4.5 Gunn diode

Module:4 Microwave Sources

Course: BECE305L – Antenna and Microwave Engineering

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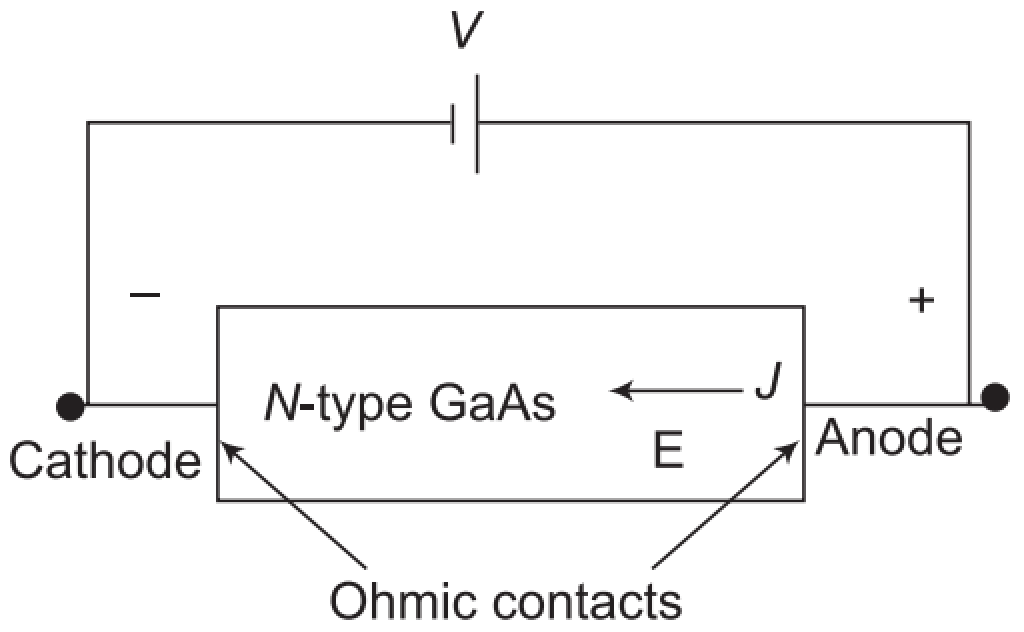
Module:4 Microwave Sources 5 hours

- Microwave frequencies and applications, Microwave Tubes: TWT, Klystron amplifier, Reflex, Klystron & Magnetron. Semiconductor Devices: Gunn diode, Tunnel diode, IMPATT – TRAPATT - BARITT diodes, PIN Diode.

8.1 Gunn diodes – Transferred electron devices (TEDs)

- GUNN diodes are also known as Transferred electron devices
- Low noise devices – named after JB Gunn



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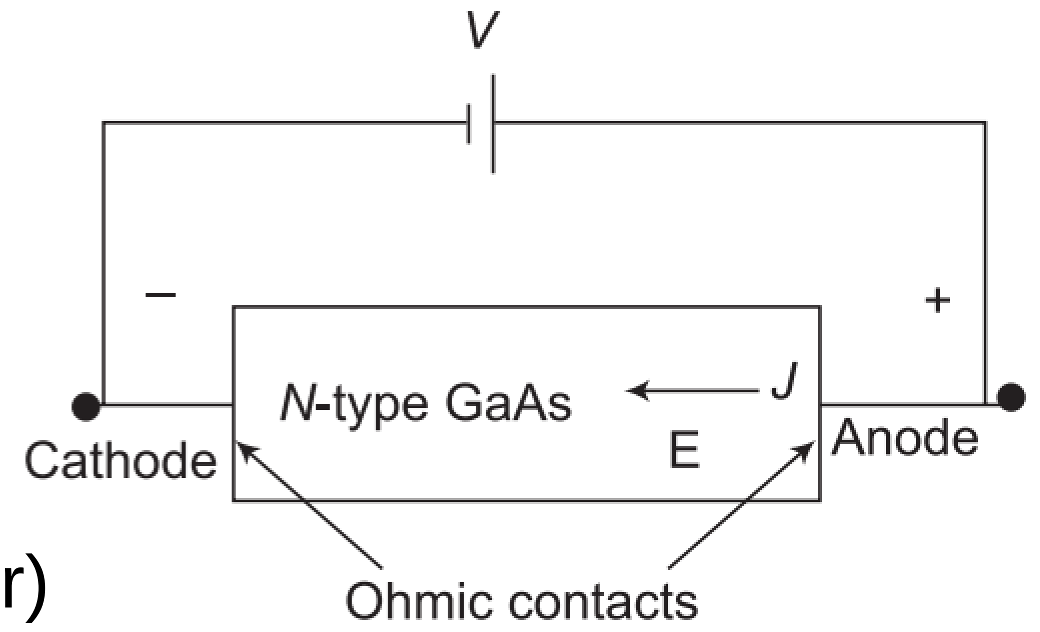
- **Periodic fluctuation of current passing through n-type gallium arsenide** (n-GaAr) sample **when the voltage difference exceeded a certain threshold**.



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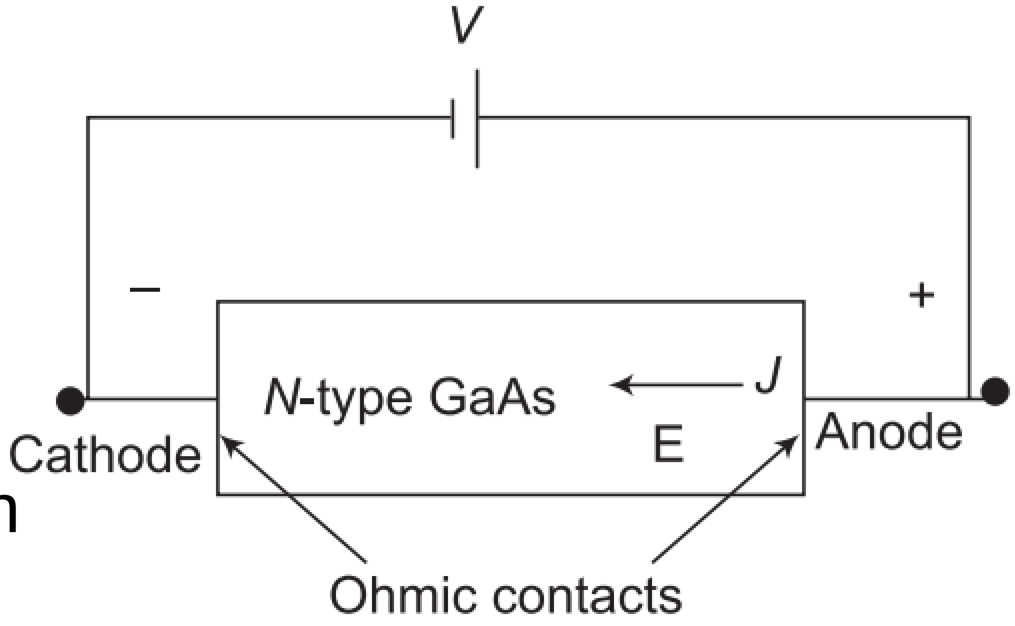
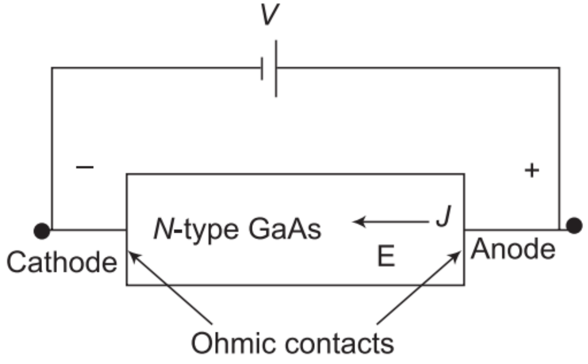
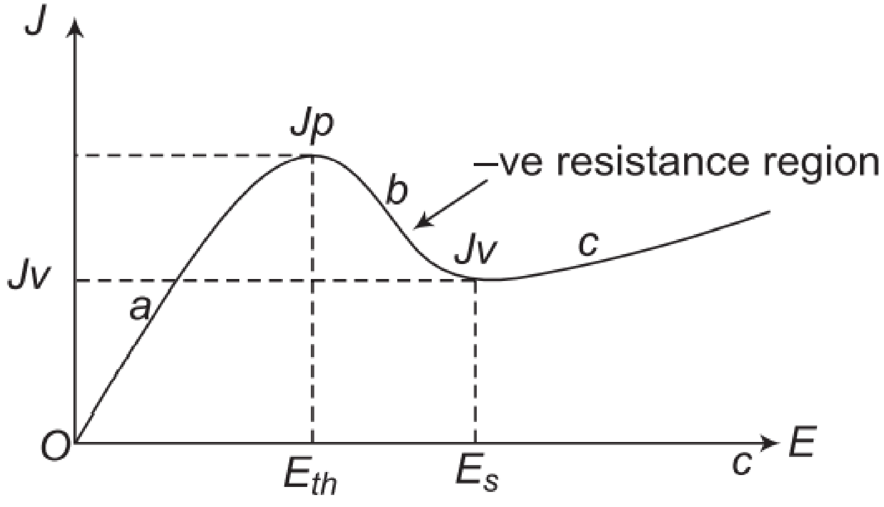


- GUNN diodes are also known as Transferred electron devices
- Low noise devices – named after JB Gunn
- Periodic fluctuation of current passing through n-type gallium arsenide (n-GaAr) sample when the voltage difference exceeded a certain threshold.
- Similar observation in p-type GaAs, Indium phosphate (InP) and in semiconductors (CdTe, Tnsb, InAs, etc)
- **Two metallic ends** act as **cathode** and **anode** in single bulk semiconductor

8.2 Gunn diodes – IV Characteristics

- **DC voltage** - **generates electric field inside the sample with electric current**.





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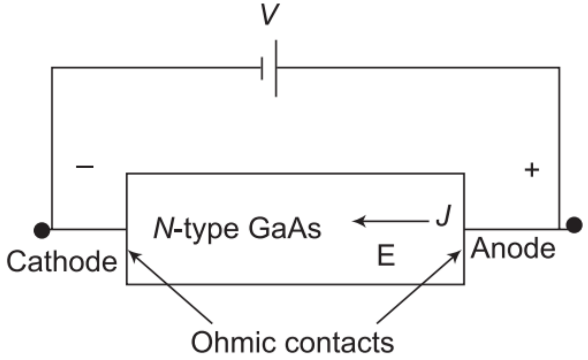

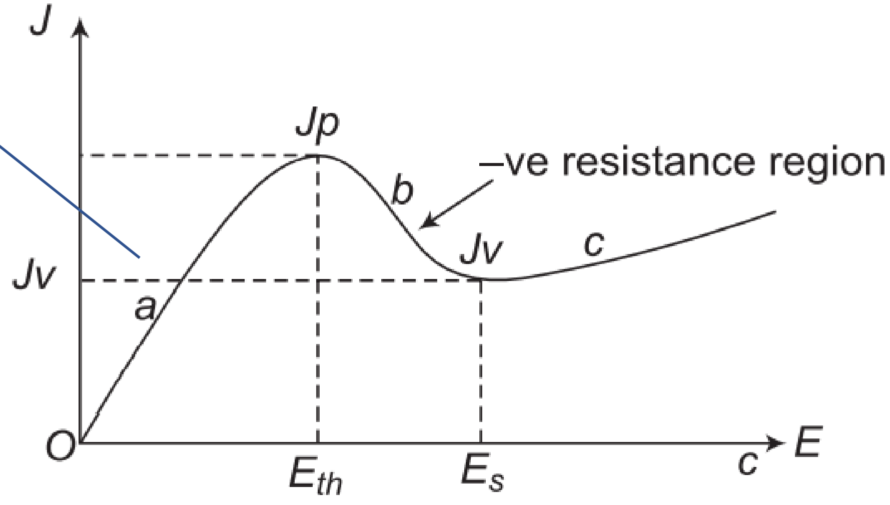

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- When $E_{th} < E$ (slightly)$< E_s$ sustaining value

Negative slope of $J - E$ curve.

Differential resistance $\frac{dV}{dI}$ or $\frac{dE}{dJ}$ is **negative**

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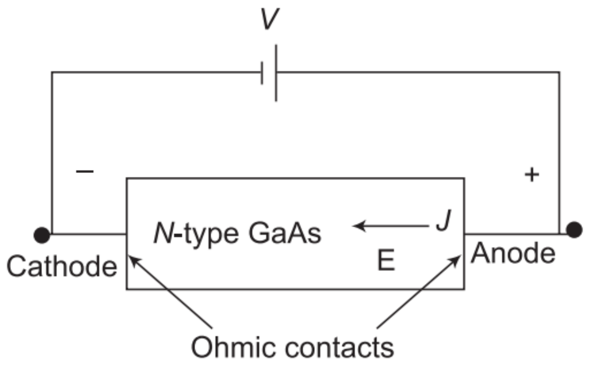

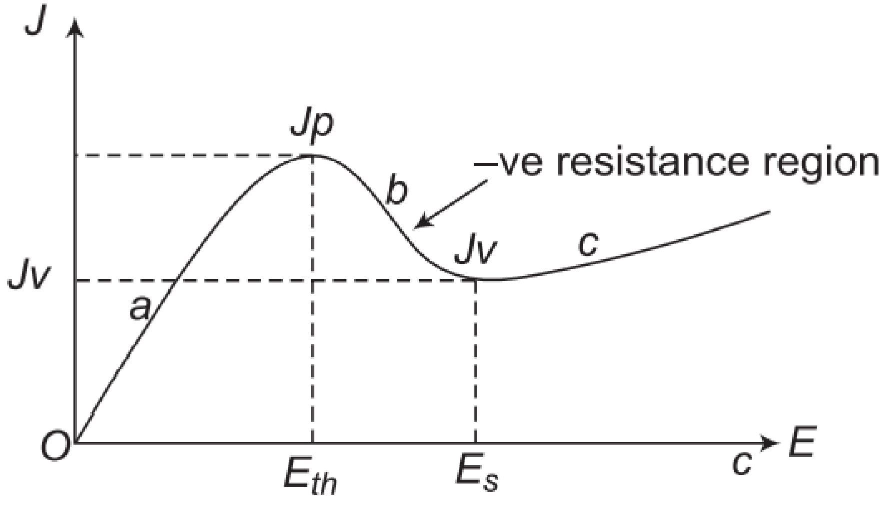

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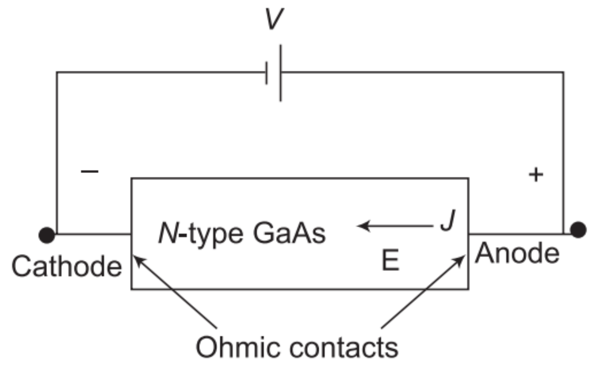
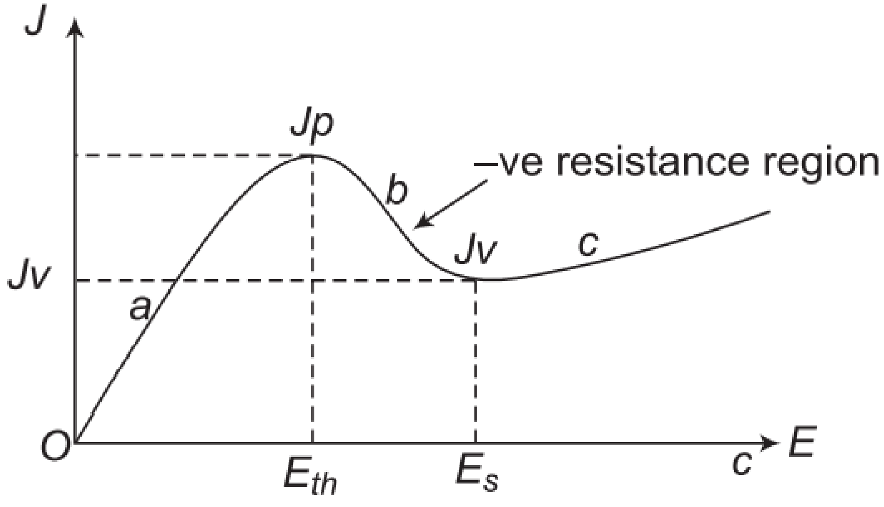
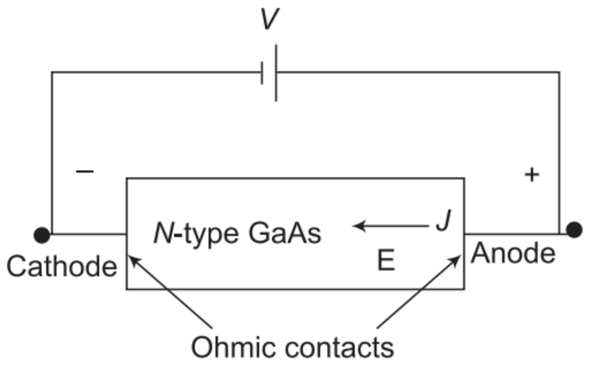


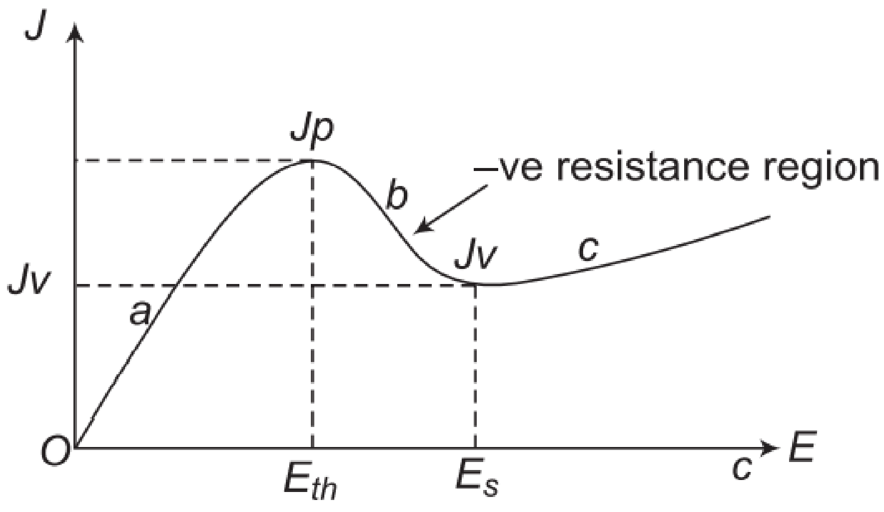
- **This differential resistance is utilized for microwave gunn oscillators**
- External resistance compensation is provided in the circuit to sustain oscillations



8.2 Gunn diodes – IV Characteristics

- Threshold value varies with type of material.
- $n - type\ \mathrm{GaAs}$, critical/ threshold value 3.2 kV/cm
- InP : 10.5 kV/cm





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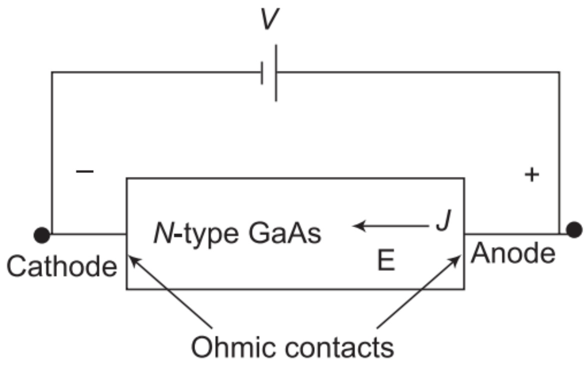
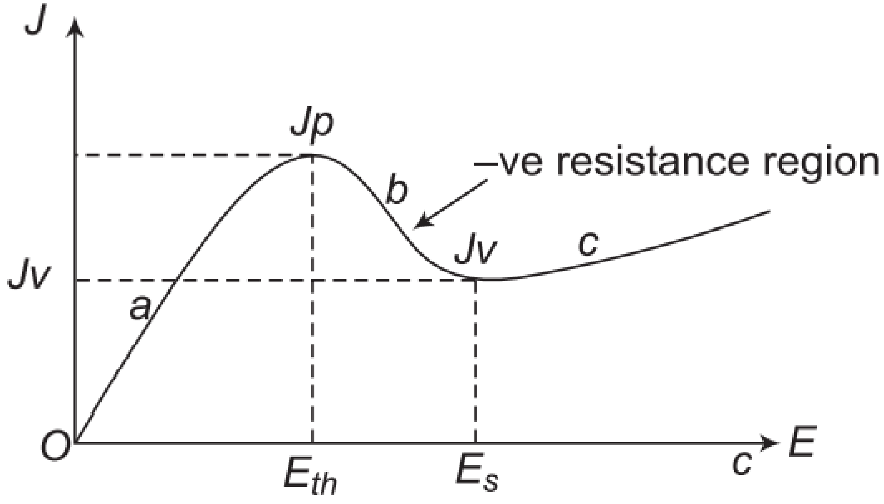


- Applications: Low power microwave oscillator at microwave frequencies in transmitters and also as local oscillators in receiver front ends

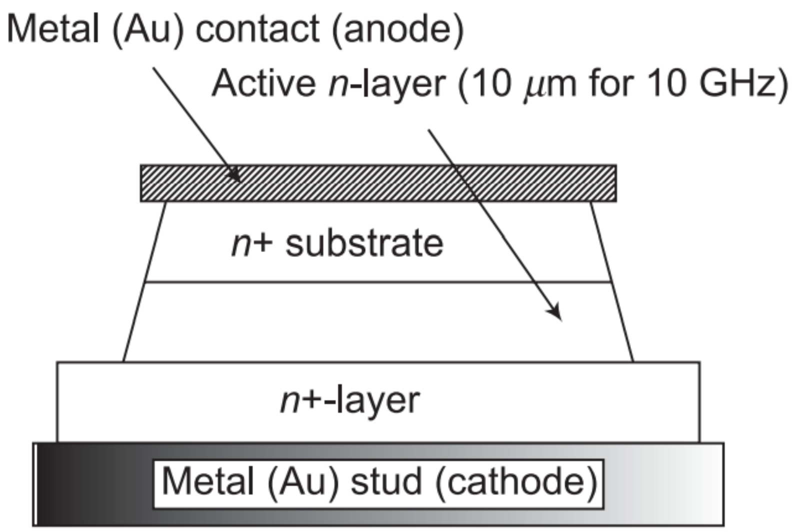


8.3 Construction details and electrical equivalent

- Gold contacts as anode and cathode
- n type GaAs semiconductor

Regions of high doping (n^+)

- GaAs is poor conductor – **heat is generated**. Hence generally a Copper heat sink is used.



