The Gunn Diode

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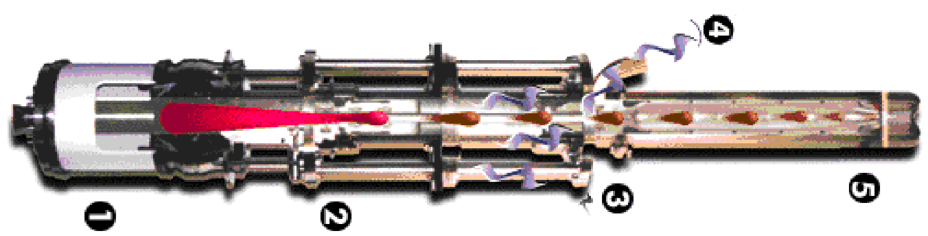
Overview of The Gunn Diode

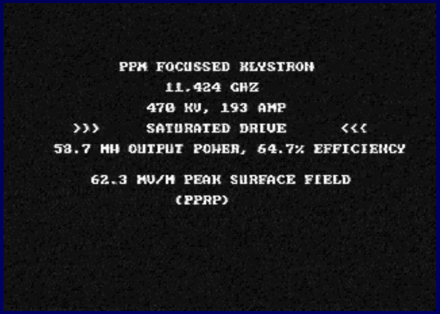
- What is it?
  - The Gunn diode is used as local oscillator covering the microwave frequency range of 1 to 100GHz
- How it works?
  - By means of the transferred electron mechanism, it has the negative resistance characteristic
- What’s the applications?
  - Local Oscillator and Avoid Collision Radar instead of Klystron etc..
- What’s the advantages?
  - Low noise, High frequency operation and Medium RF Power

