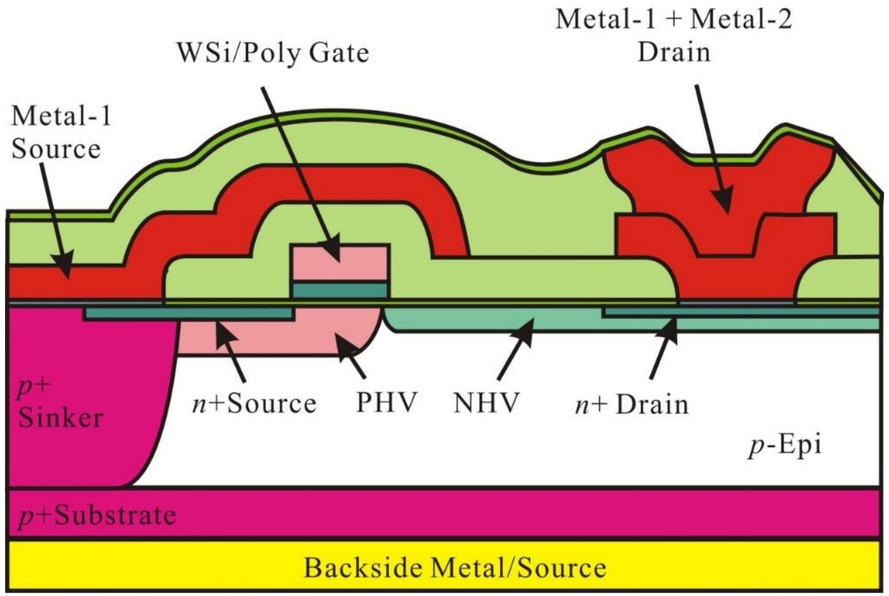
❖Cross-section of LDMOSFET



- PHV: a high voltage P-region, NHV; a high voltage N-region with

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LDMOSFET

Structure of LDMOSFET

- the drain region is laterally divided into
  - a shallow doped region and
  - high impurity-doped region for the ohmic contact.
- the drain terminal is located at a considerable distance from the channel.
  - As a result, the accelerated electrons in the channel primarily collide in the drain region with low impurity concentration and
  - consequently, lose energy when they reach the n+ drain region.
  - Thus, this leads to a higher breakdown voltage

LDMOSFET

- compared with the case in which the electrons collide directly in the drain region.
- The next thing to note is that, the source terminal is attached to the bottom of the device.
- By so doing,
  - wire bonding is not required to connect the source terminal to the ground.
  - Thus, the inductance arising from the wire-bonding during packaging assembly is eliminated
  - which is an advantage in assembly.

BJT DC Bias Circuit Design

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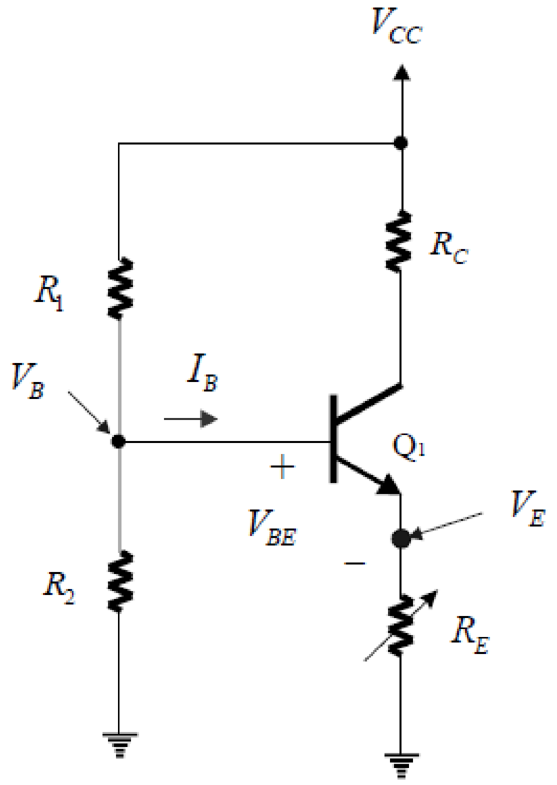
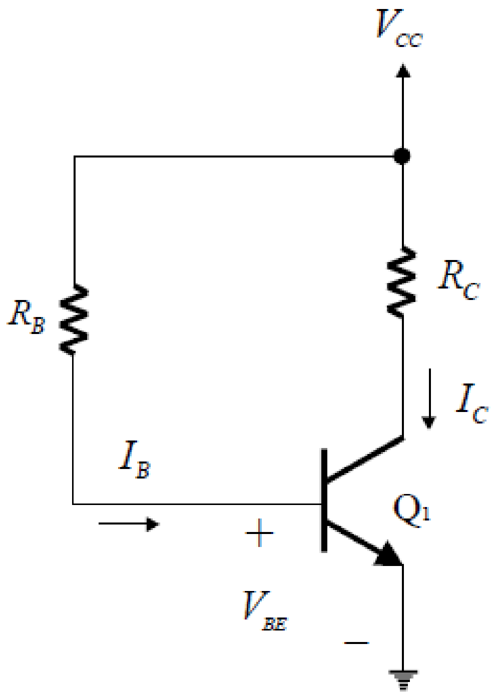