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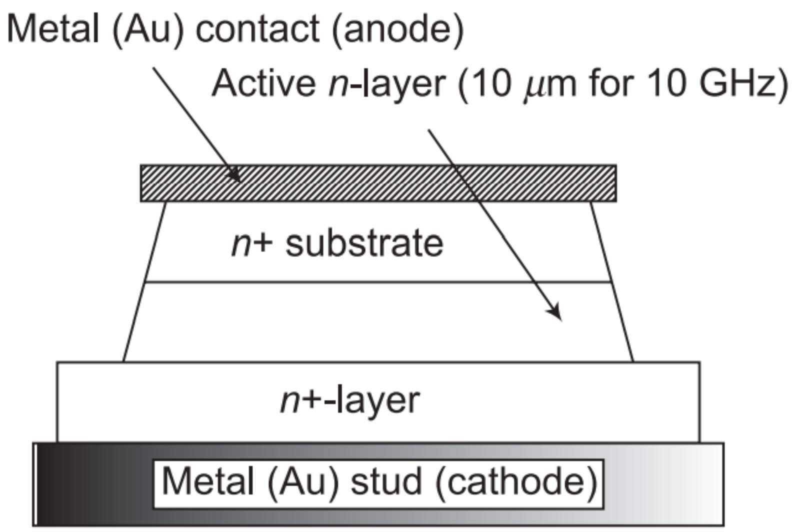
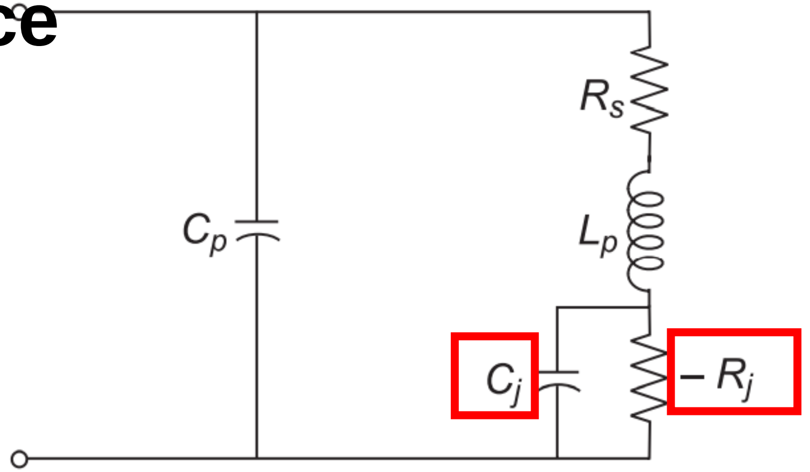
- C_j, $-R_j$: **Diode capacitance and resistance**

  <u>Negative resistance </u>- -5Ω to -20Ω





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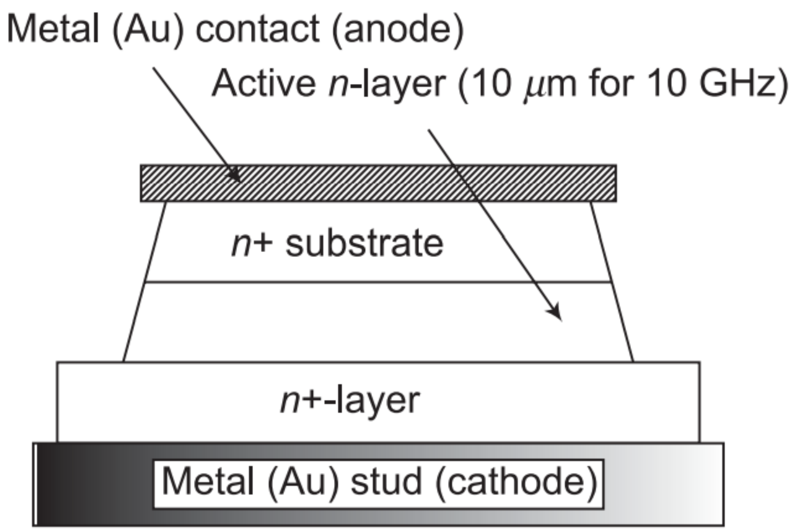

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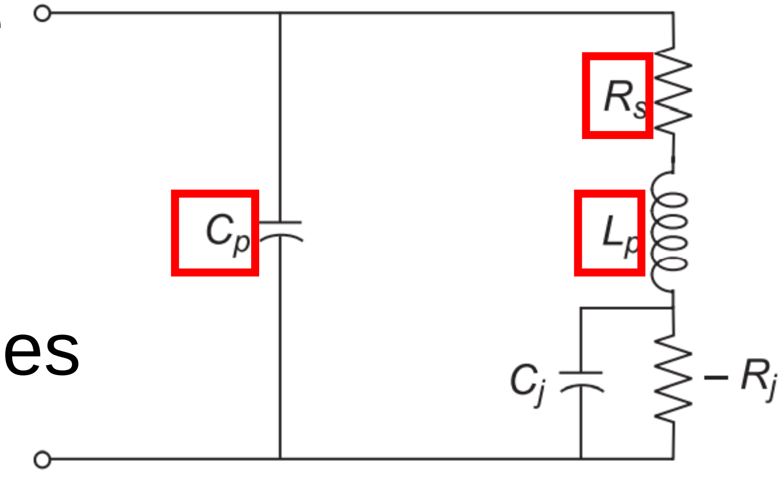
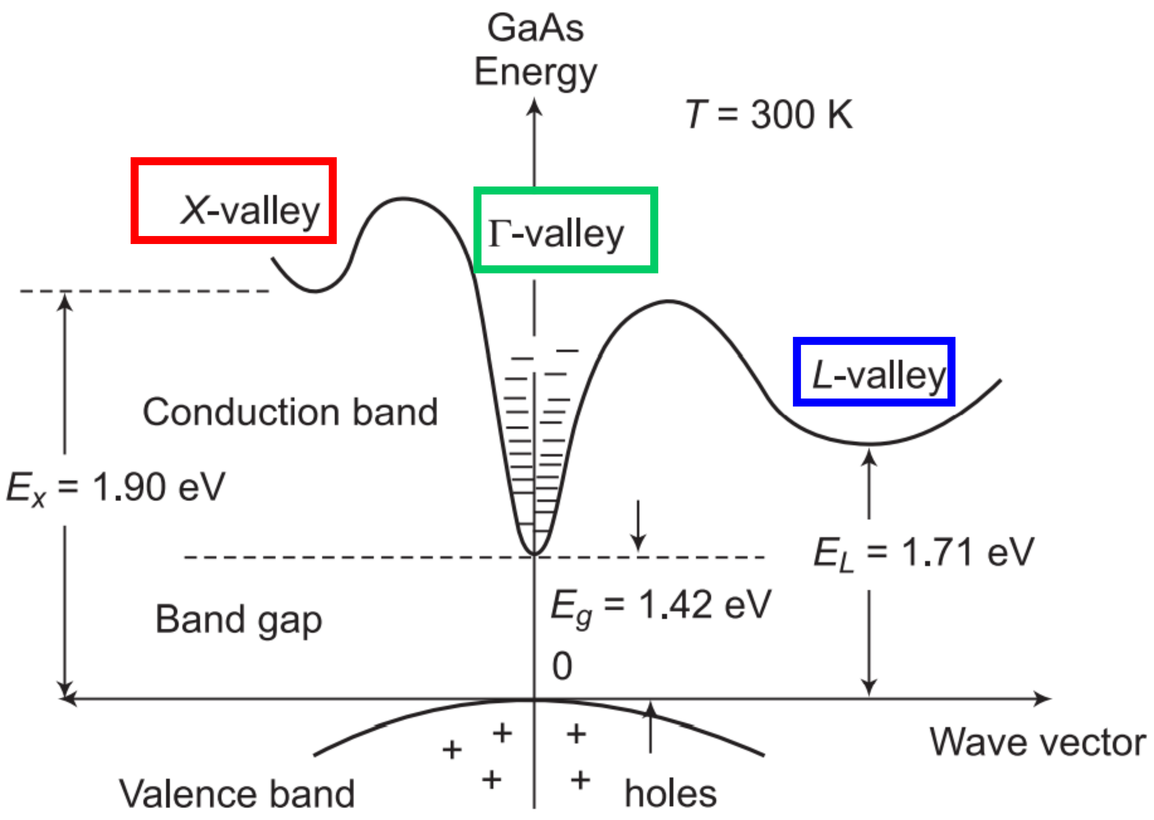
- R_s Total resistance due to ohmic contacts
- C_p, L_p: package capacitance and inductances



8.4 Theory of operation

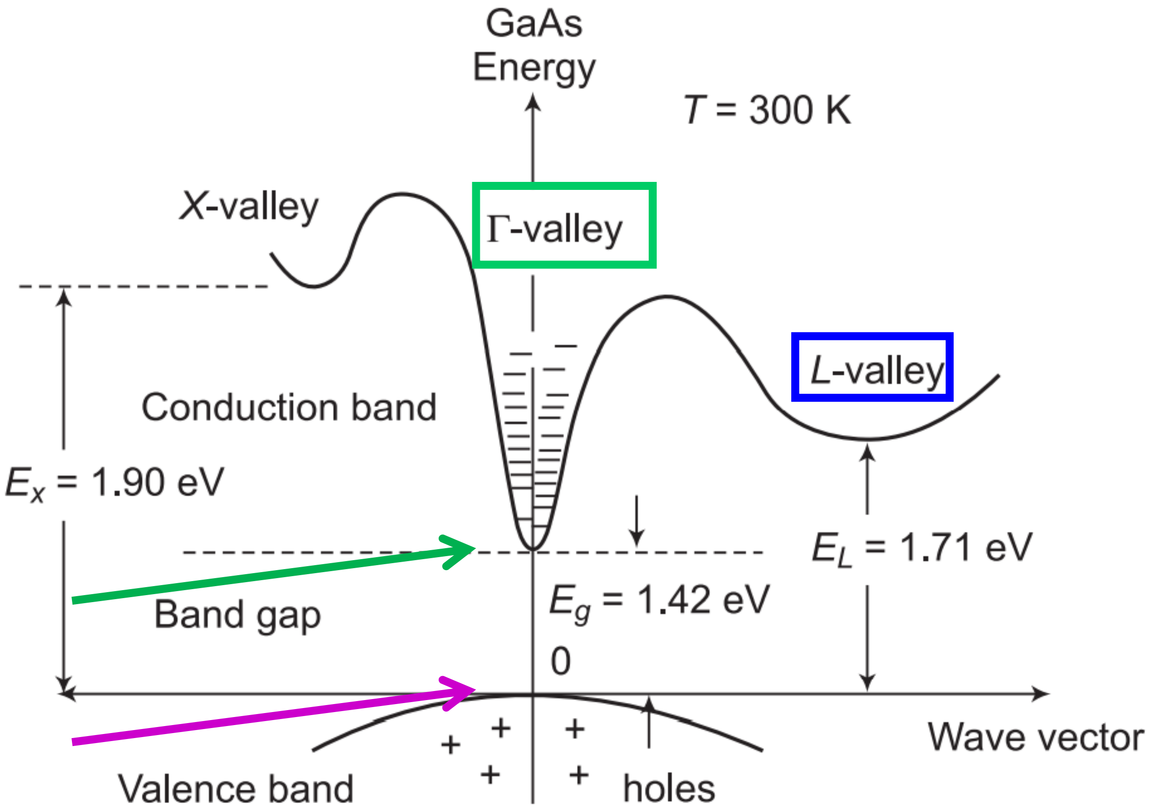
- GaAs: Three conduction sub-bands or valleys (X, Γ, L)



Energy band diagram

8.4 Theory of operation

- GaAs: Three conduction sub-bands or valleys $(\Gamma, \mathrm{L}, \mathrm{X})$
- GaAs: **Superior electron mobility** with one maximum valence band and one minimum conduction band(Γ) **occurring at same wave vector**. (k =propagation constant = $2\pi/\lambda$).



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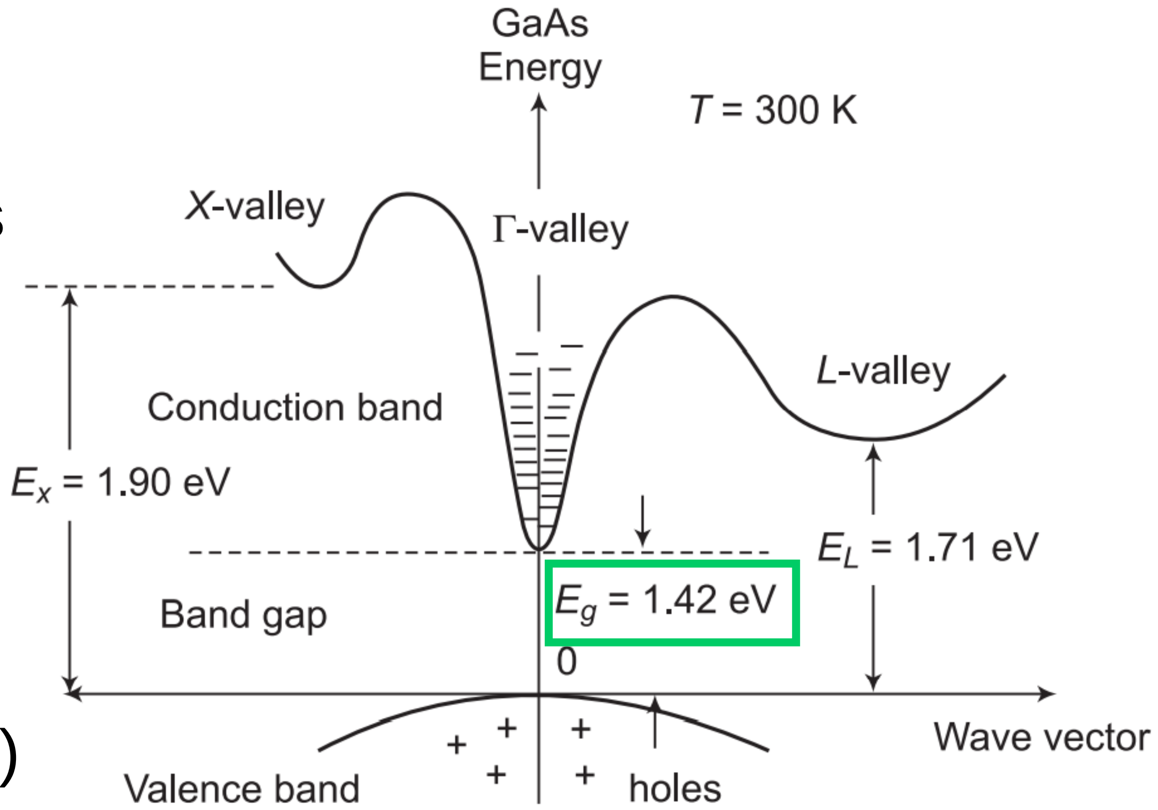
- 1.42 eV band gap energy of separation between the valence and conduction bands(Γ)

Conductivity of the material ∝ electron mobility μ_n



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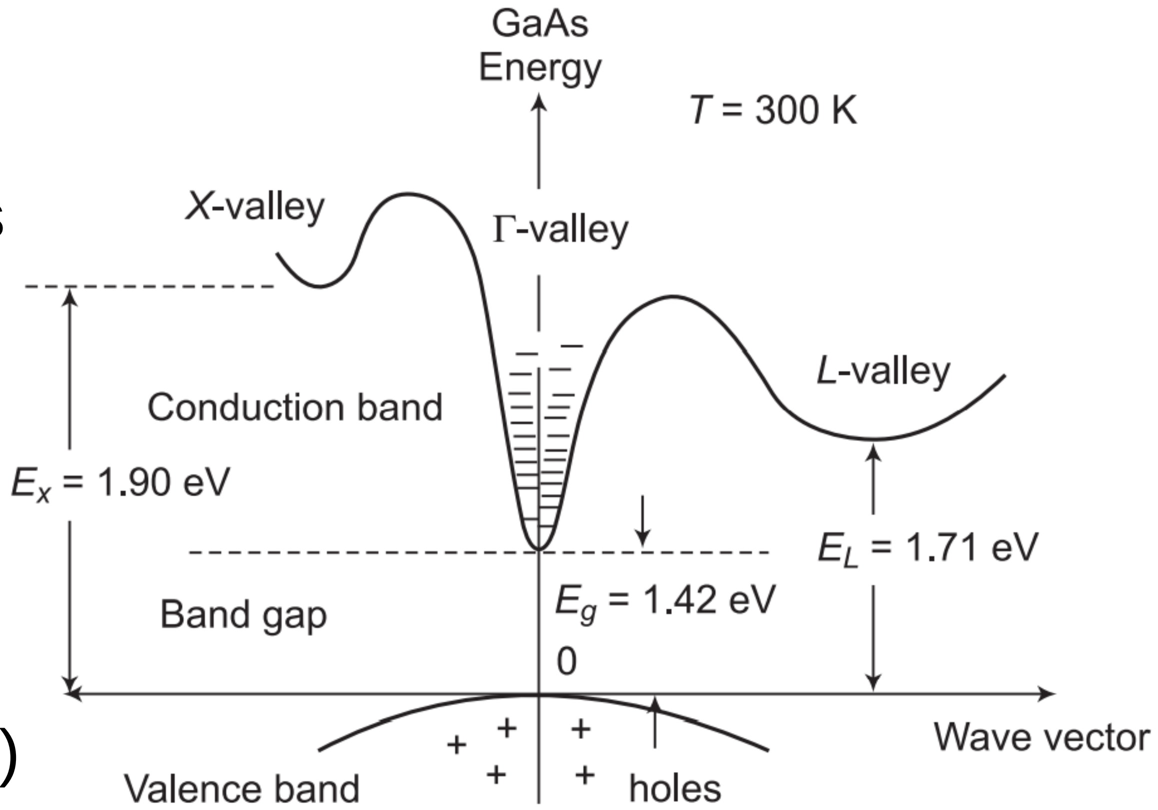