Overview of The Gunn Diode

- Comparison with Klystron
  - How did we obtain Microwave before

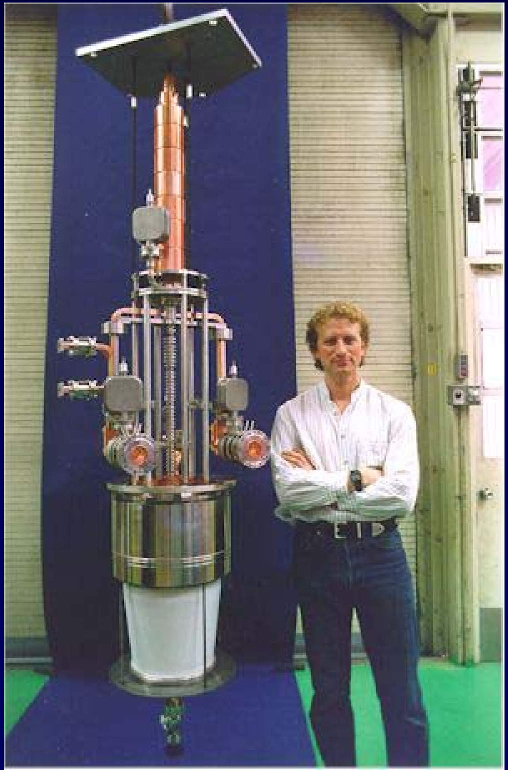


1. The electron gun
2. The bunching cavities
3. The output cavity
4. The waveguide
5. The Accelerator



PPM FOCUSSED KLYSTRON
11.424 GHZ
470 KV, 193 AMP
>>> SATURATED DRIVE <<<
58.7 MW OUTPUT POWER, 64.7% EFFICIENCY

62.3 MV/M PEAK SURFACE FIELD
(PPRP)

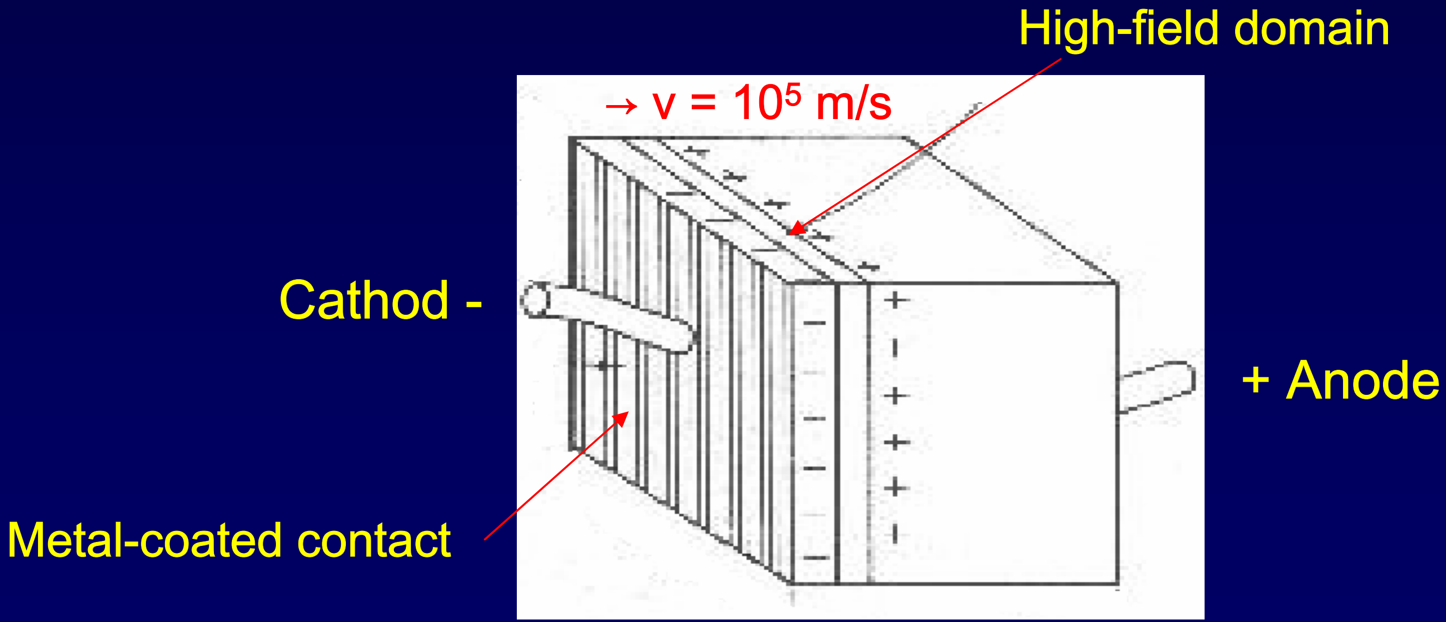


http://www.slac.stanford.edu/grp/kly/

Gunn Effect

- Gunn effect was discovered by J.B Gunn in IBM : 1963

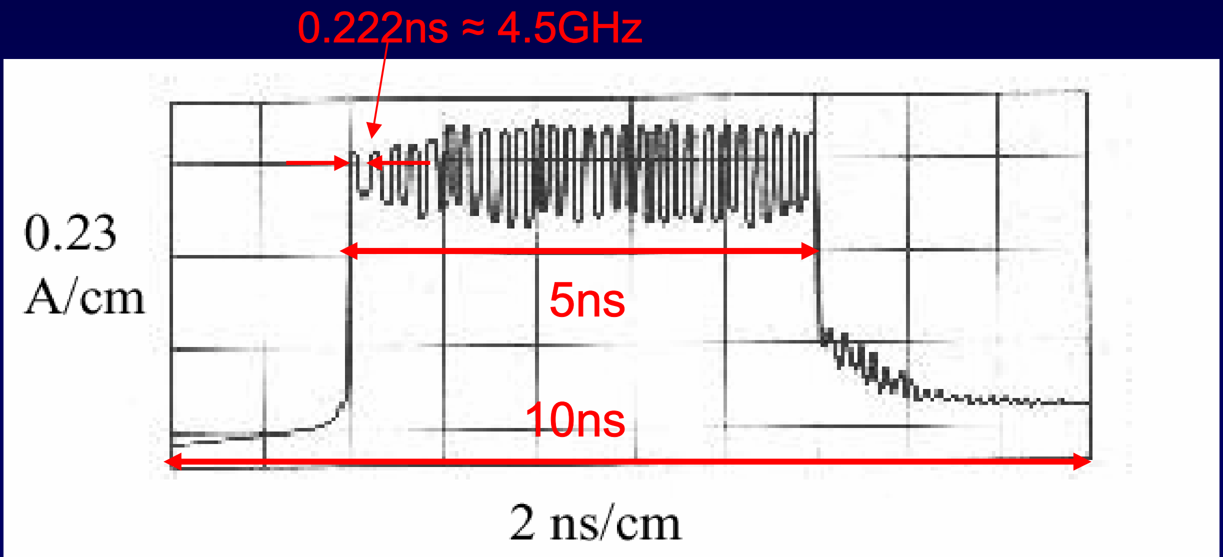
“Above some critical voltage, corresponding to an electric field of 2000~4000 V/cm, the current in every spectrum (GaAs) became a fluctuating function of time”