Prefered at low frequency



preferred at high frequency

$$V_B = \frac{R_2}{R_1 + R_2} V_{CC}$$

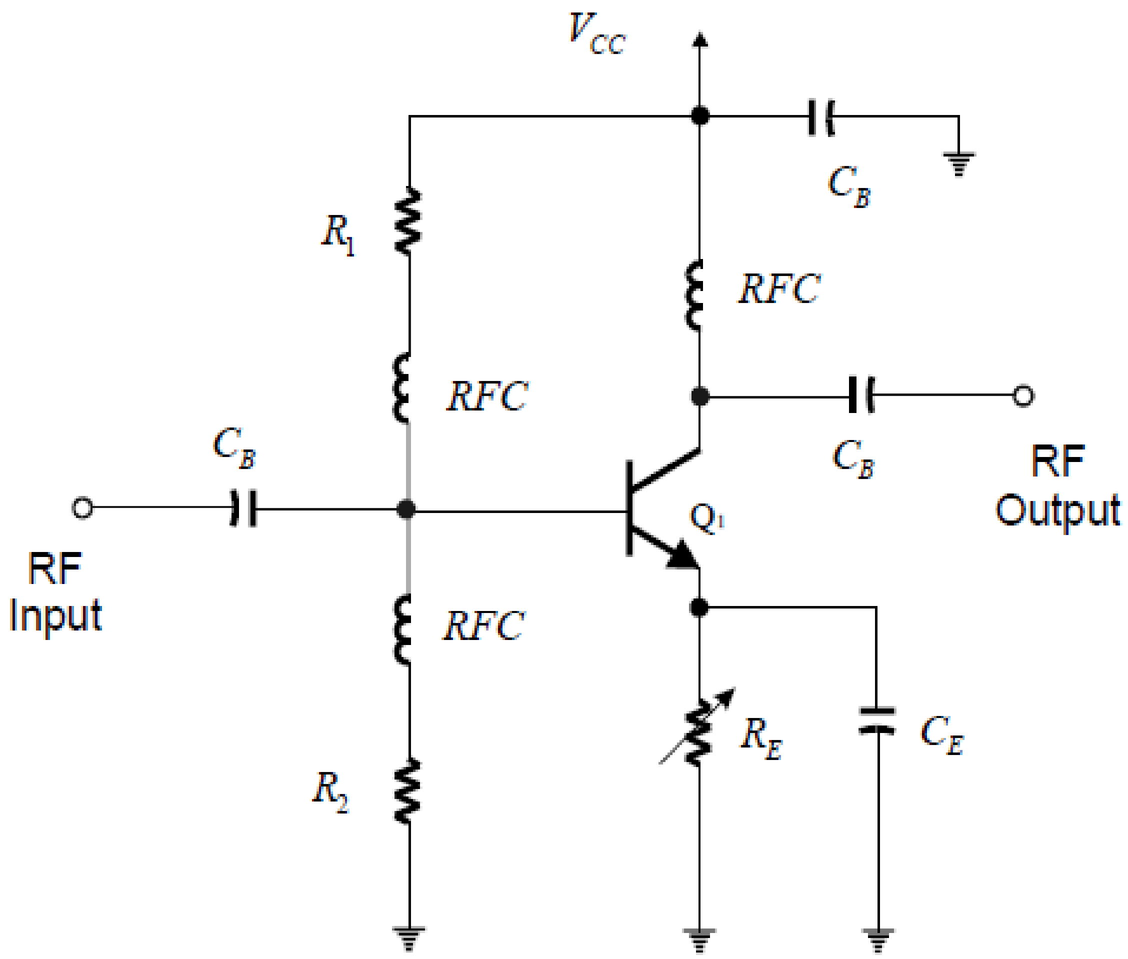
$$I_E = \frac{V_B - V_{BE}}{R_E}$$

$$I_B = \frac{V_{CC} - V_{BE}}{R_B}$$

$$I_C = \beta I_B$$

RF Decoupling

- RFCs are not necessary where a resistor can sufficiently ensure an open-circuit for RF.
- RFC in the figure shows an open circuit at the operating frequency and makes the collector terminal to be open.



FET DC Bias Circuit Design

- FET DC bias circuit:
  - Self bias circuit
  - DC bias circuit using two DC sources