Energy band diagram

Conductivity of the material ∝ electron mobility μ_n

<u>Mobility of electron depends upon:</u>

Concentration of impurity N in the semiconductor

Temperature T Kelvin

Is inversely proportional to electron effective mass, m_n

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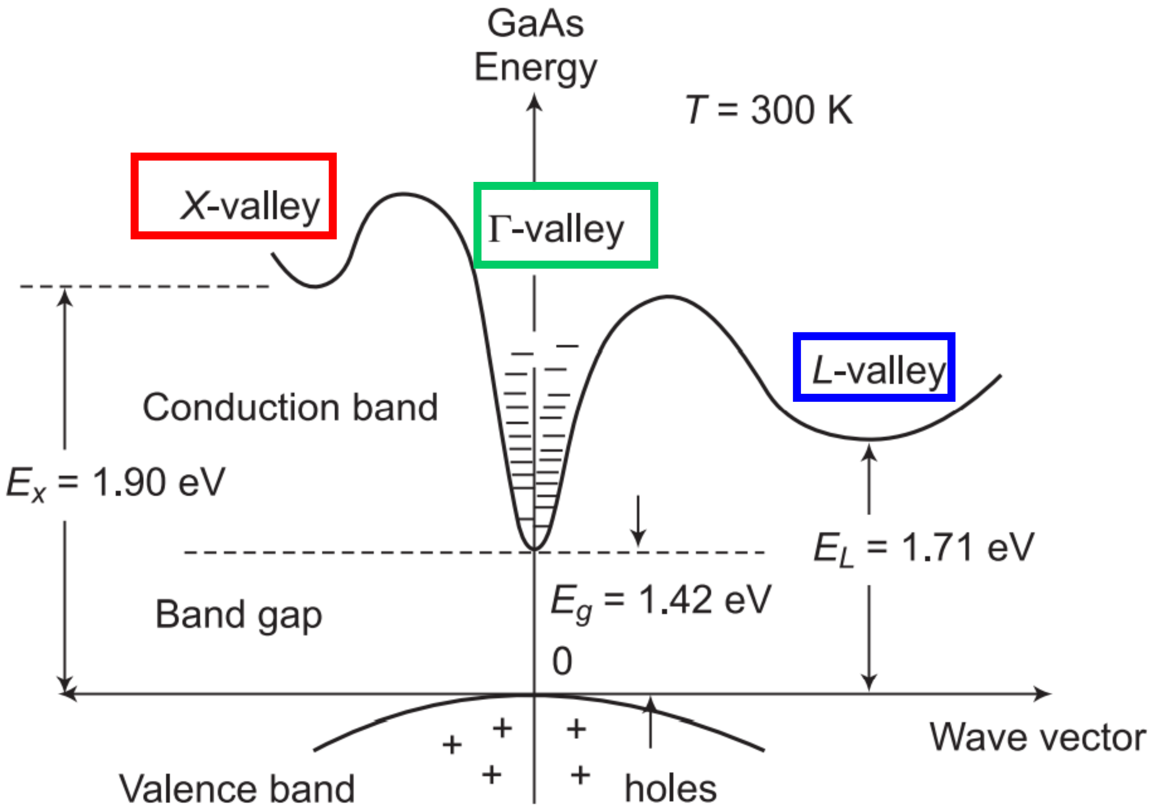
- Current density is related to mobility by

$$J = en\mu_n E = e(n_X\mu_X + n_\Gamma\mu_\Gamma + n_L\mu_L)E$$



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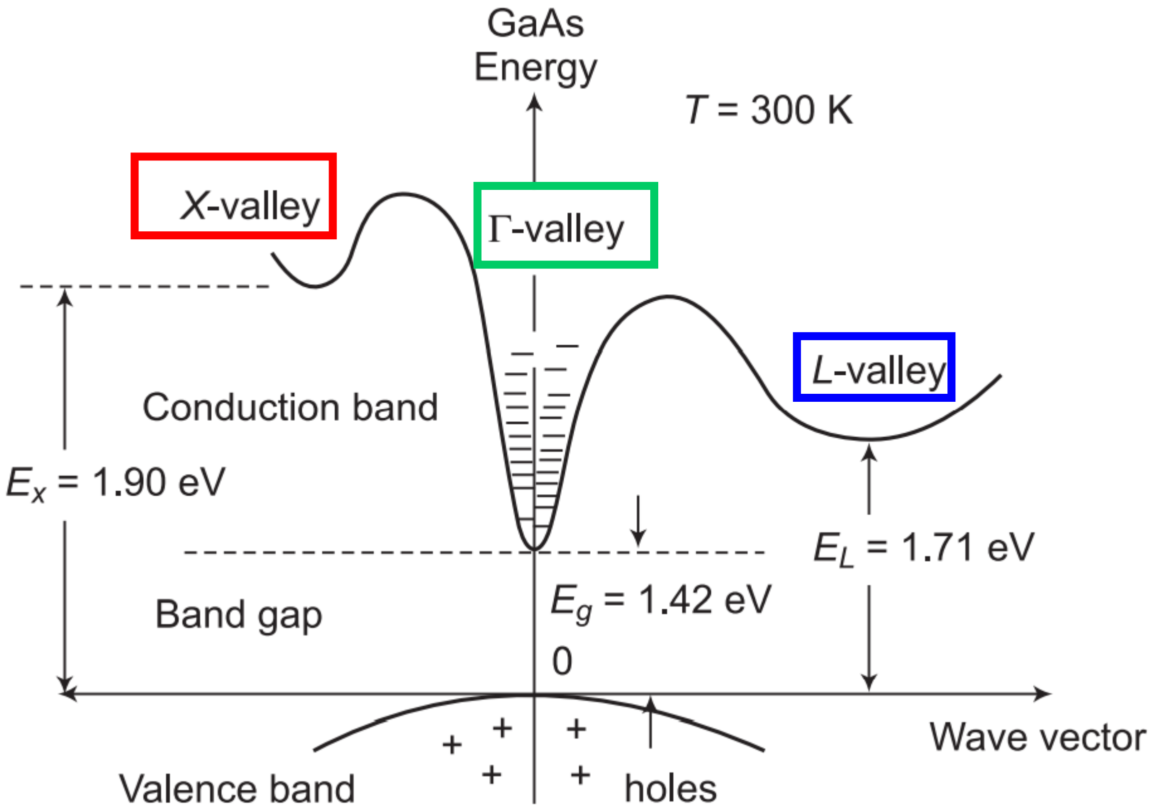
- $e = 1.6 \times 10^{-19} C$ electronic charge
- E: Electric field in semiconductor sample



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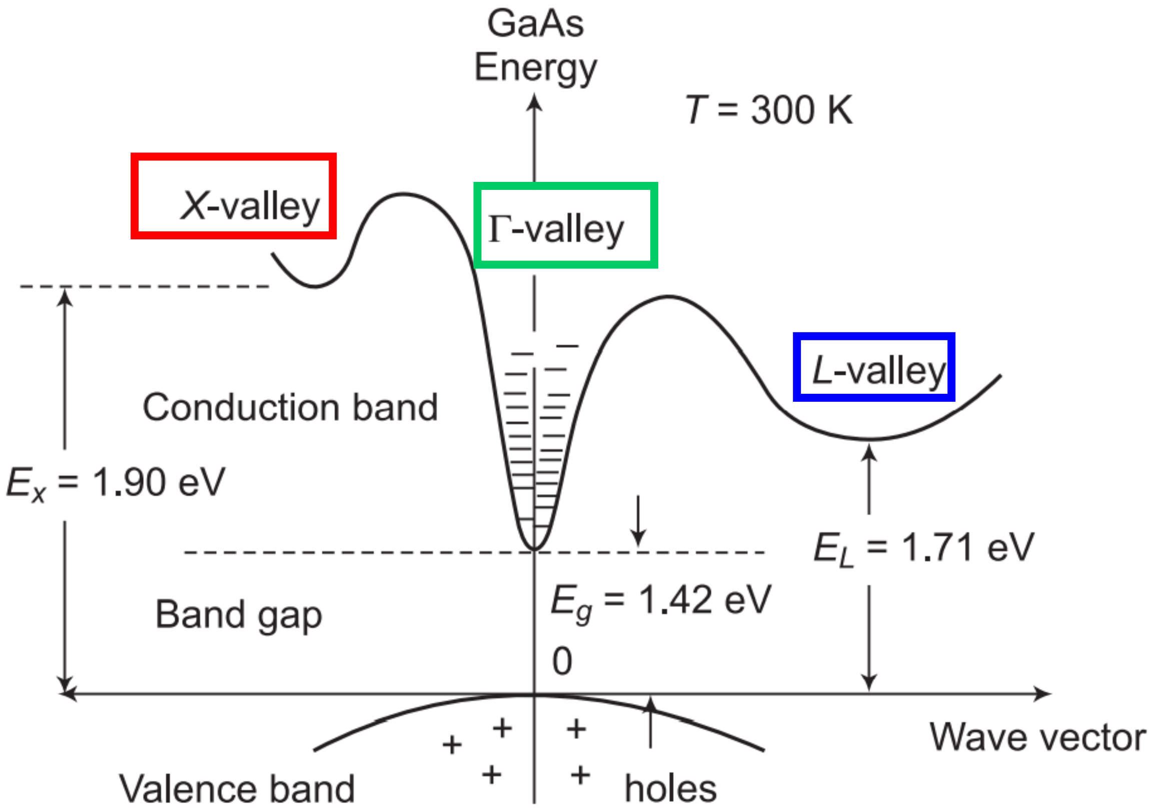

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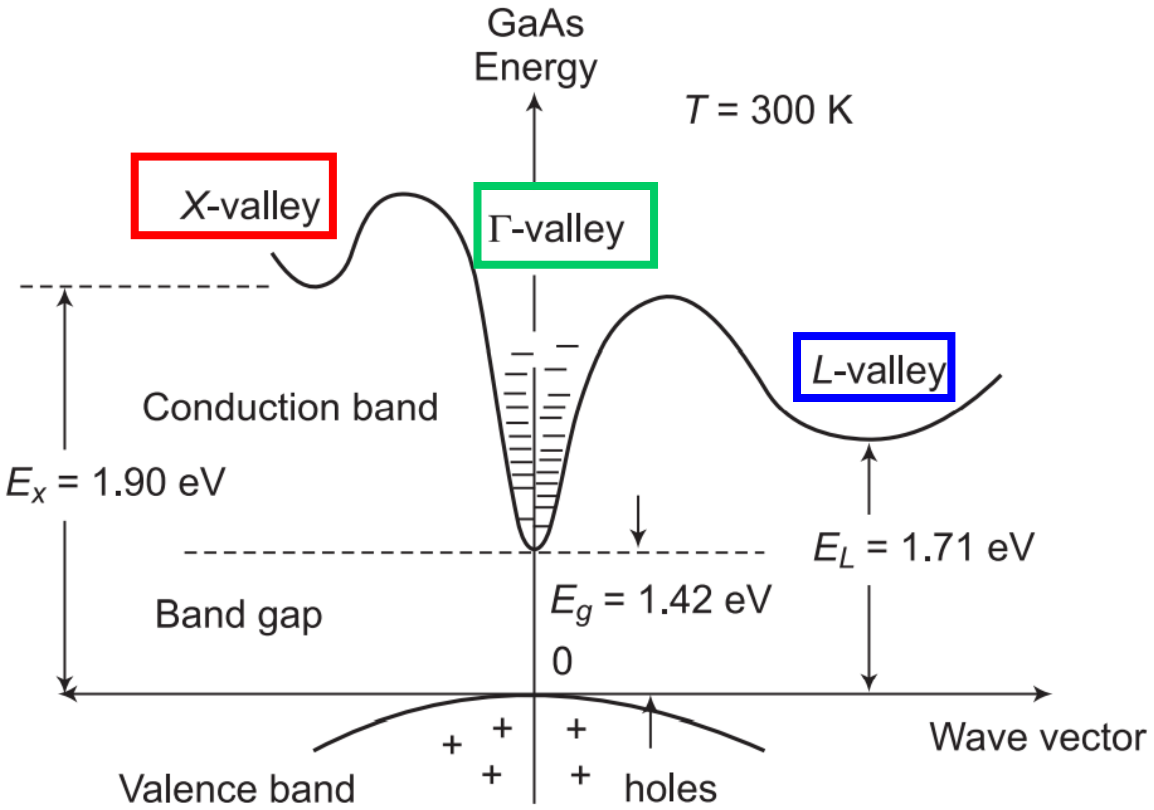

Energy band diagram

Lowest valley in conduction band (Γ) **is narrow** and **highest slope (dE/dk)** – **Electrons** have **low effective mass and high mobility**.

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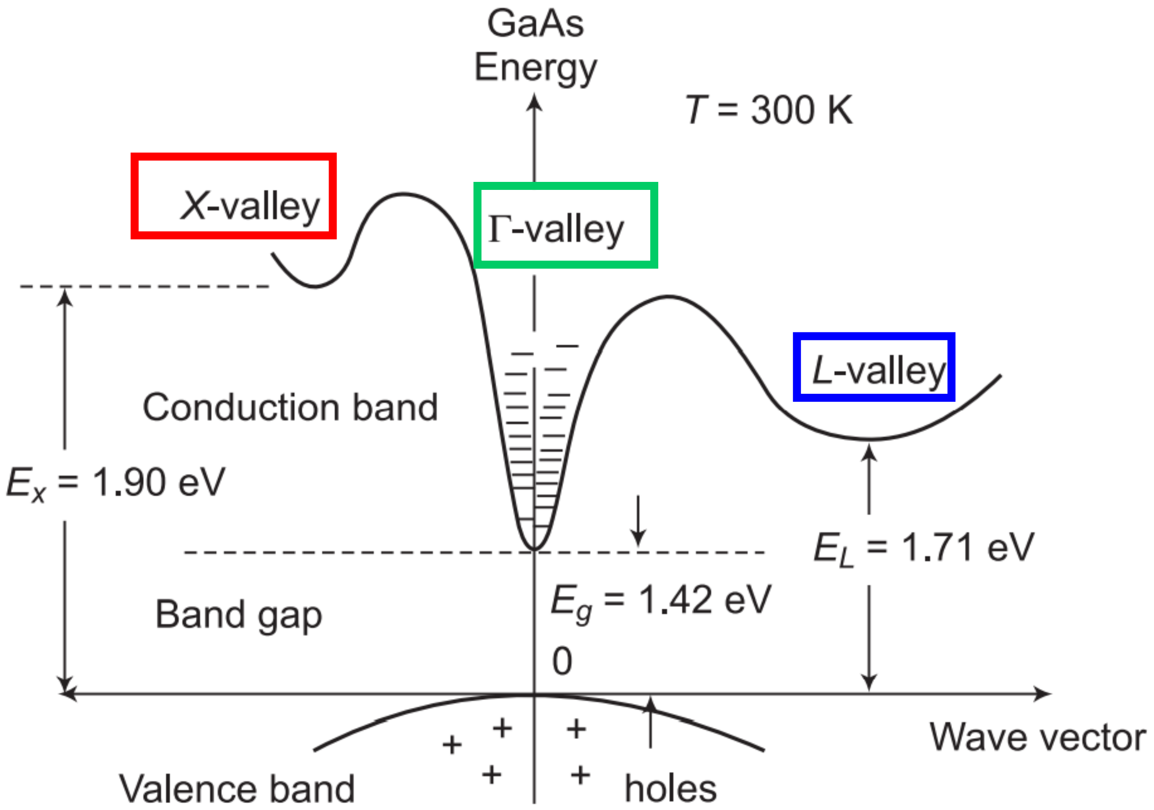

Energy band diagram

Lowest valley in conduction band (Γ) is narrow and highest slope (dE/dk) – Electrons have low effective mass and high mobility. Valleys X and L are wider with lower slopes, **hence large effective mass and lower electron mobility.**

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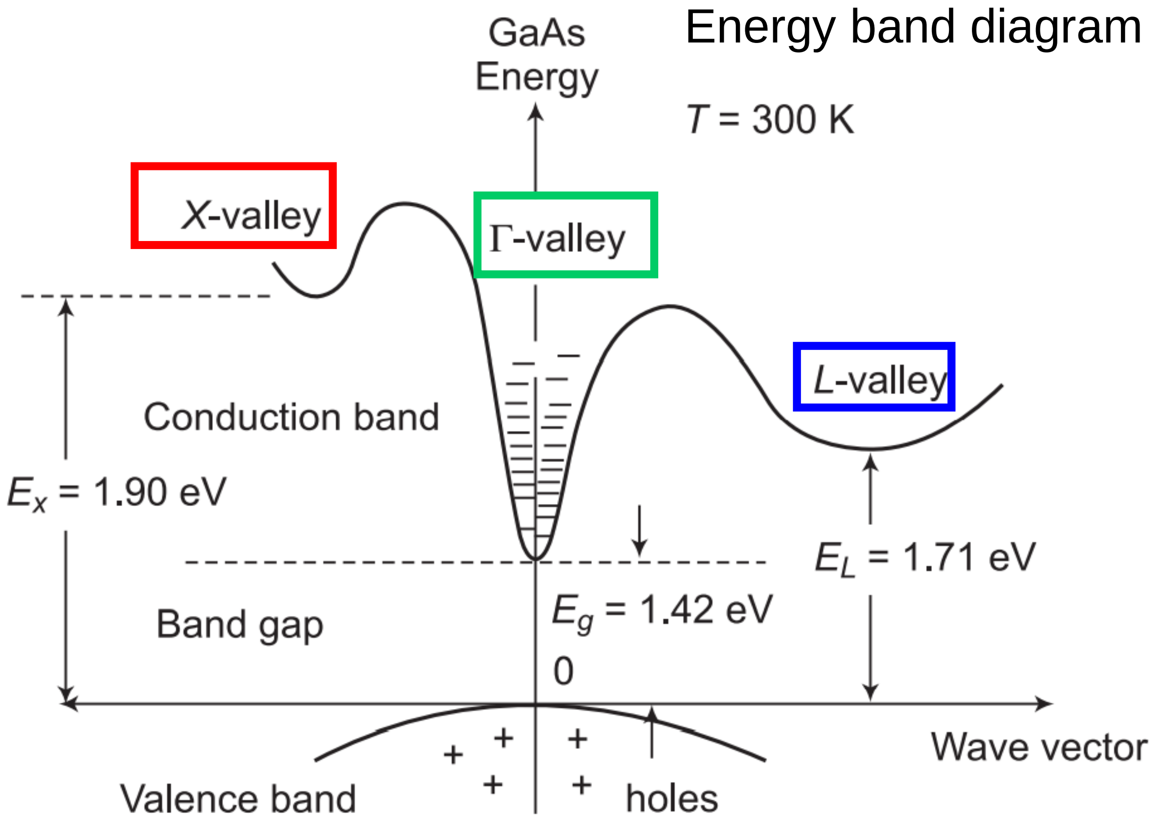
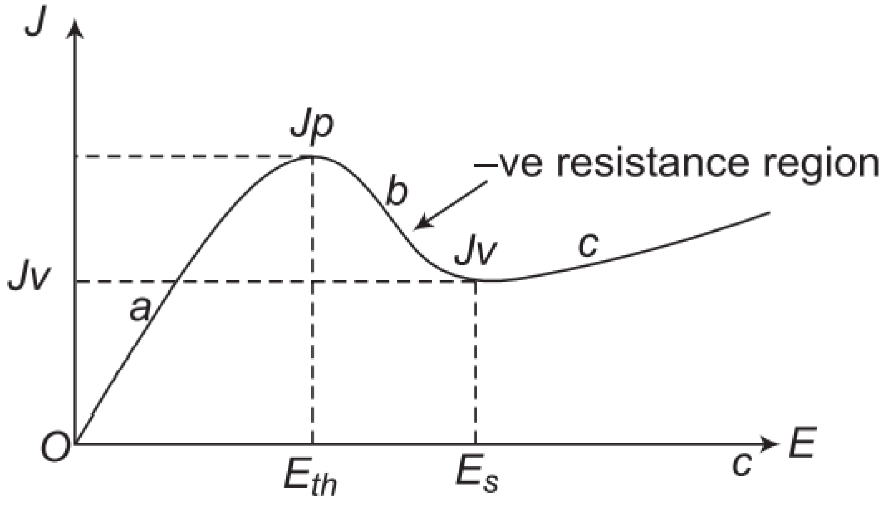
- At room temperature $300K$, most electrons of conduction band are in Γ valley (lowest)
- When Gunn diode is biased with a dc voltage, electric field E is established across it.