Schematic diagram for n-type GaAs diode

Gunn Effect

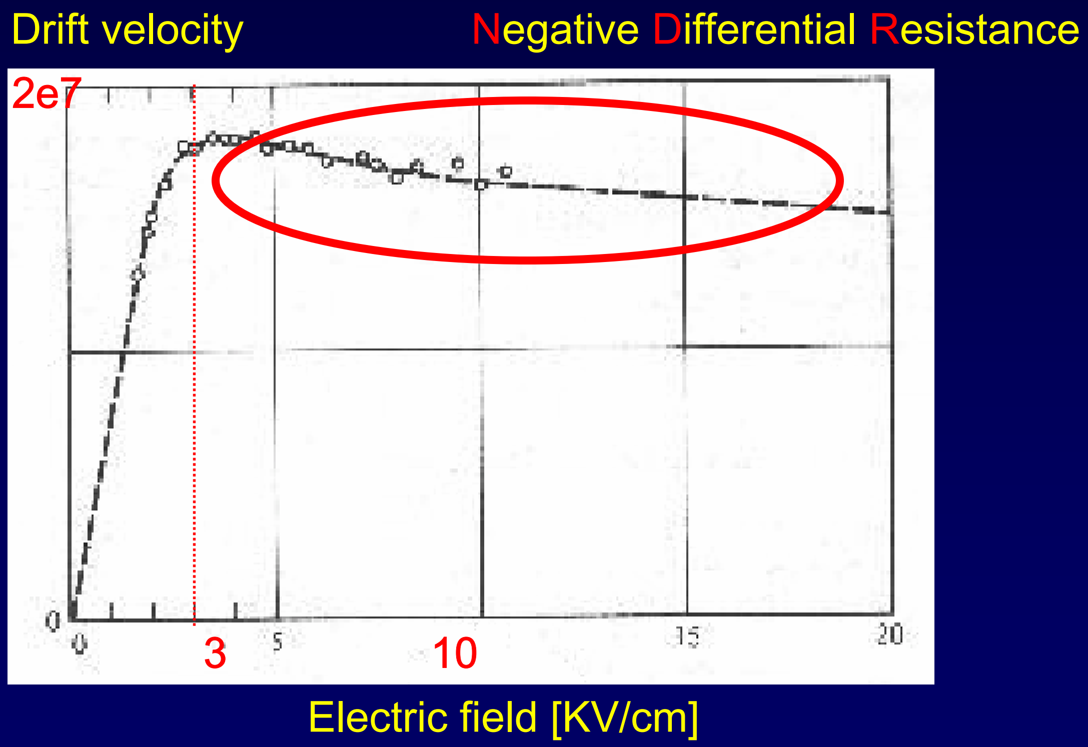
- (Continue)
- The current waveform was produced by applying a voltage pulse of 59V And 10ns duration
- Oscillation frequency was 4.5Ghz
- The period of oscillation is equal to the transit time of electrons through the device



Current fluctuation of N-type GaAs reported by Gunn

Gunn Effect-Negative Differntial Resistance

- Drift velocity of electrons decrease when electric field excess certain value
- Threshold electric field about 3000V/cm for n-type GaAs.



Drift velocity of electrons in GaAs bulk Vs electric field

Two-Valley Model Theory

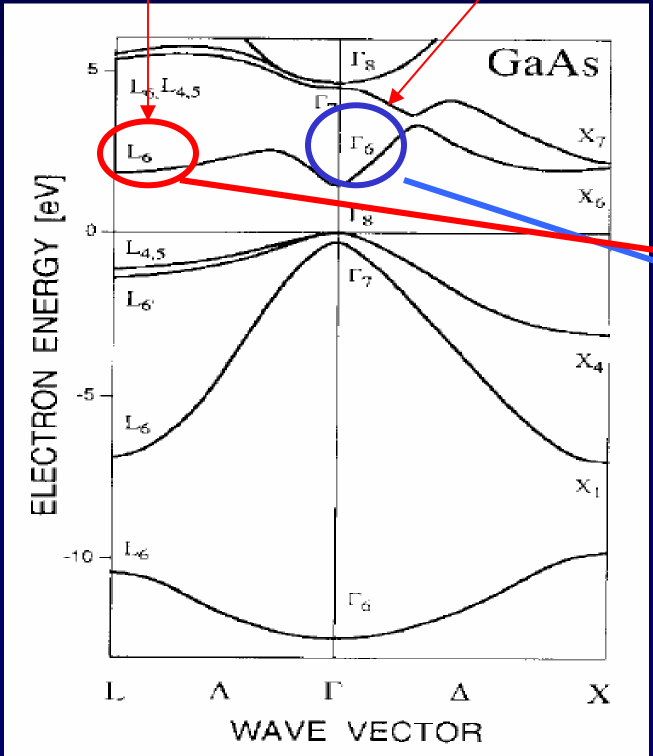
- According to the energy-band theory of n-type GaAs, there are two valleys in the conduction band
- Effective mass of electron is given by:

$$m^* = \frac{\hbar^2}{\dfrac{d^2E}{dk^2}}$$

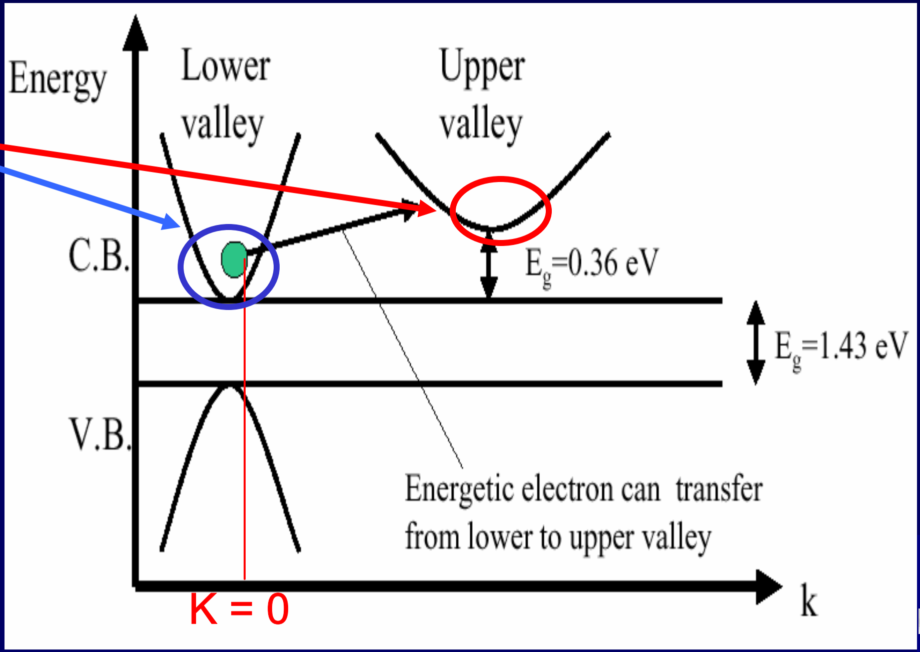
Rate of change of the valley curves slope

Upper valley (Satellite valley)

Lower valley (Central valley)



Central valley Satellite valley



Energetic electron can transfer from lower to upper valley

Two-Valley Model Theory

- Effective mass of electron is given by:

$$m^* = \frac{\hbar^2}{\frac{d^2E}{dk^2}}$$

Rate of change of the valley curves slope

- Since the lower valley slope is shaper then the one in upper valley, thus electron effective mass in lower valley is higher then that in upper valley
- So that, the mobility of electron in upper valley is less due to the higher effective mass