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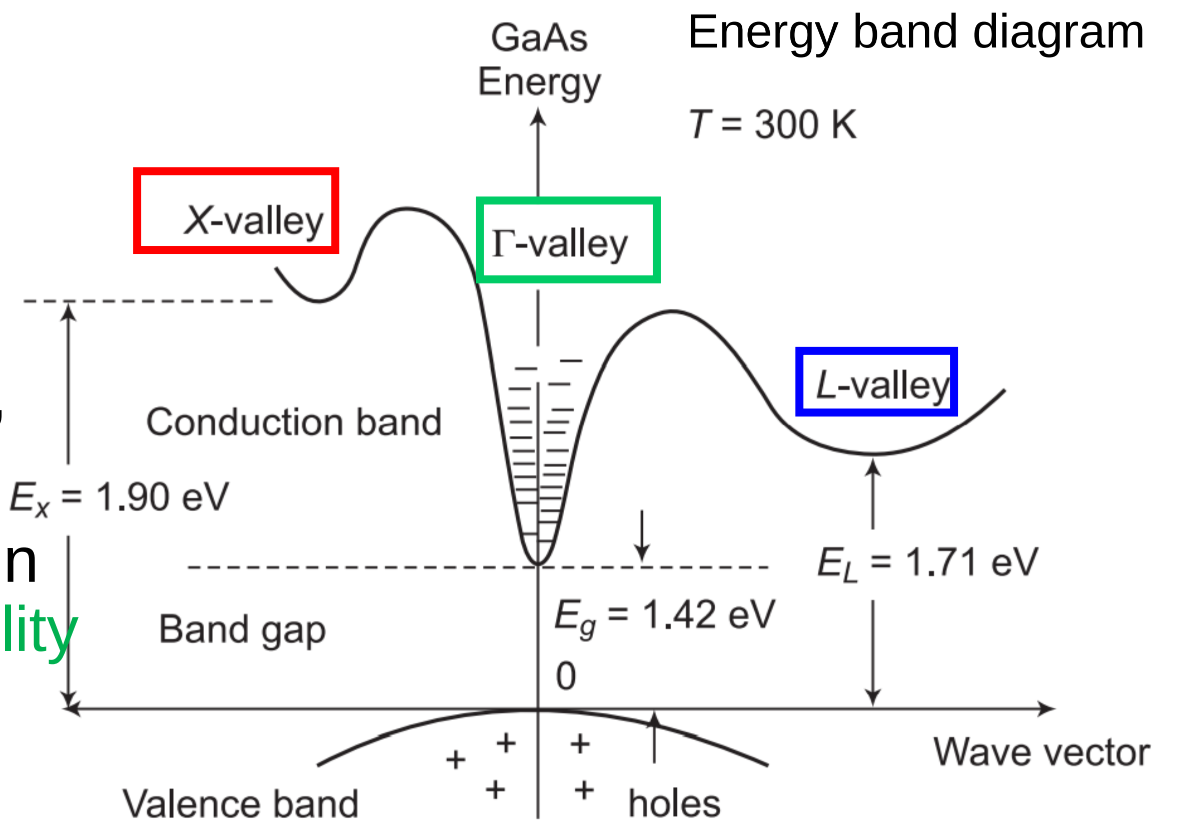

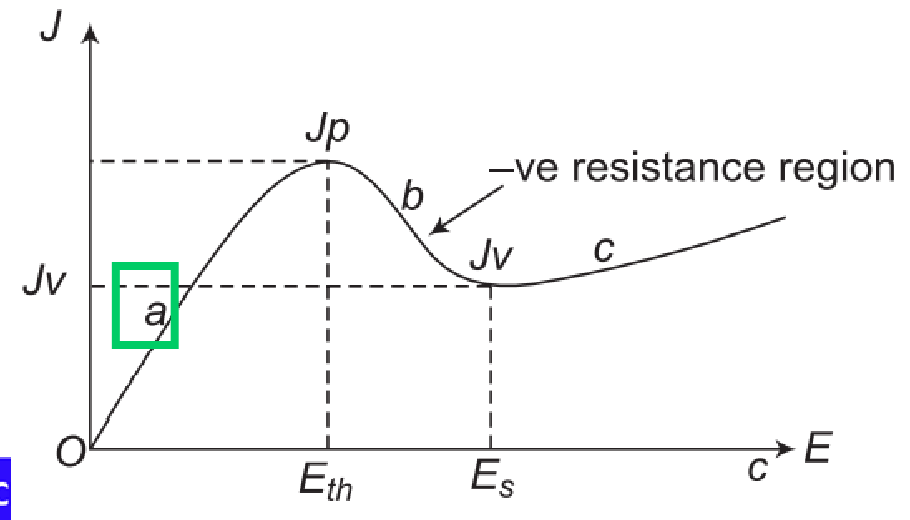

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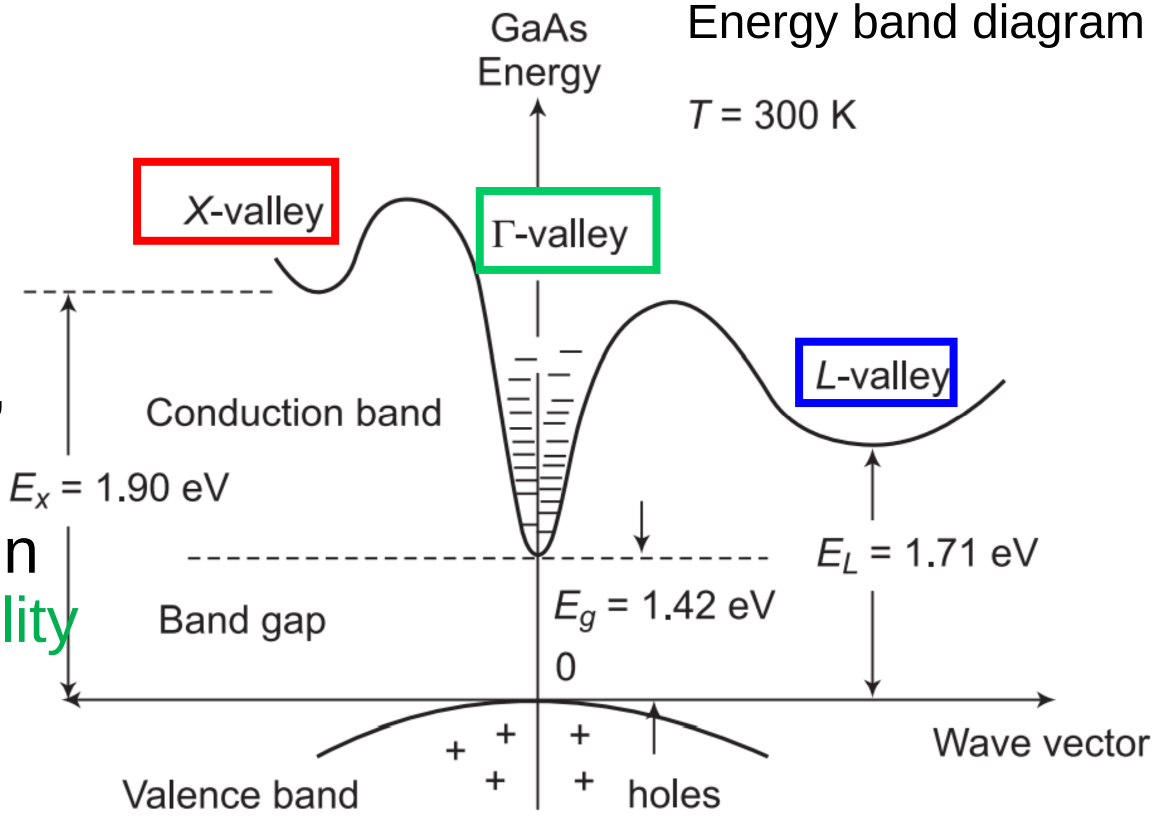

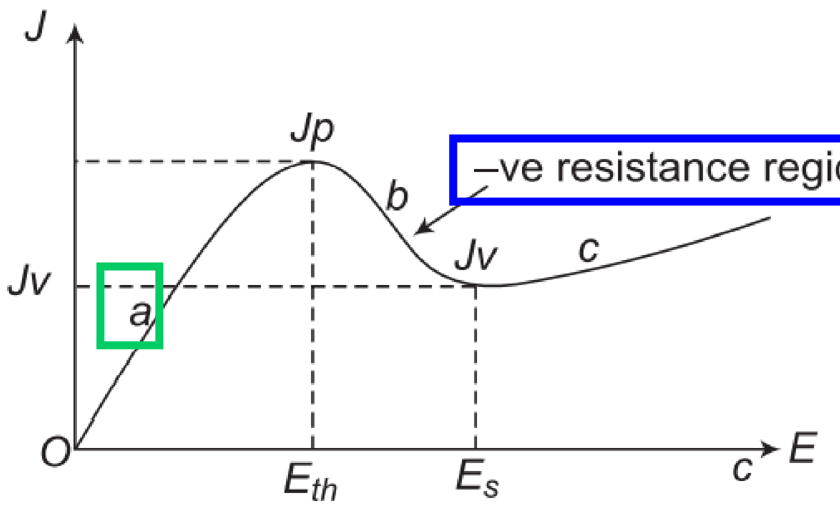

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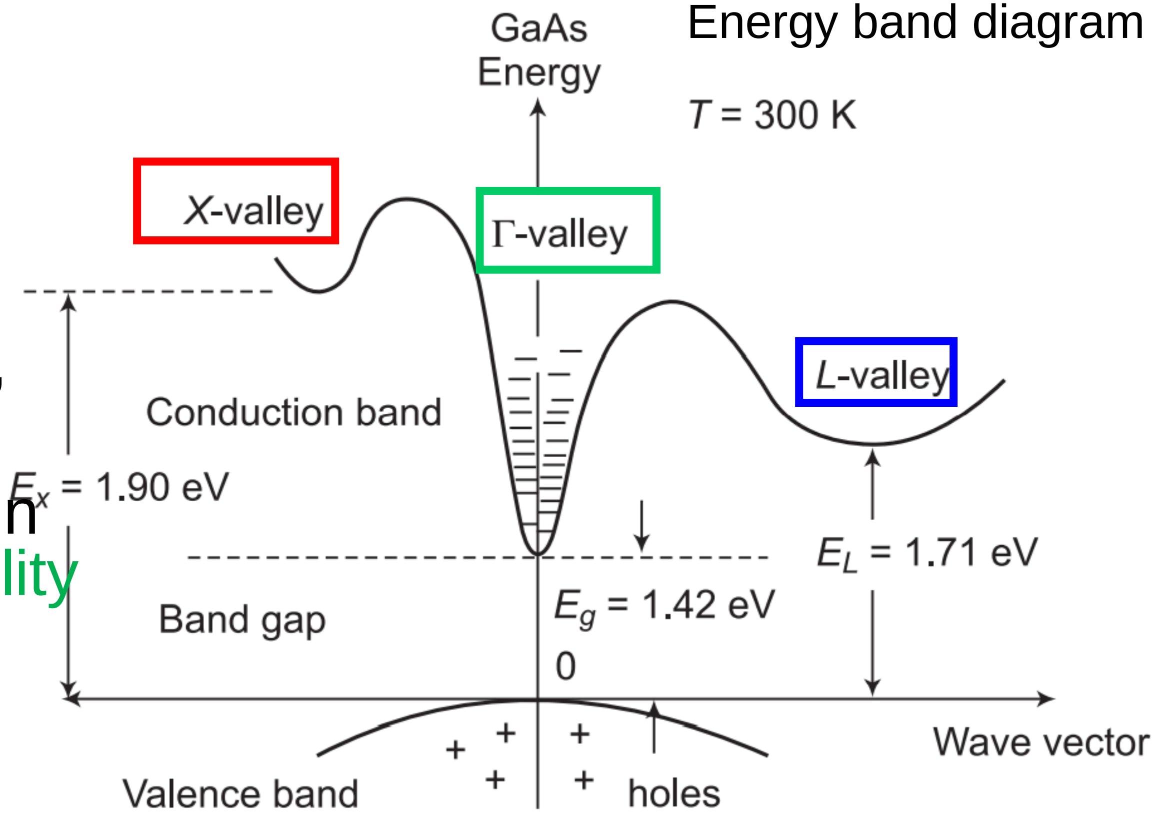
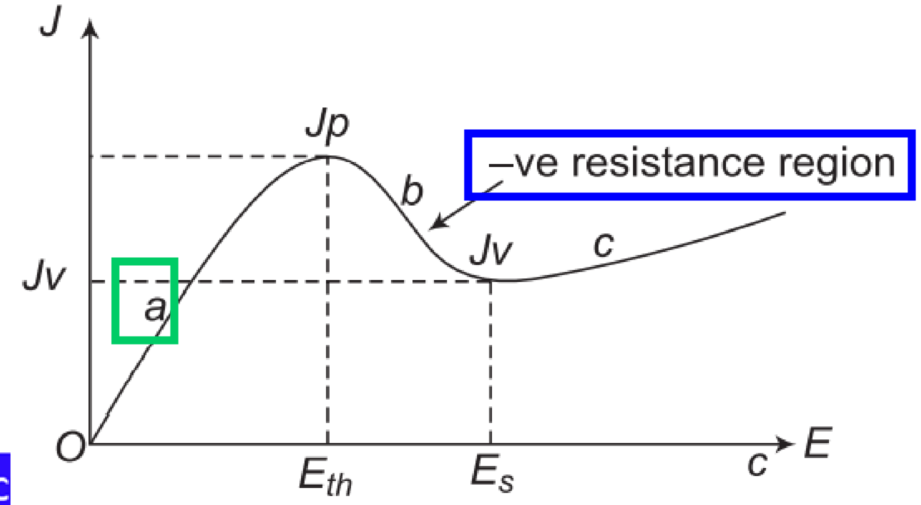
- Beyond a E_{th}, majority of conduction band electrons are transferred to lower mobility upper valley -> Beyond which conductivity decreases with increase in Electric field.





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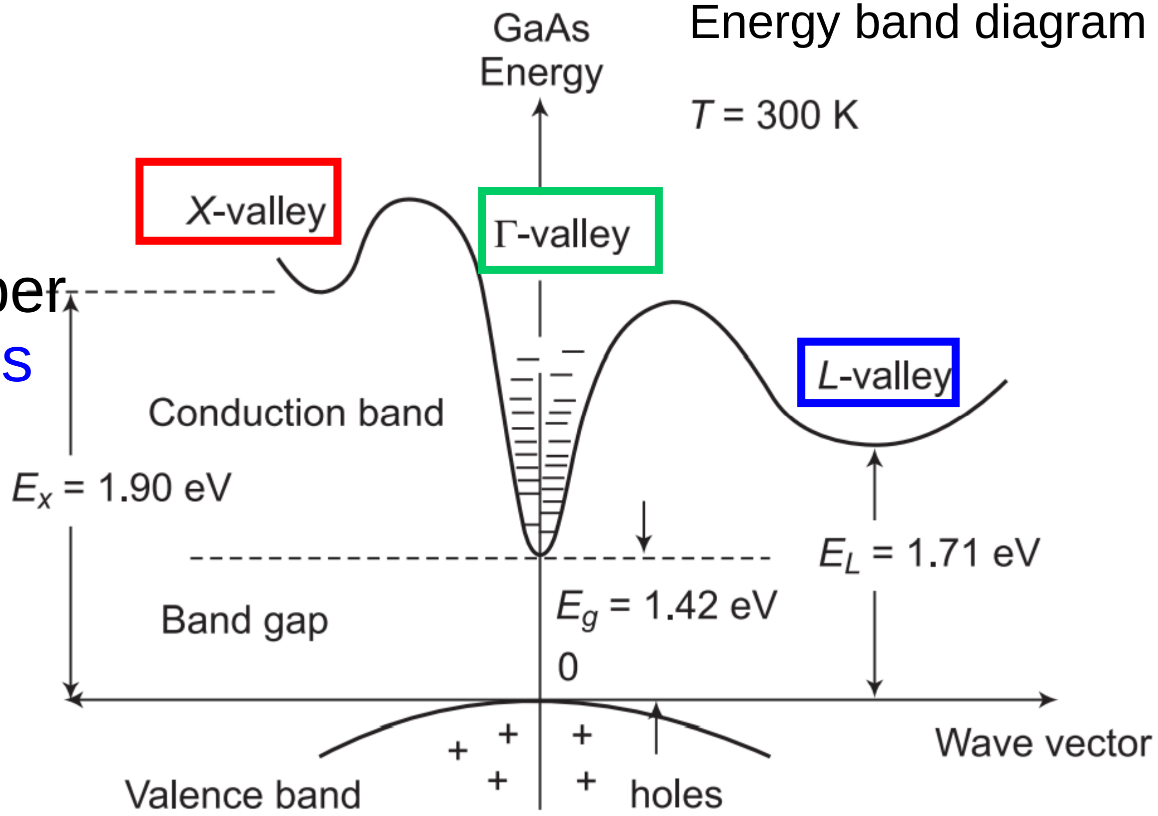
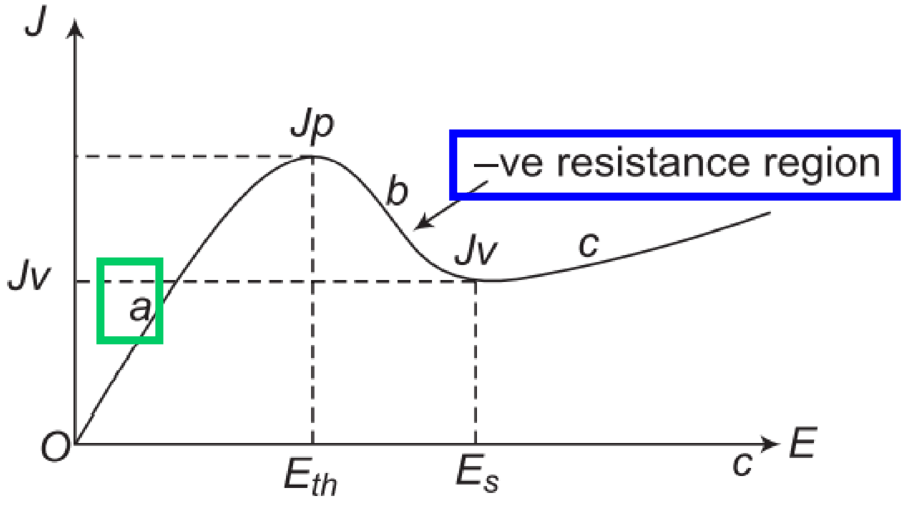
- Beyond a E_{th}, majority of conduction band electrons are transferred to lower mobility upper valley -> Beyond which conductivity decreases with increase in Electric field. **“Transferred Electron effect”**





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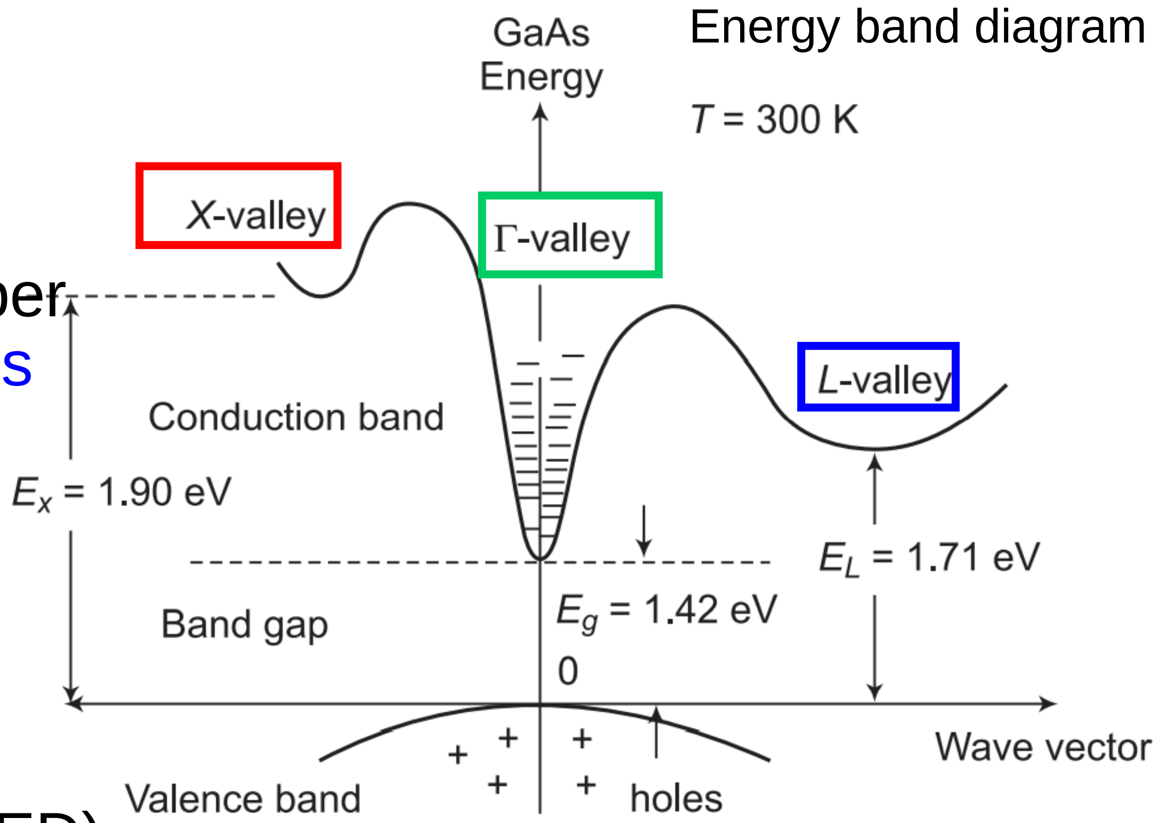

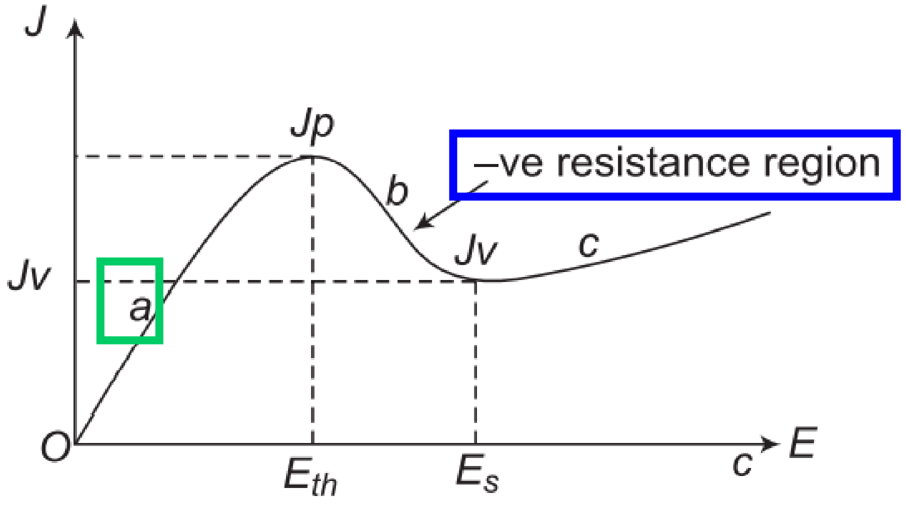

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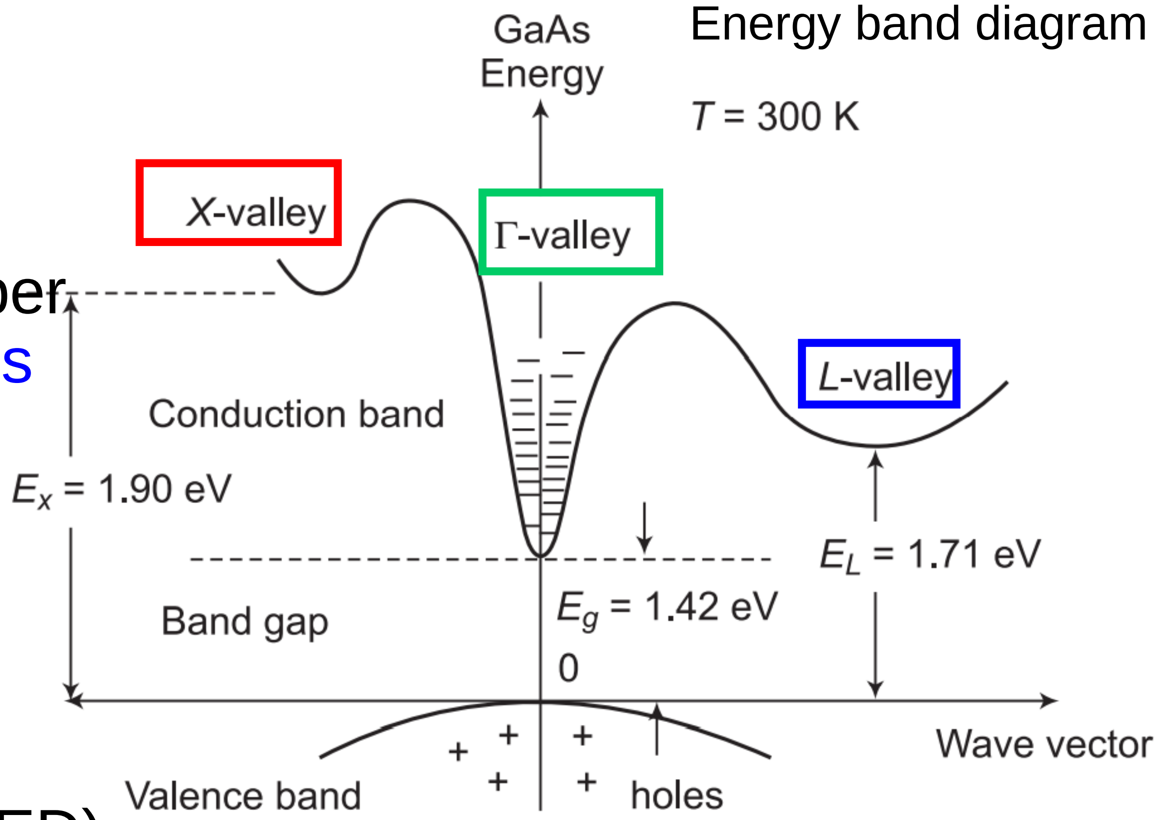

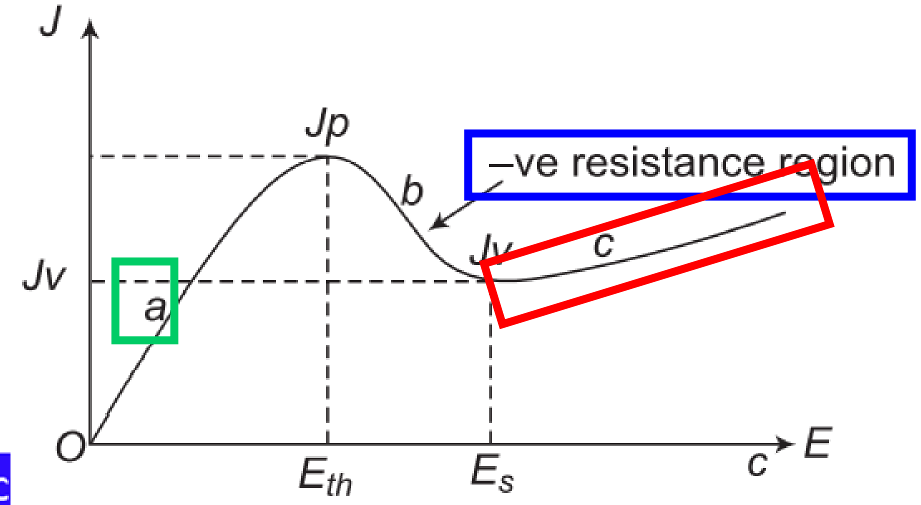

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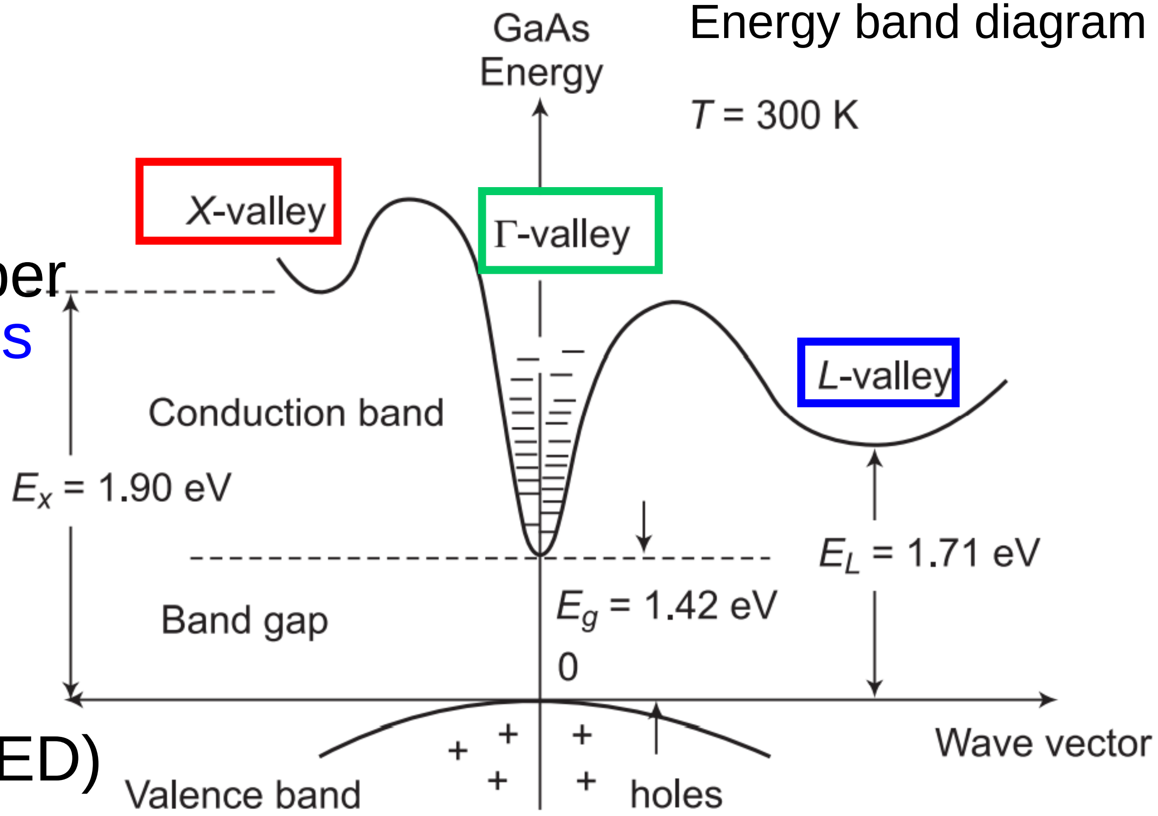
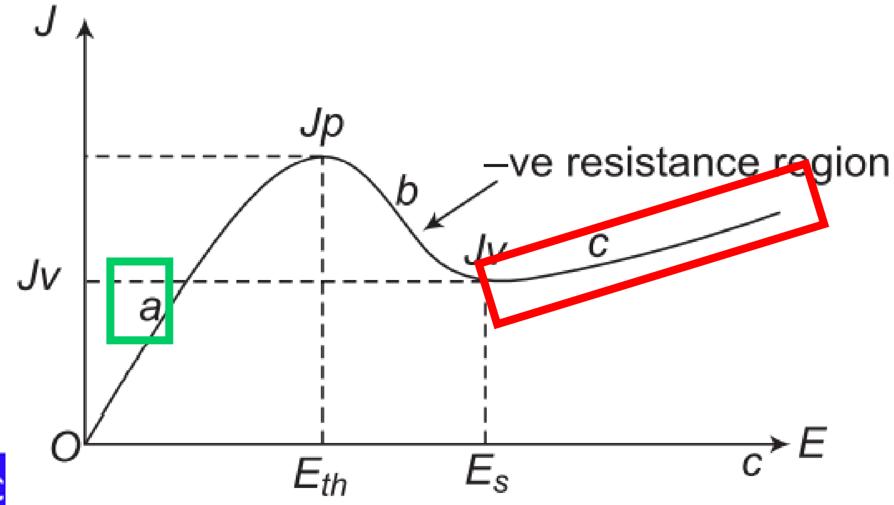
- Beyond a sustaining field $E = E_s$, almost all conduction band electrons are in the upper valley: Upper valley mobility is less than lower valley.
- $E > E_s$: net mobility of electrons – determined by Upper valley mobility: slope is positive $J - E$

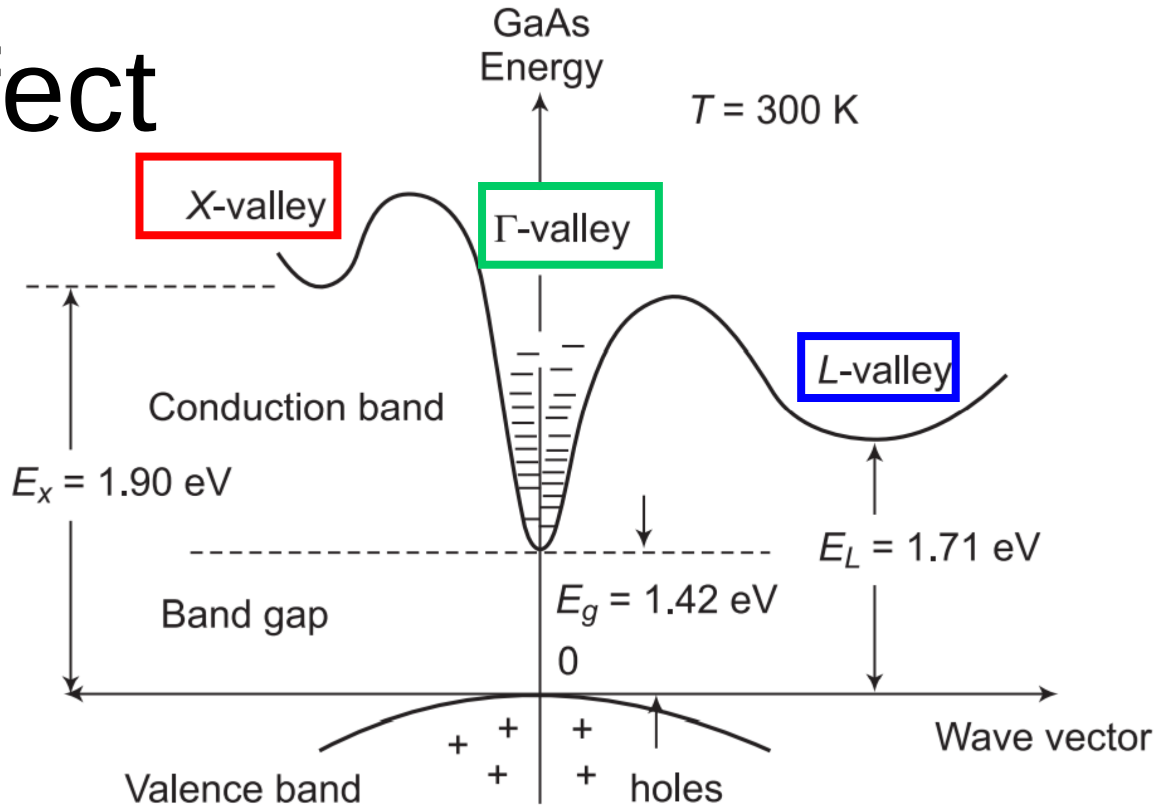
but lower than lower valley.





8.5 Criteria for Gunn effect

- Atleast two sub-bands in conduction band with lower conduction sub band should have high mobility than upper valley sub-band.



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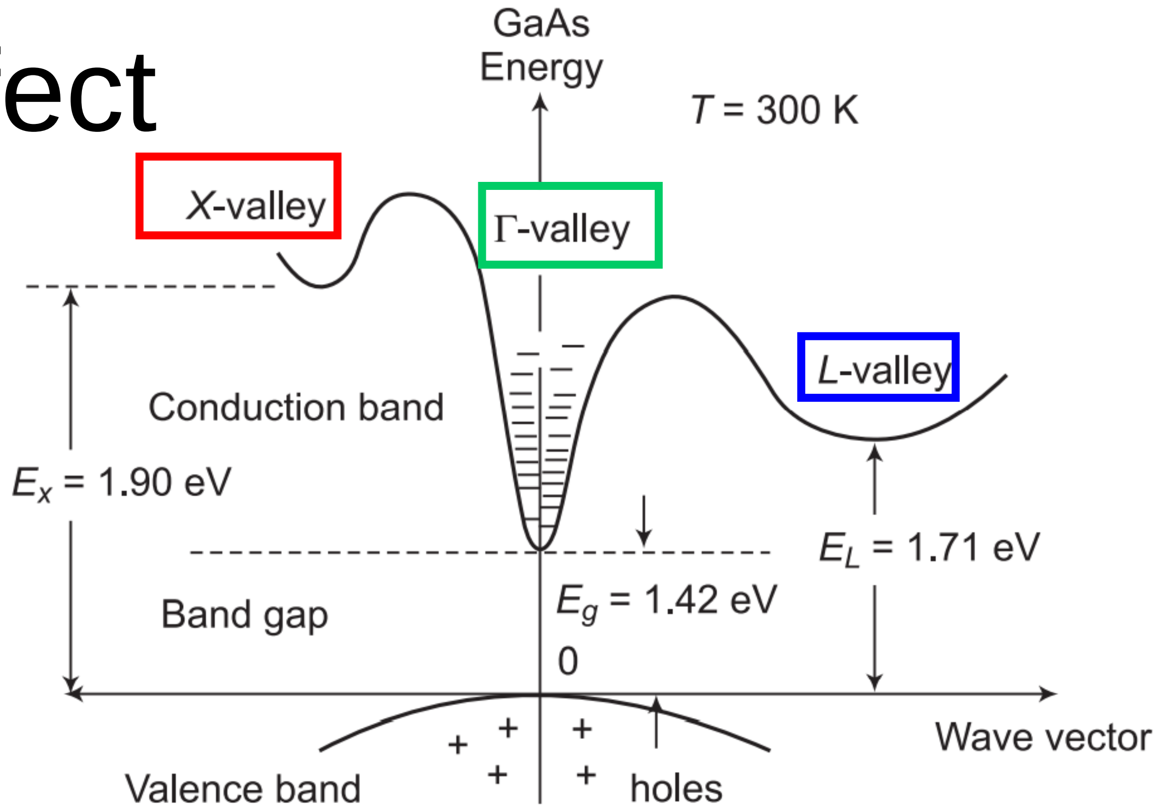

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- Band gap energy $E_g \gg$ thermal energy $kT = 0.026eV$ at room temperature
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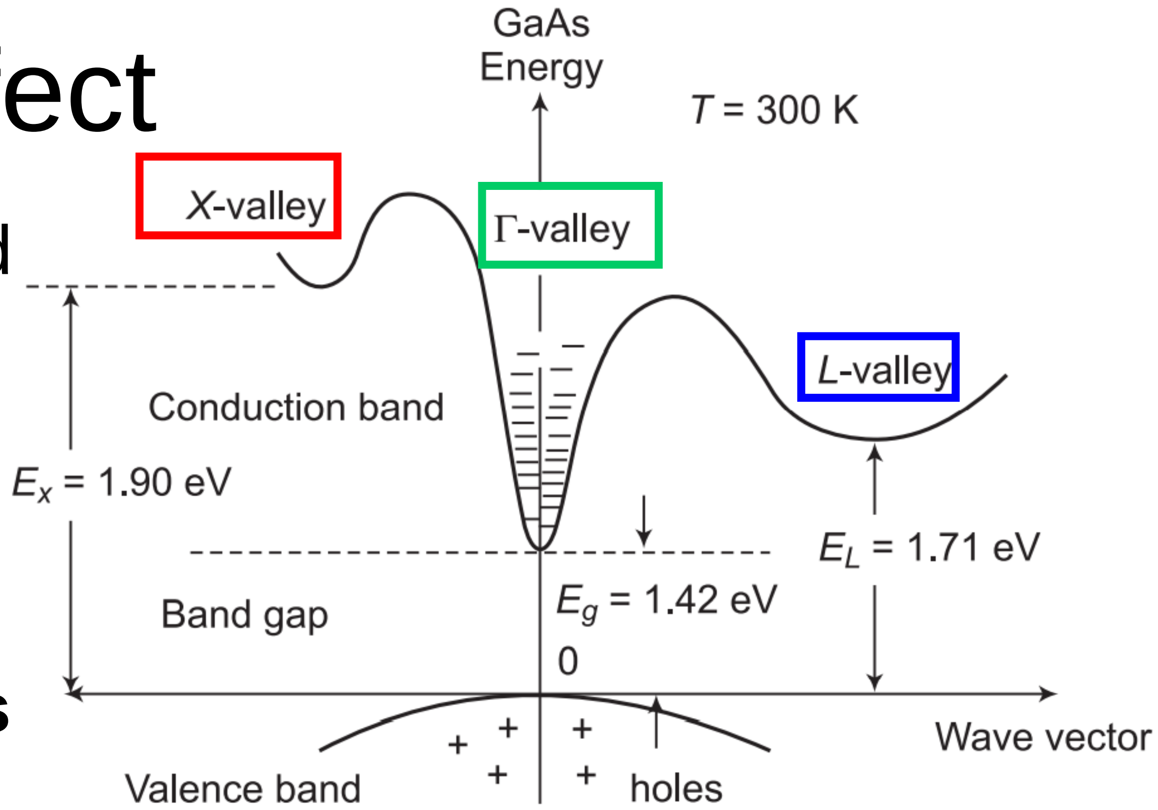
- Band gap energy $E_g \gg$ thermal energy $kT = 0.026eV$ at room temperature
- **Energy separation between two bands must be much lower than E_g** but higher than kT

kT << Energy separation << E_g

- GaAs, InP (Indium Phosphate), CdTe (Cadmium telluride)

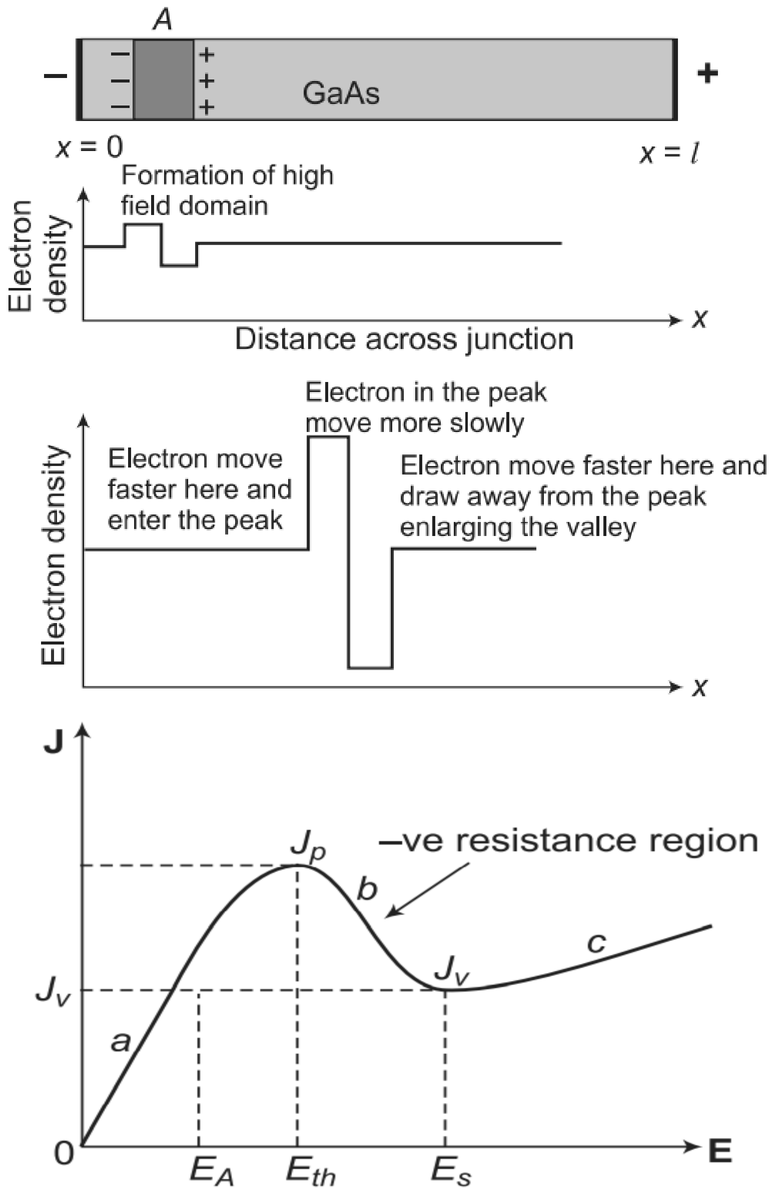


8.5 Criteria for Gunn effect

Properties	*Si*	*G.*	*GaAs*
Breakdown Field, V/m	approx. 3×10^5	approx. 1×10^5	approx. 4×10^5
Dielectric Constant	119	16.0	13 1
Effective Density of States in the Conduction Band, N/cm^3	2.8×10^{19}	1.04×10^{10}	4.7×10^{17}
Effective Density of States in the Valence Band, Nv/cm^3	1.04×10^{18}	6.0×10^{18}	7.0×10^{18}
Energy Gap at 300K (eV)	1.12	066	$\boxed{1.424}$
Intrinsic Carrier Concentration (cm^3)	1.45×10^{10}	2.4×10^{13}	1.79×10^6
Electron Mobility μ (cm^2/V.s)	1500	3900	$\boxed{8500}$
Hole Mobility μ_p (cm^2/V.s)	475	1900	400
Thermal Conductivity at 300 K (W/cm·°C)	15	0.6	0.46

8.6 Gunn mode of oscillations (Transit time TT mode)

- In GaAs, in region b, the drift velocity decreases as there is decrease in mobility in upper valley (conduction band) with increase in electric field – Forms high field domain.