$$\mu_n = \frac{e\overset{\frown}{\tau}}{m_n^*}$$

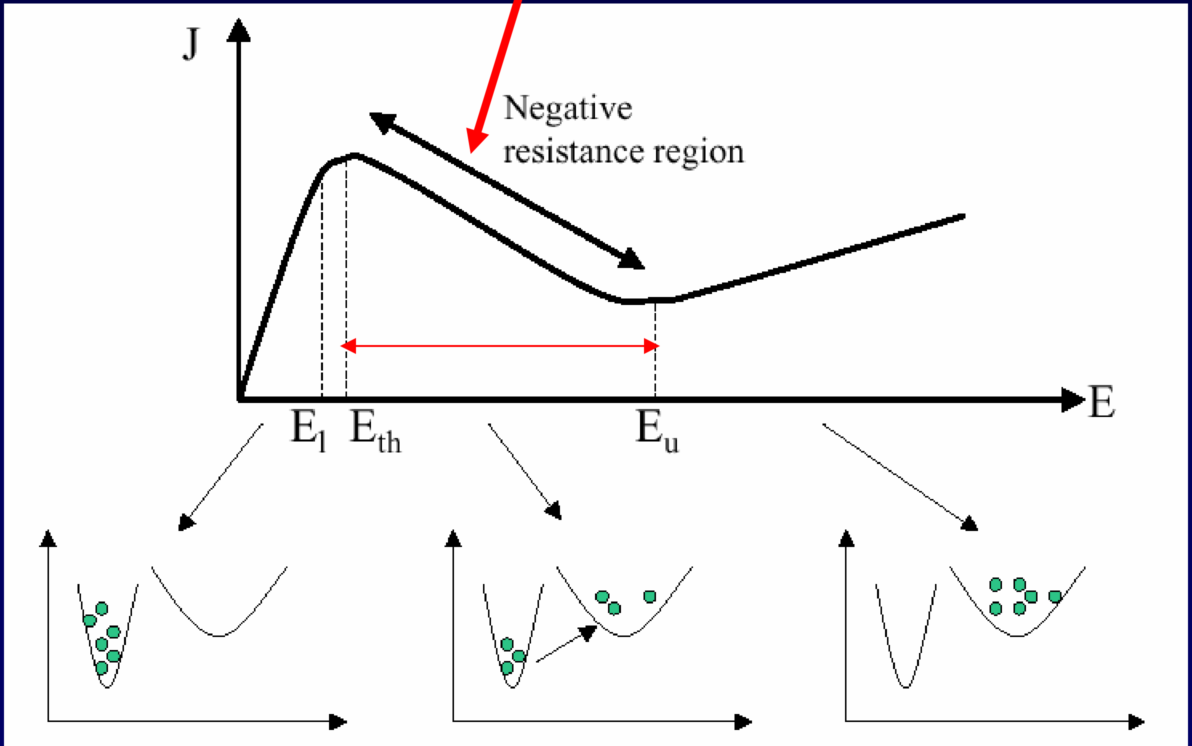
Valley	Effective mass M_e	Mobility u $Cm^2/V.s$
Lower	0.068	8000
Upper	1.2	180

* n-type GaAs

Two-Valley Model Theory

- The current density vs E-field according to equation

$$J = e(\mu_l \overset{\downarrow}{n_l} + \mu_u \overset{\uparrow}{n_u})E \qquad \mu_l > \mu_u$$



Two-Valley Model Theory

- Negative resistance : the current and voltage of a device are out of phase by 180degree → $P = -I^2 R$

- Conductivity of n-type GaAs is given by

$$\sigma = e(\mu_l n_l + \mu_u n_u)$$

$n_{l,u}$: *Electron density in lower/upper valley*

$\mu_{l,u}$: *Mobility in lower/upper valley*

- The differential resistance of the device is

$$\frac{d\sigma}{dE} = e\left(\mu_l \frac{dn_l}{dE} + \mu_u \frac{dn_u}{dE}\right) + e\left(n_l \frac{d\mu_l}{dE} + n_u \frac{d\mu_u}{dE}\right) \qquad (1)$$