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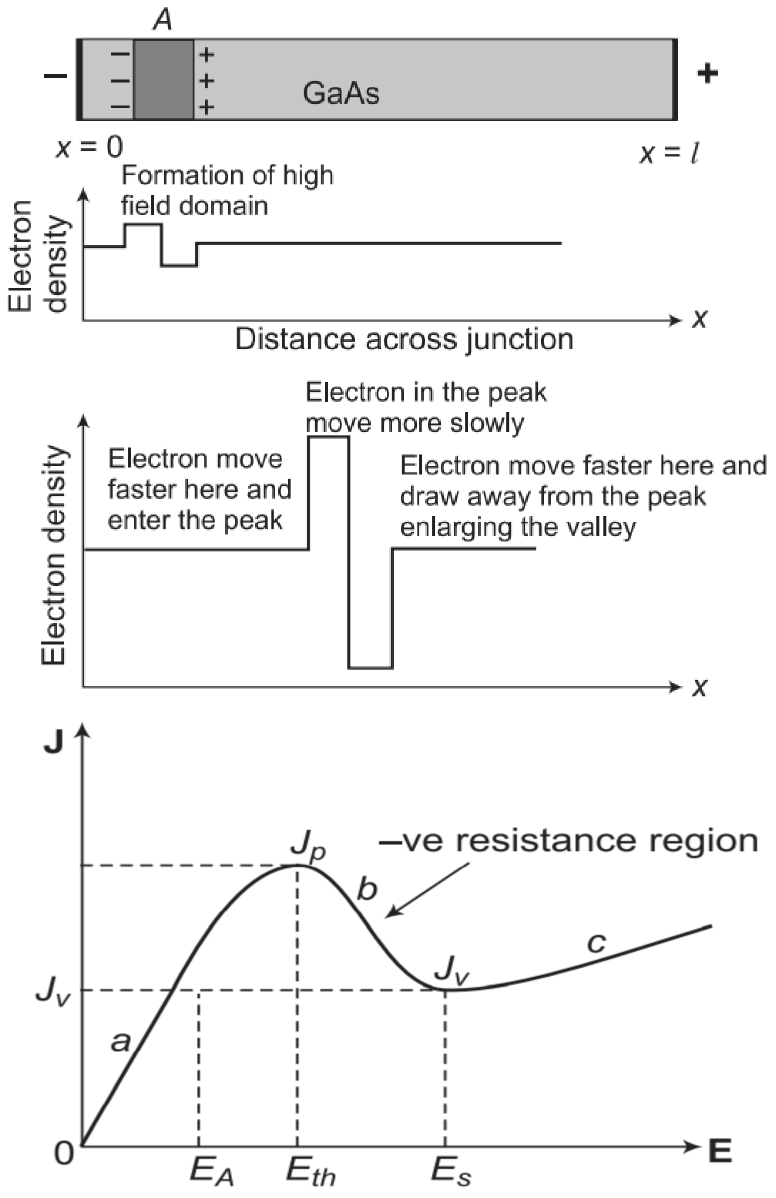

- In GaAs, in region b, the drift velocity decreases as there is decrease in mobility in upper valley (conduction band) with increase in electric field – Forms high field domain.
- Assume at point A, **excess –ve charge due to random noise/fluctuation** on biasing/non-uniform doping. This creates electric field.
- **Field towards left (cathode) is lower than field towards right (anode)**.

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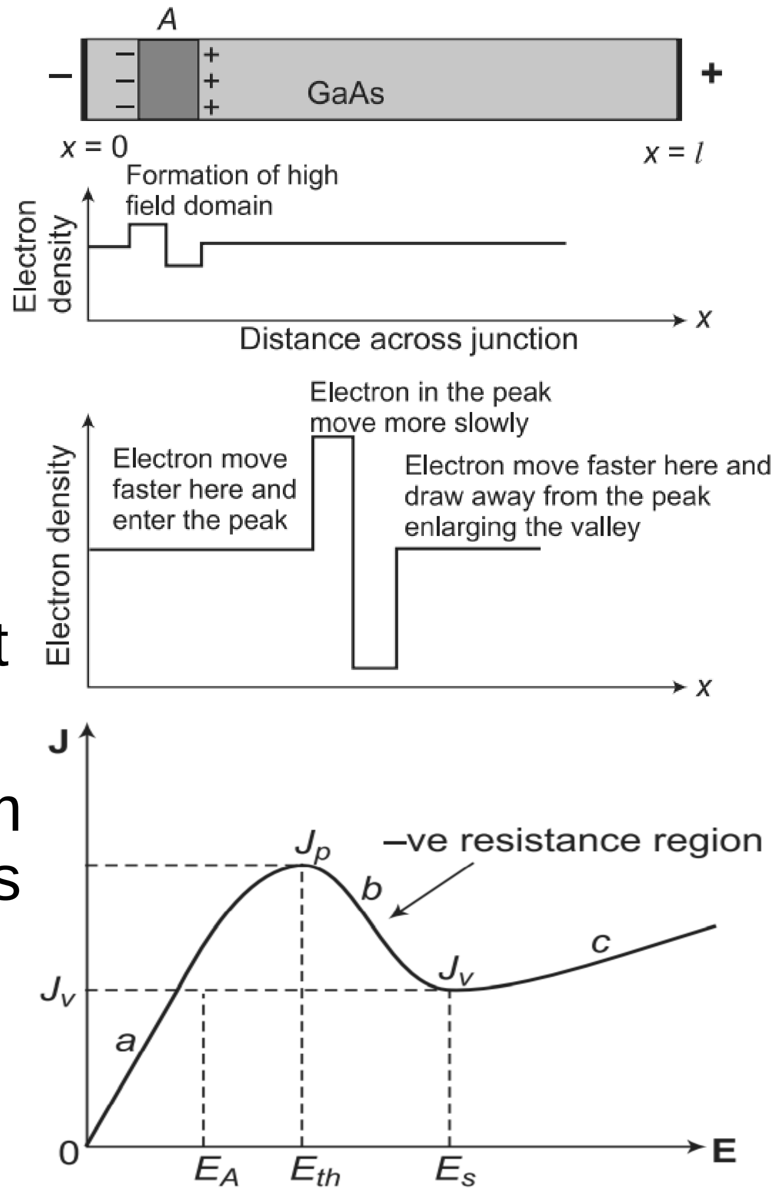
- Field towards left (cathode) is lower than fiedld towards right (anode).
- When diode is biased at E_A(a), carriers (current) flowing from cathode are larger than carriers from anode – This increases excess –ve charge at A.



8.6 Gunn mode of oscillations (Transit time TT mode)

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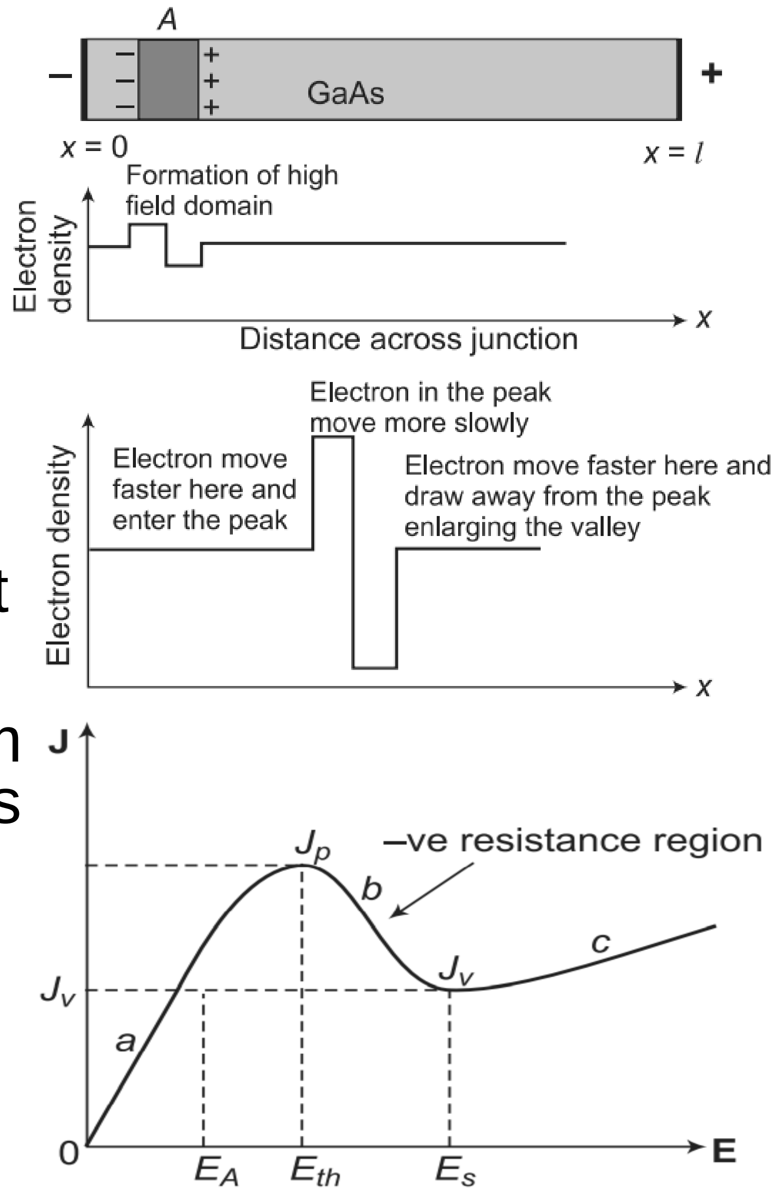
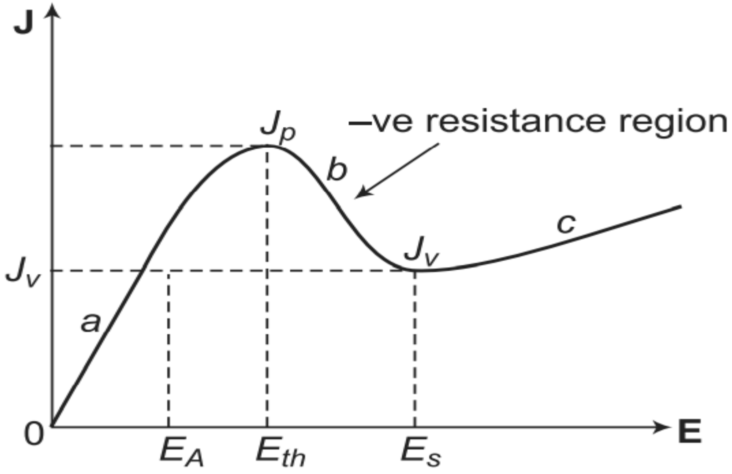
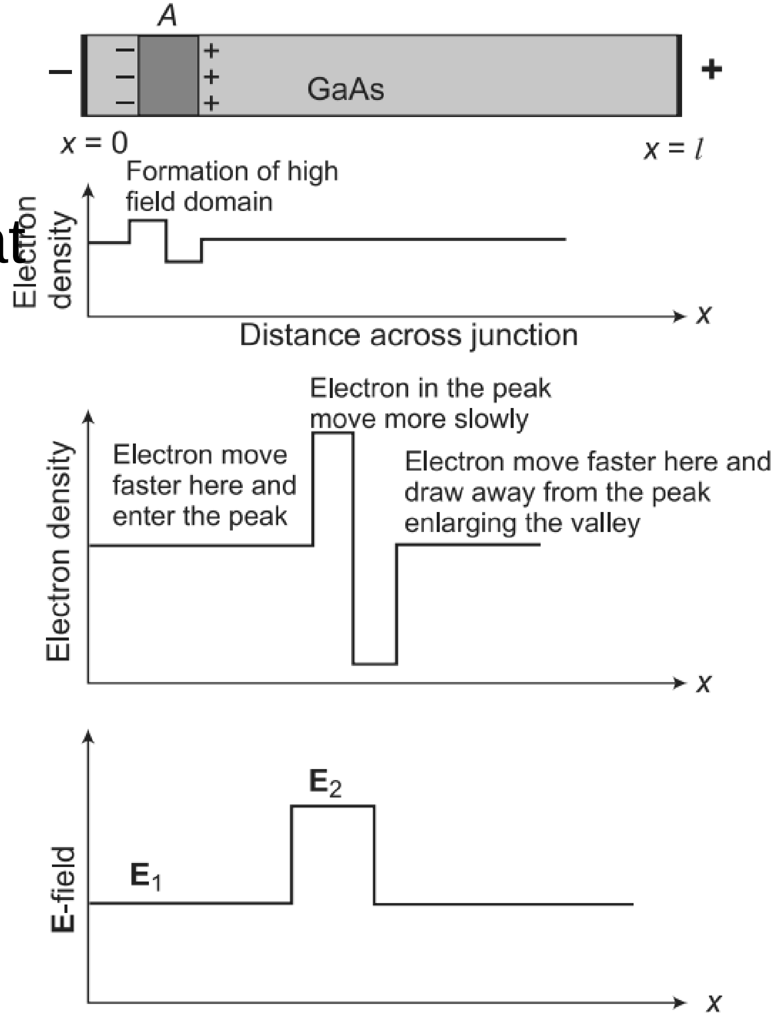
- Assume at point A, excess –ve charge due to random noise/fluctuation on biasing/non-uniform doping. This creates electric field.
- Field towards left (cathode) is lower than fiedld towards right (anode).
- When diode is biased at E_A(a), carriers (current) flowing from cathode are larger than carriers from anode – This increases excess –ve charge at A.
- When RF noise reverses, field at left of A is lower than before, field towards right is greater than previous. – More space charge accumulation. – **Fields accumulate and increase towards Eth**



8.6 Gunn mode of oscillations (Transit time TT mode)

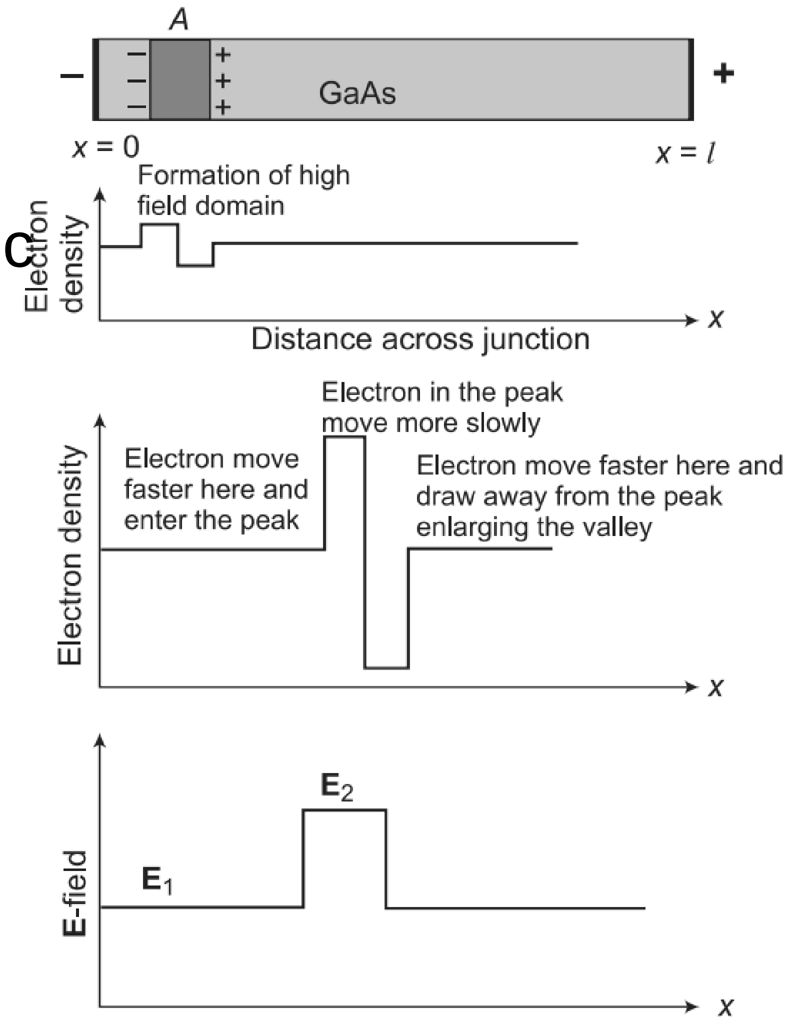
- This **process continues until high and low fields both reach values outside the** b region (-ve resistance region) at a and c (currents in both regions are equal now)



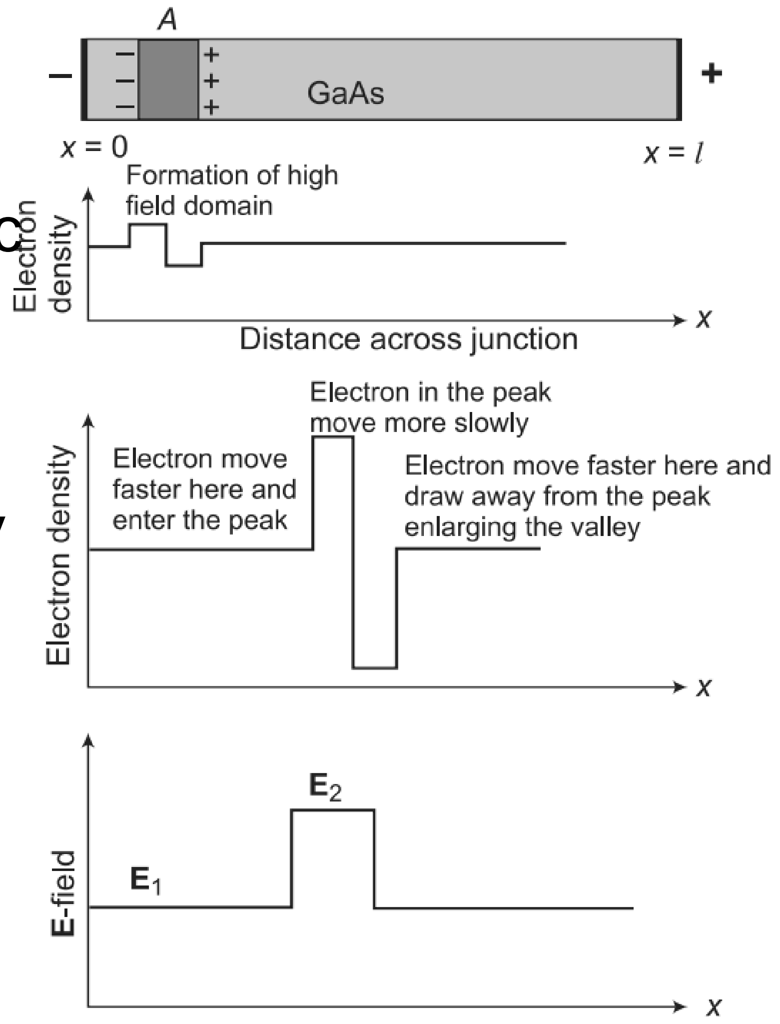


8.6 Gunn mode of oscillations (Transit time TT mode)

- This process continues until high and low fields both reach values outside the b region (-ve resistance region) at a and c (currents in both regions are equal now)
- No further accumulation of Charge at A, and stable accumulation layer is formed.
- When the **accumulation and depletion layers approach, they attract each other and pass through the diode in the form of domain**.



8.6 Gunn mode of oscillations (Transit time TT mode)



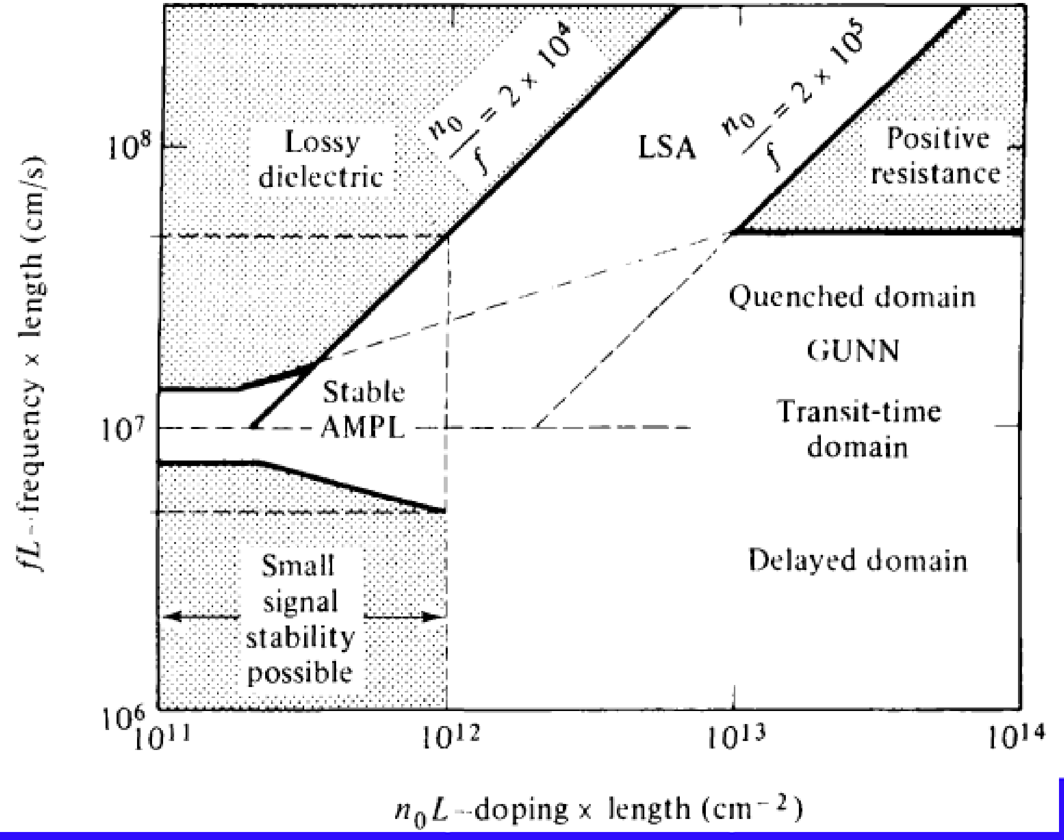
- This process continues until high and low fields both reach values outside the b region (-ve resistance region) at a and c (currents in both regions are equal now)
- No further accumulation of Charge at A, and stable accumulation layer is formed.
- When the accumulation and depletion layers approach, they attract each other and pass through the diode in the form of domain.
- Since $V = -\int E dx$ **across semiconductor remains** **constant**, **field inside the domain will be large. No additional domain forms** until the **existing domain disappears at Anode**.
- Domain starts at cathode due to instability in carrier distribution.

8.7 Four modes of operation of Gunn Diode

Formation of **strong space charge instability** depends on
a) conditions of availability of enough charge in crystal (doping)
b) sufficient length of the specimen should be available for building up of charges within the electron's transit time

For uniformly doped bulk diodes, four basic modes are:

1. Gunn Oscillation mode
2. Stable amplification mode
3. LSA oscillation mode
4. Bias circuit oscillation mode



8.7 Four modes of operation of Gunn Diode

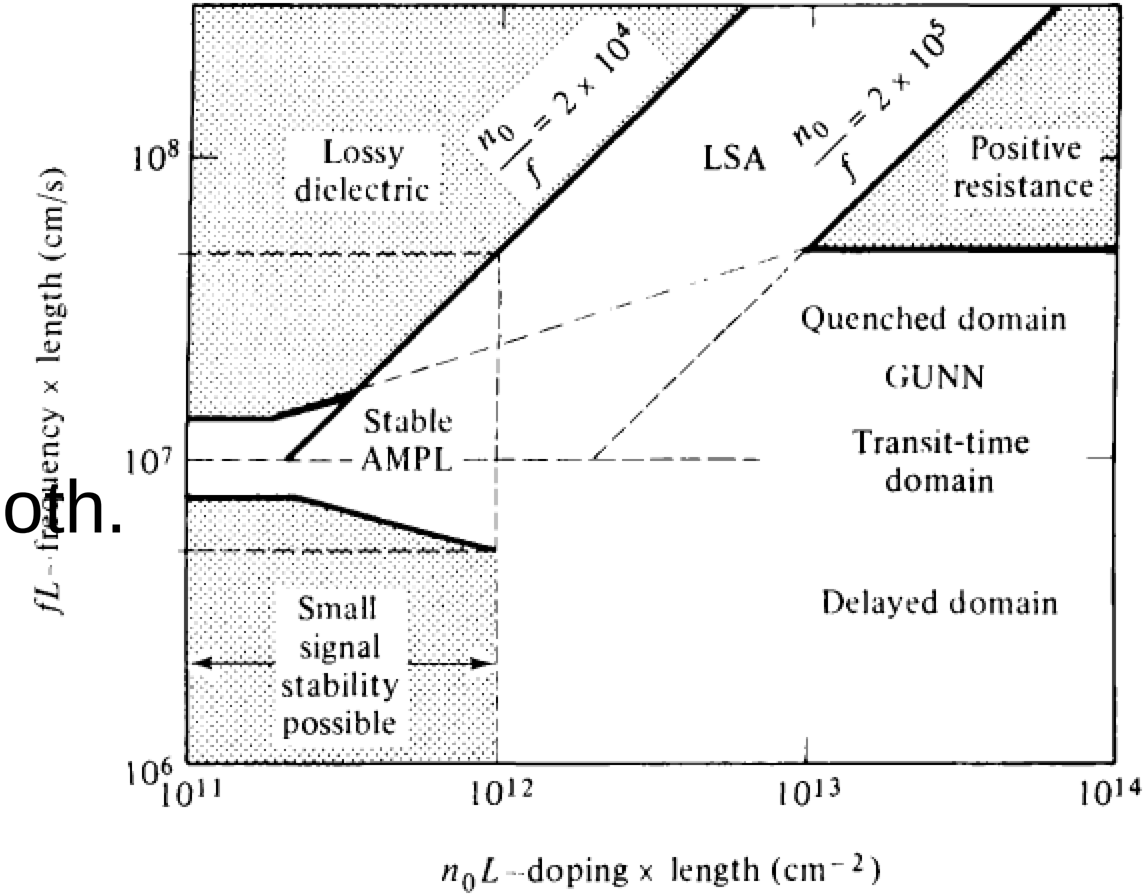
1. **Gunn Oscillation mode**:

Product of frequency and length $fl = 10^7 cm/s$

Product of doping and length $n_0 l > 10^{12}/cm^2$

Unstable due to cyclic formation of
- a) accumulation layer or
- b) high field domain:
  in a circuit with low impedance
  ($f_{oscillation}$: near $f_{intrinsic}$)

For high Q cavity, when coupled properly to load, domain is quenched/delayed or both.
Oscillation frequency:
Depends on resonant frequency of the cavity

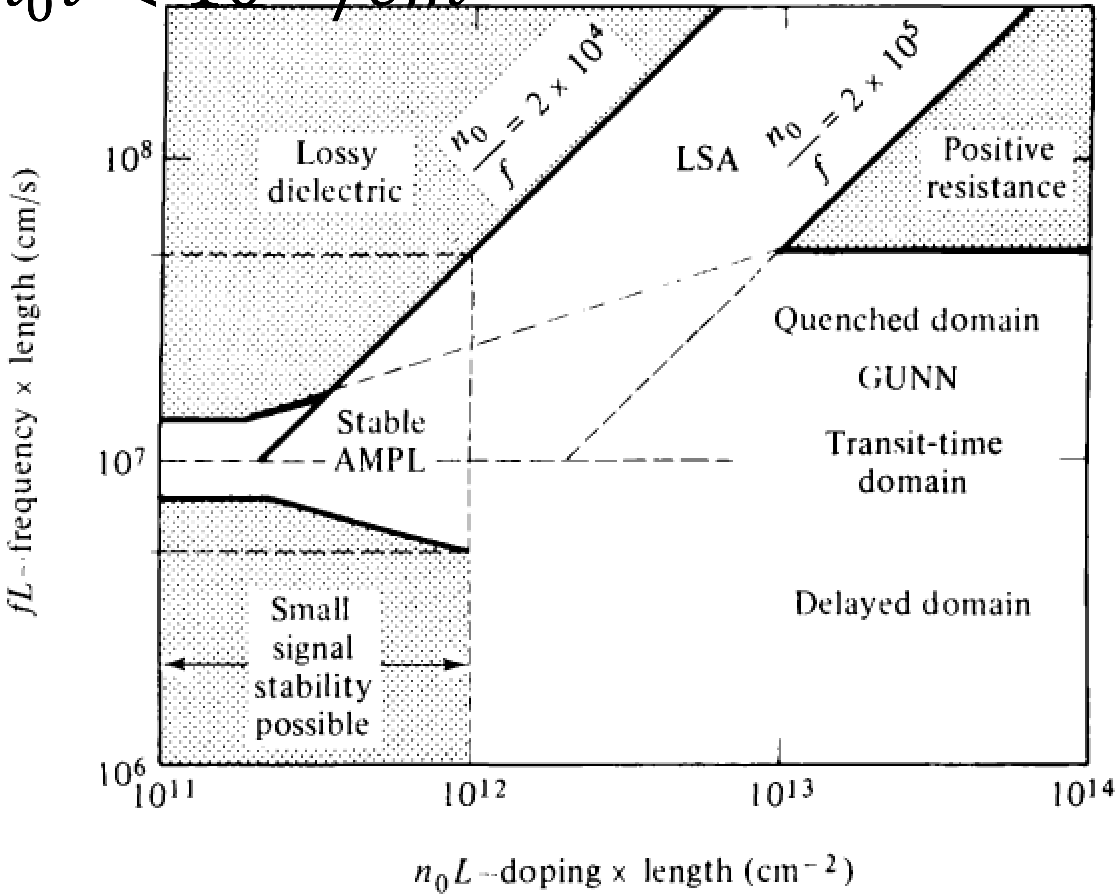


8.7 Four modes of operation of Gunn Diode

2. **Stable amplification mode**:

Product of frequency and length $fl = 10^7 cm/s$

Product of doping and length $10^{11}/cm^2 < n_0 l < 10^{12}/cm^2$

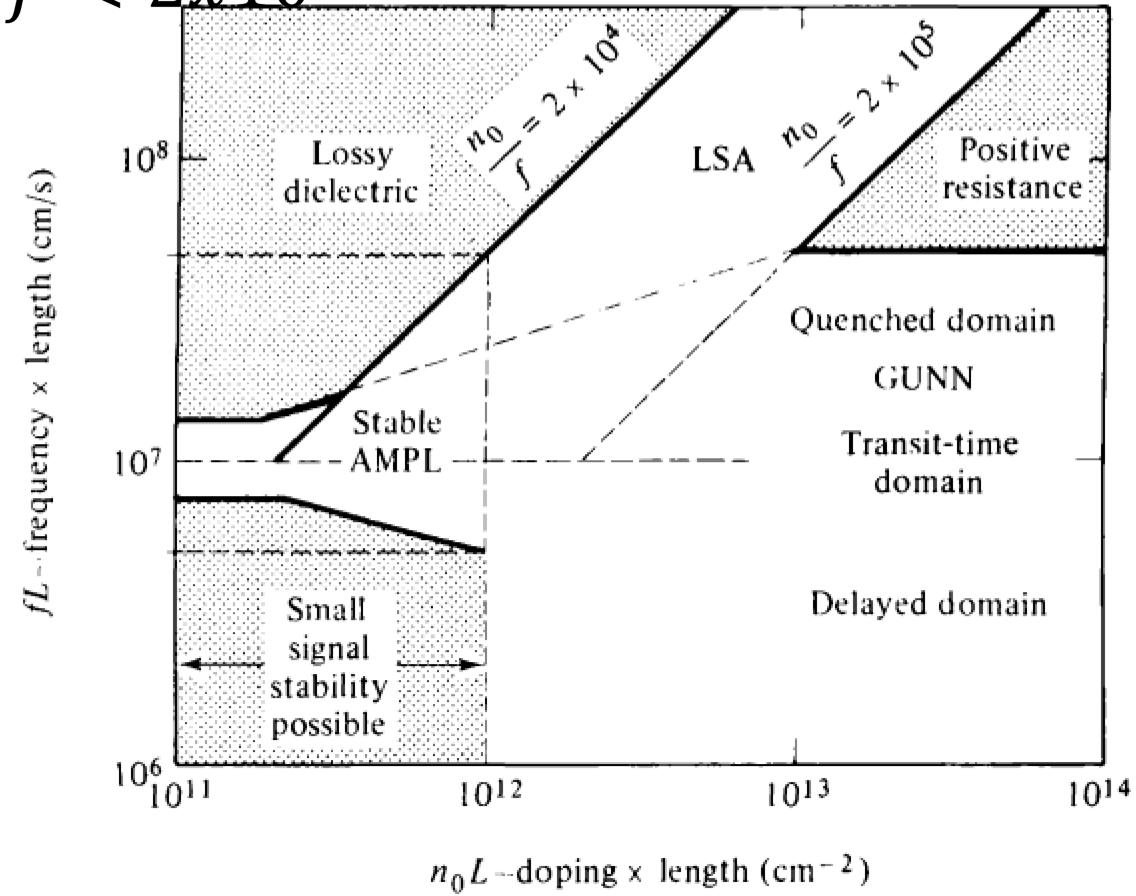


8.7 Four modes of operation of Gunn Diode

3. **LSA oscillation mode**:

Product of frequency and length $fl > 10^7 cm/s$ (greater than)

doping divided by frequency: 2x10$^4 < n_0/f < 2x10^5$



8.7 Four modes of operation of Gunn Diode

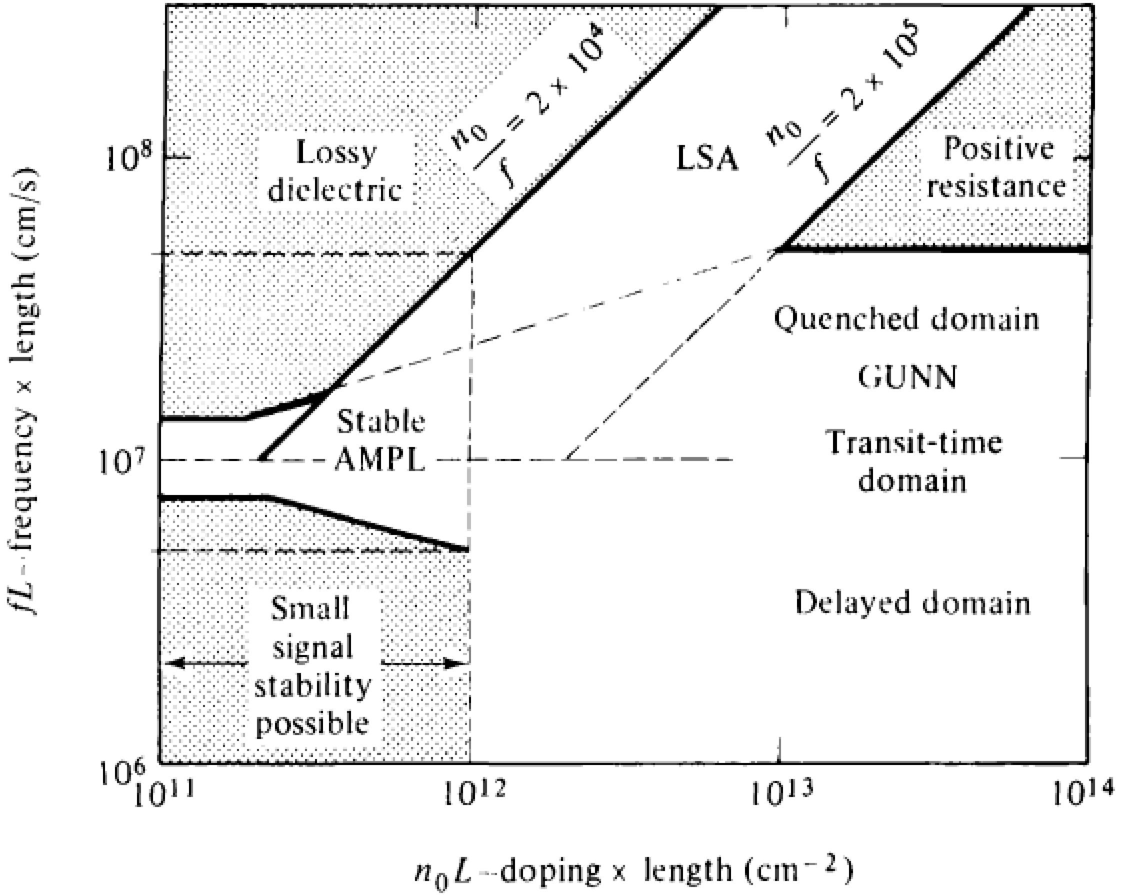
4. **Bias circuit oscillation mode**:

When there is either Gunn or LSA oscillations
Product of frequency and length $fl \ll 10^6 cm/s$

When bulk diode is biased to threshold, average current suddenly drops and Gunn oscillations begins.

This results in oscillations in bias circuit

1 kHz to 100 MHz



8.8 LSA mode: Limited Spacecharge Accumulation mode

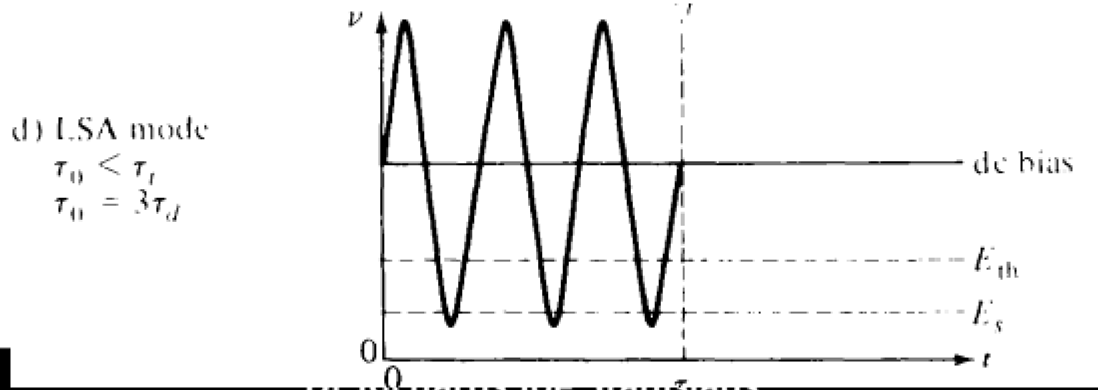
- Most of the operating domains are maintained in negative conductance state
- Space charge accumulation near cathode has time to collapse when signal voltage is maintained below threshold (maximum)
- Simplest state
- Uniformly doped semiconductor without any internal space-charge
- Internal electric field will be uniform without and proportional to applied field level