Two-Valley Model Theory

- According to Ohm's law: $J = \sigma E$

$$\frac{dJ}{dE} = \sigma + \frac{d\sigma}{dE} E \qquad (2)$$

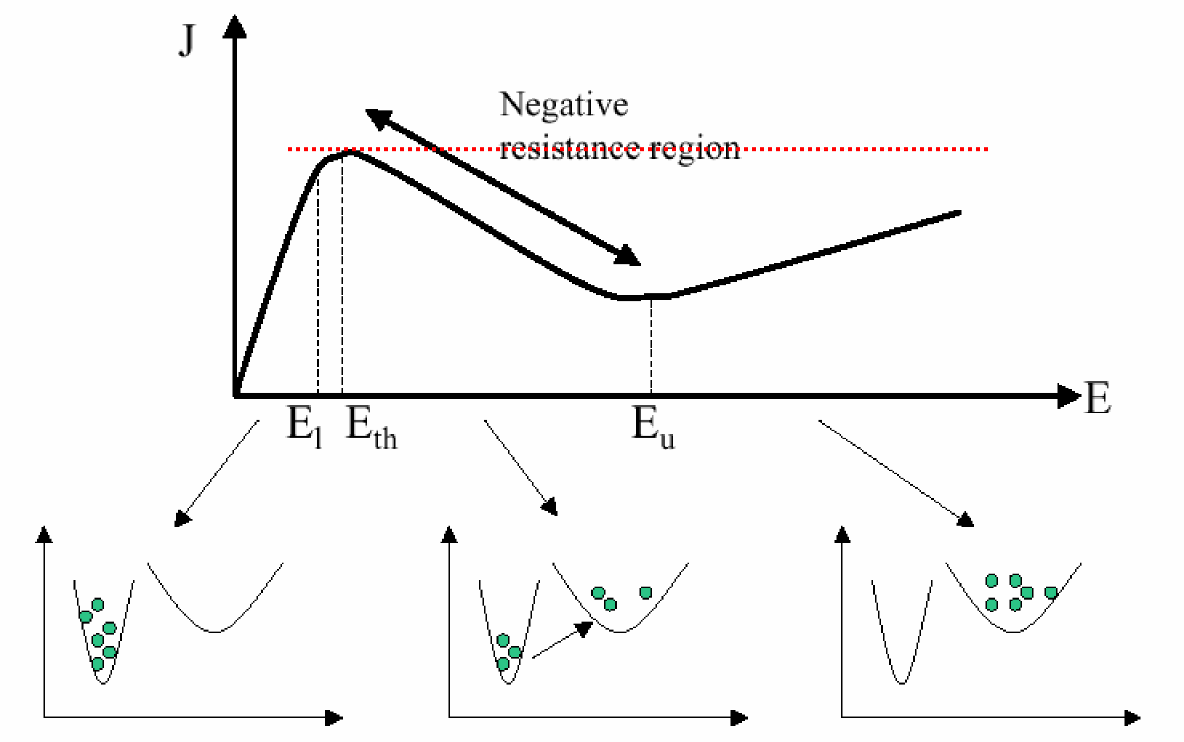
- Combine and rewrite equation 1 and 2:

$$\frac{1}{\sigma}\frac{dJ}{dE} = 1 + \frac{\frac{d\sigma}{dE}}{\frac{\sigma}{E}} \qquad (3)$$

- Negative resistance occurs when
- $$-\frac{\frac{d\sigma}{dE}}{\frac{\sigma}{E}} > 1 \qquad (4)$$

Two-Valley Model Theory

- Plot current density vs E-field according to equation *(3)*

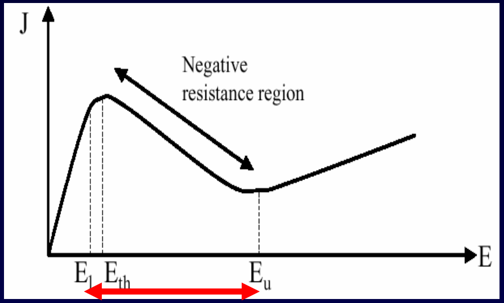


Two-Valley Model Theory

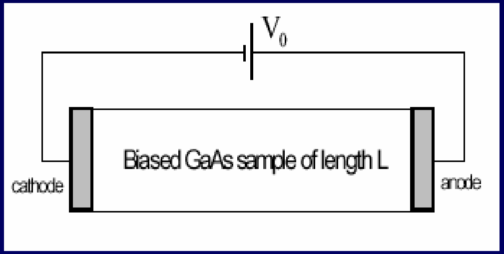
1. The energy difference between two valleys must be several times larger than the thermal energy (KT~0.0259eV)
2. The energy difference between the valleys must be smaller than the bandgap energy (E_g)
3. Electron in lower valley must have a higher mobility and smaller effective mass than that of in upper valley