8.8 LSA mode: Limited Spacecharge Accumulation mode

3. LSA oscillation mode:

Product of frequency and length $fl > 10^7 cm/s$ (greater than)

doping times length: $n_0 L = 10^{12}/cm^2$



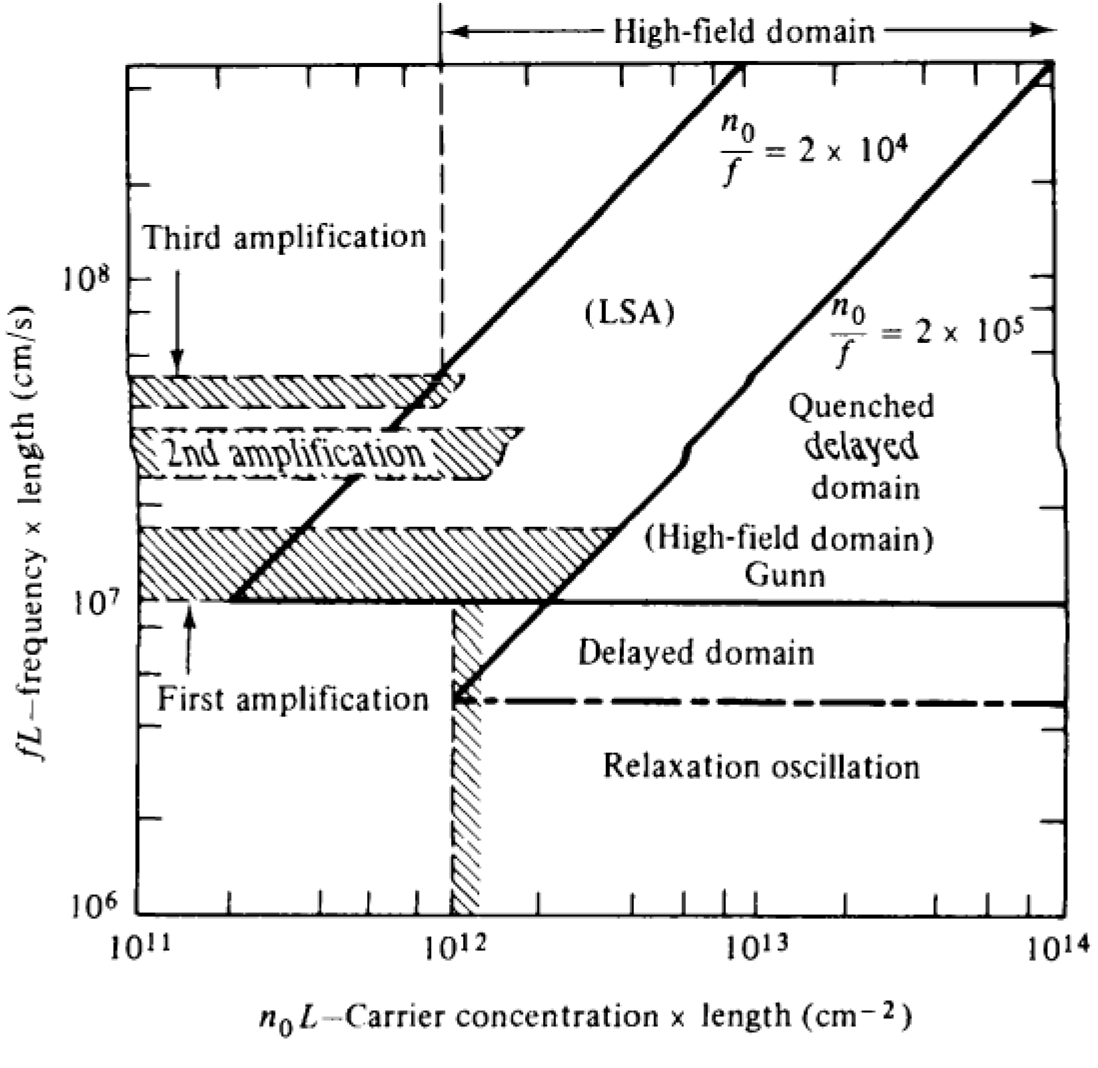
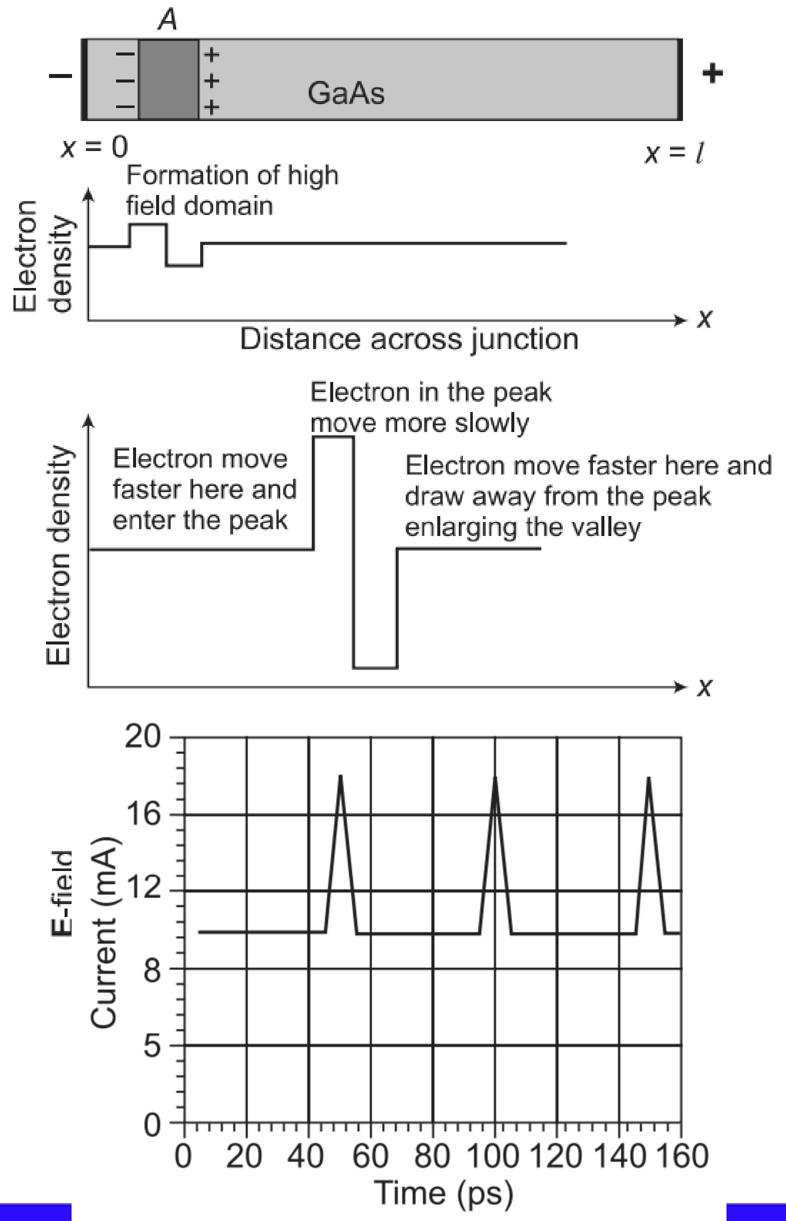


Figure 7-3-5 Mode chart. (*After M. Uenohara [24]; reprinted by permission of McGraw-Hill Book Company.*)

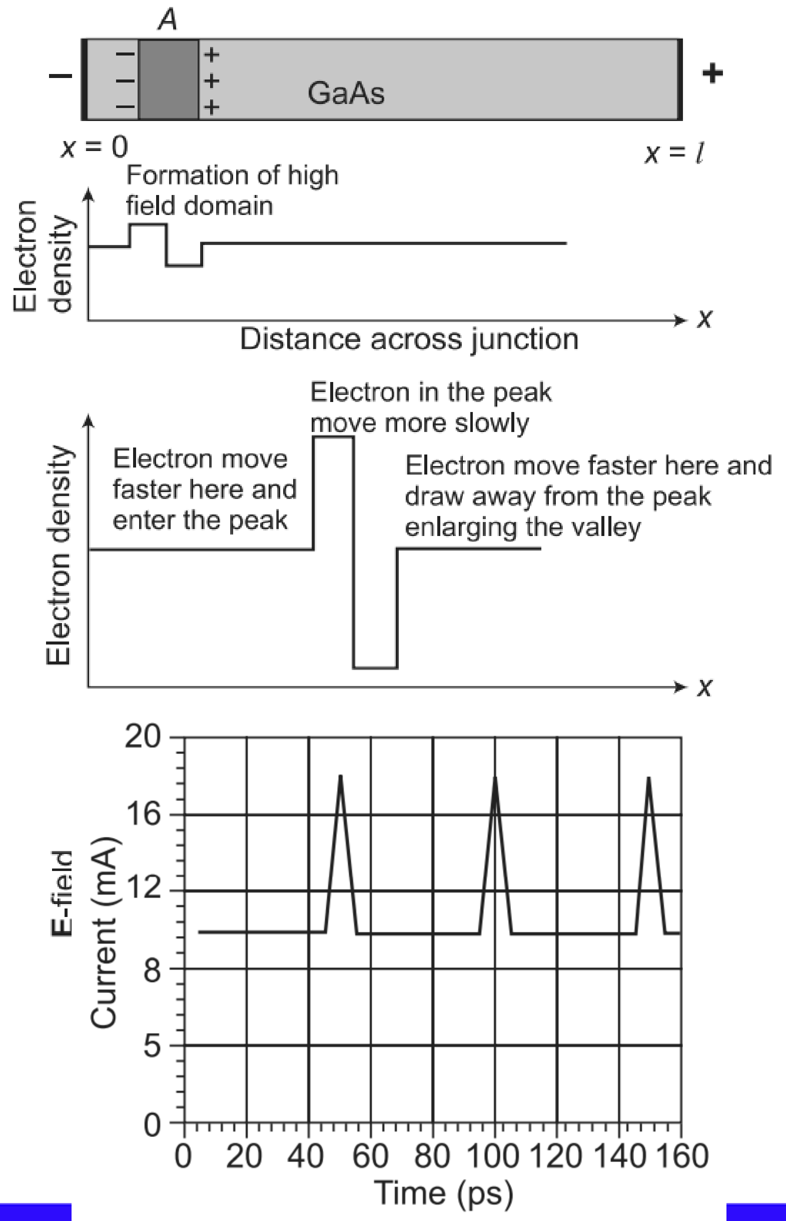
8.9 Microwave generation

- High field domain moves through the sample with uniform velocity v_d and gets collected at anode.
- New domain forms at cathode and again the process repeats as pulse.



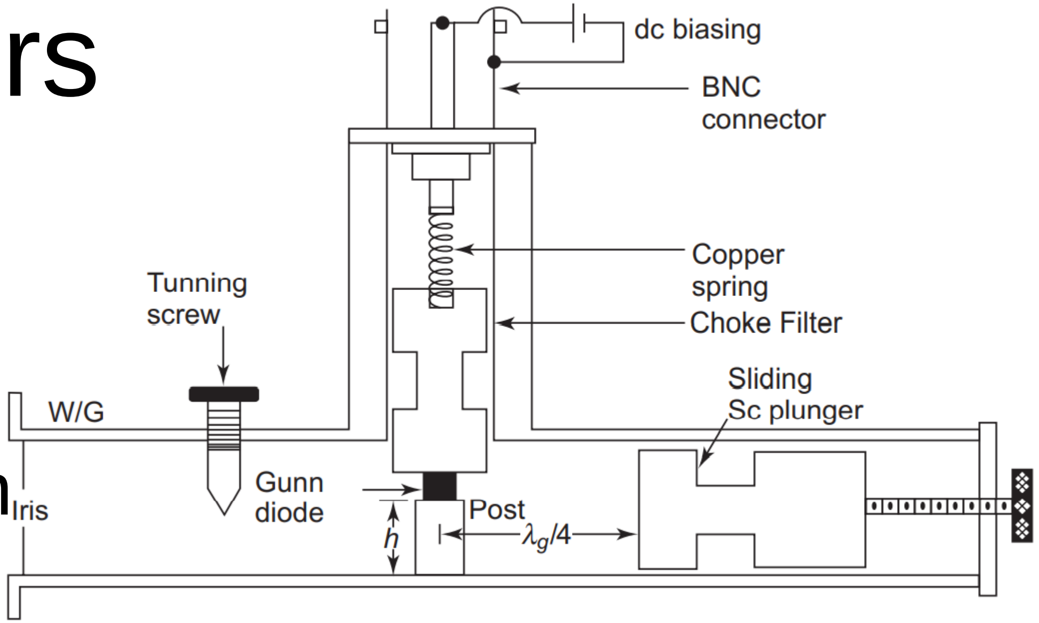
8.9 Microwave generation

- High field domain moves through the sample with uniform velocity v_d and gets collected at anode.
- New domain forms at cathode and again the process repeats as pulse.
- Pulse current output with intrinsic period T = transit time of domain
- $T = l_{eff}/v_d$ where $l_{eff} \approx l$ length of sample and v_d is the drift velocity.



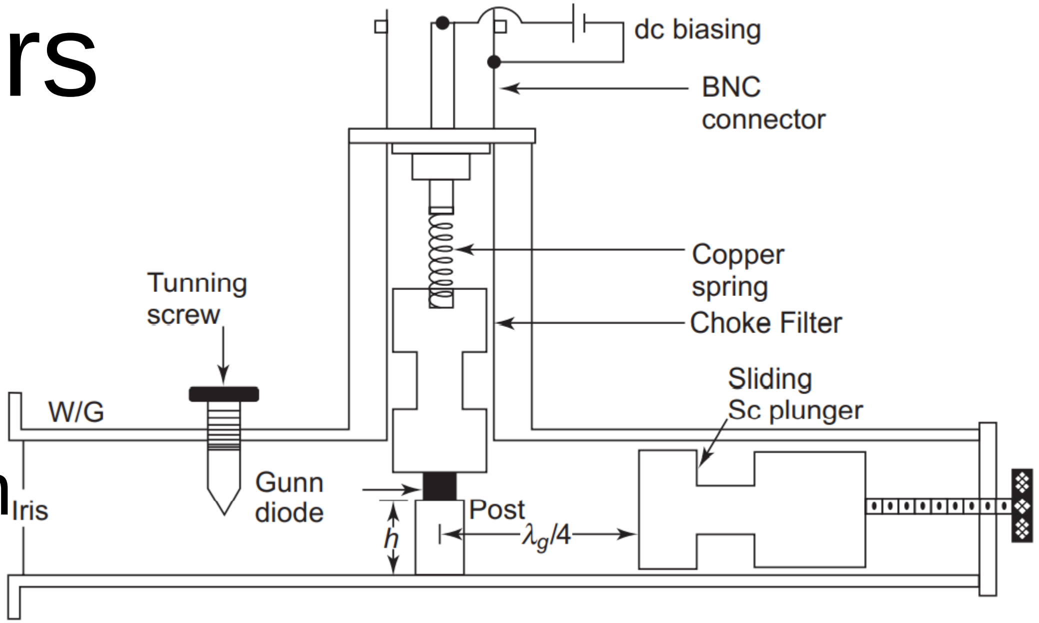
8.10 Gunn diode oscillators

- Local oscillators in Radars, signal sources in lab
- Gunn diode is Mounted in waveguide cavity formed by short circuit termination at one end and by an iris at other end.



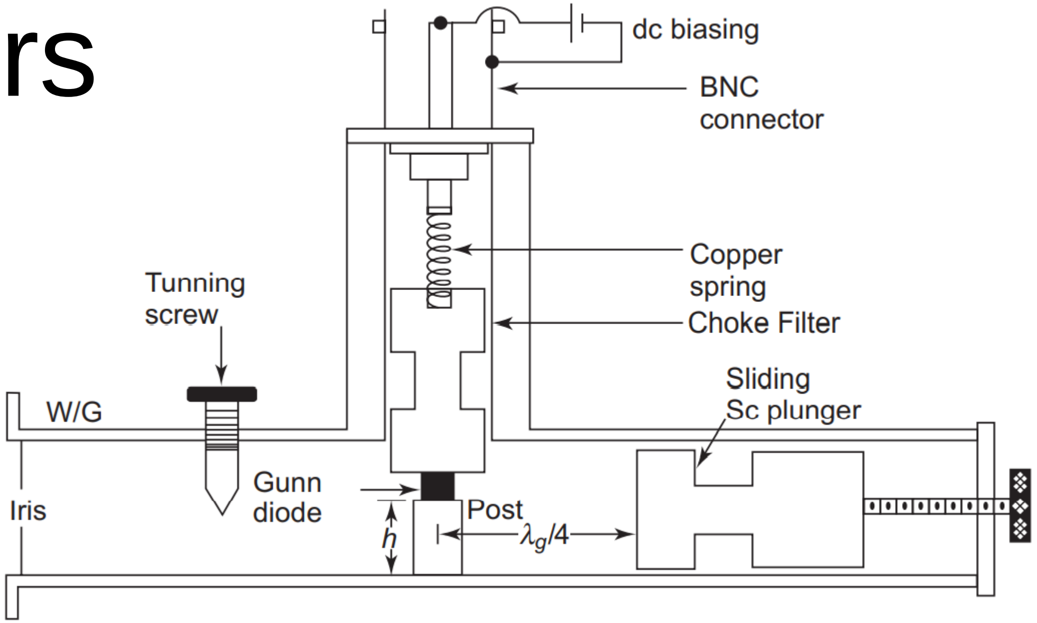
8.10 Gunn diode oscillators

- Local oscillators in Radars, signal sources in lab
- Gunn diode is Mounted in waveguide cavity formed by short circuit termination at one end and by an iris at other end.
- Diode is mounted at center perpendicular to broadwall - at maximum electric field point (TE10).
- Intrinsic frequency f_0 of oscillations depends on the drift velocity v_d due to the high field domain and effective length l. $f_0 = v_d/l$



8.10 Gunn diode oscillators

- GaAs: $v_d = 10^5 m/s$
- Cavity is tuned by SC plunger
- For frequency fine-tuning, tuning screw is used before iris



Degree of coupling - adjusted by selecting inductive iris.

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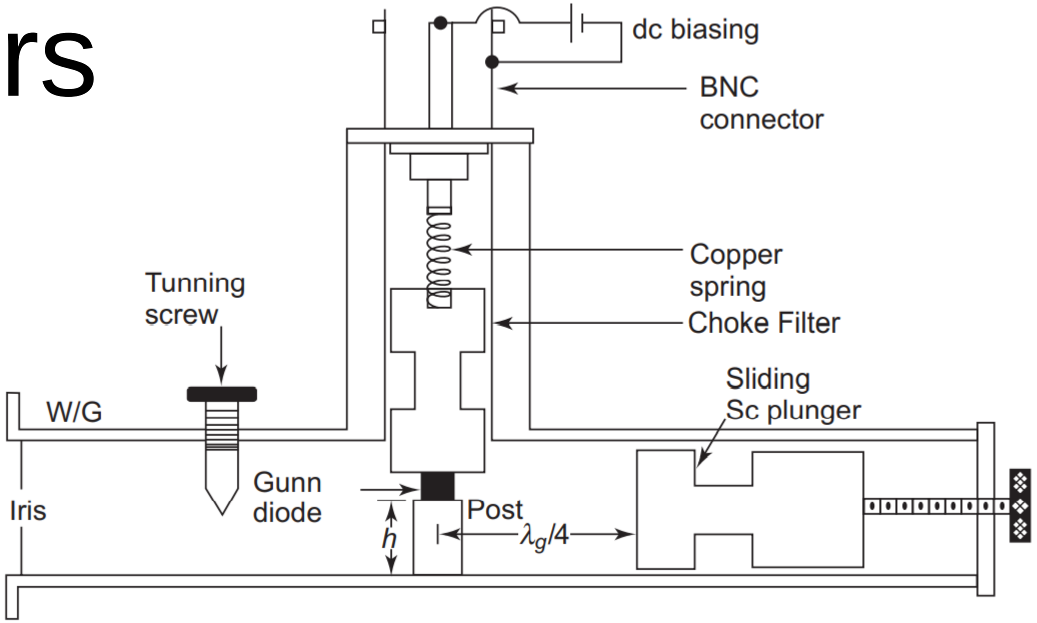
- Total resistive loading from cavity and external load >1.20 x Gunn device resistance $-R_j$
- $-\frac{R_L R_j}{R_L - R_j}$ will be negative



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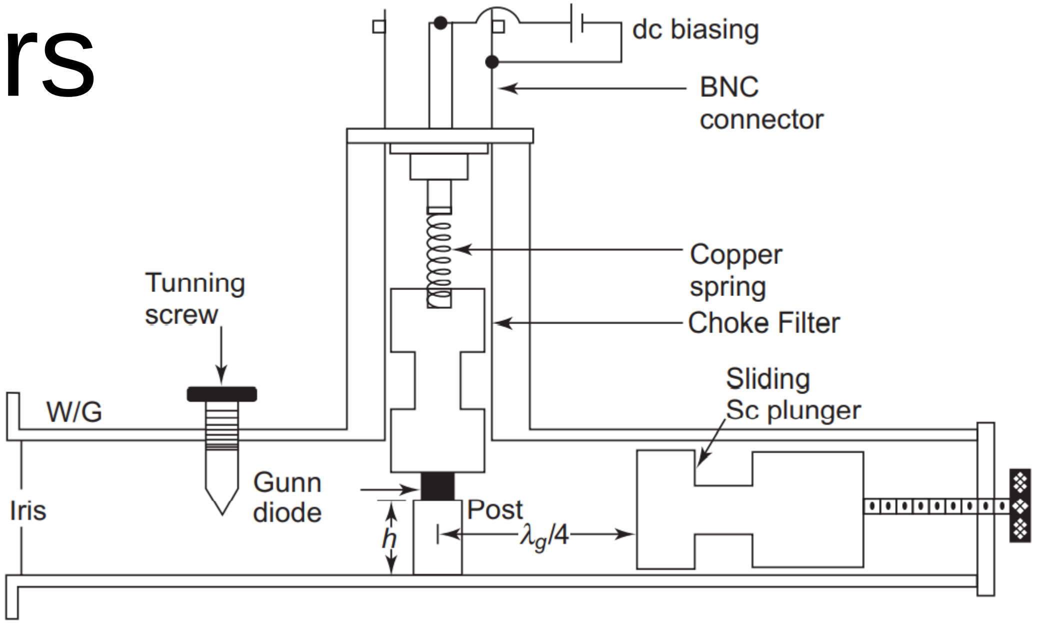
- Total resistive loading from cavity and external load >1.20 x Gunn device resistance $-R_j$
- $-\frac{R_L R_j}{R_L - R_j}$ will be negative
- Gun diode at metal post ($<\lambda/4$)
- Post diameter 5mm at 10GHz



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