Gunn-Oscillation

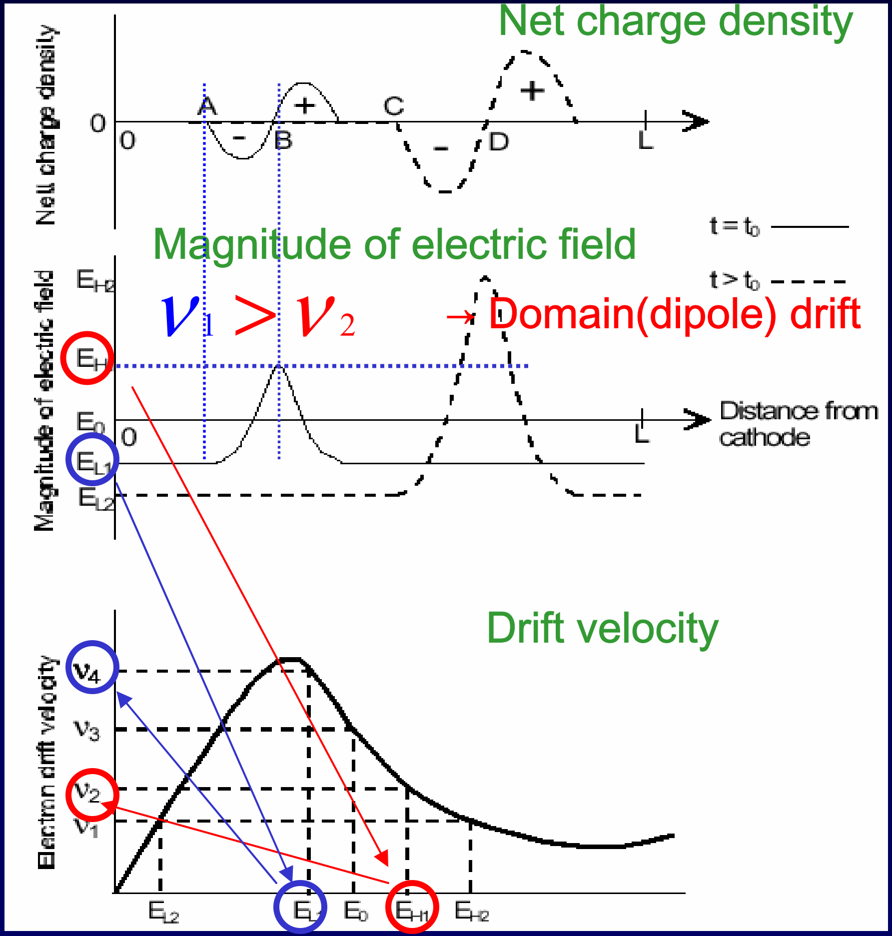
- How the NDR results in Gunn-Oscillation?



- $J = \sigma E$
- $\tau_d \left(= \frac{\varepsilon}{\sigma} \right) \le 0$ The electric relaxation time



$$Q(t) = Q_0 e^{-\frac{t}{\tau_d}} \Longrightarrow Q(t) = Q_0 e^{+\frac{t}{\tau_d}}$$



Net charge density

Magnitude of electric field

$v_1 > v_2$ → Domain(dipole) drift

Drift velocity

Gunn-Oscillation

- How the NDR results in Gunn-Oscillation?(Summary)
  - Above Eth, A domain will start to form and drift with the carrier stream. When E increases, drift velocity decreases and diode exhibits negative resistance
  - If more Vin is applied, the domain will increase and the current will decrease.
  - A domain will not disappear before reaching the anode unless Vin is dropped below Vth
  - The formation of a new domain can be prevented by decreasing the E field below Eth

Gunn-Oscillation

- The condition for the successful Domain(Dipole) drift

The transit time($\frac{L}{v_s}$) > The electric relaxation time $\tau_d = \frac{\varepsilon}{\sigma} = \frac{\varepsilon}{e\mu^* n_0}$

L : The sample length

- Therefore, there is a critical product of electron concentration and sample length : $Ln_0 > \frac{\varepsilon v_s}{e\mu^*}$ (1)

- The frequency of oscillation : $f = \frac{v_{domain}}{L_{eff}}$

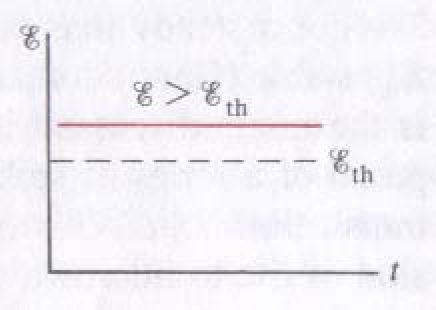
Gunn Oscillation Modes

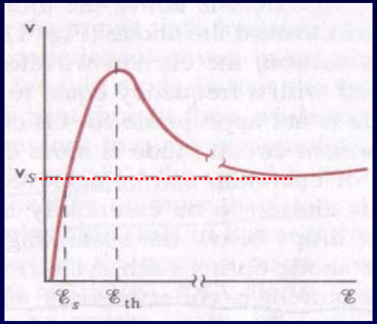
- The Operation in Resonant Circuit

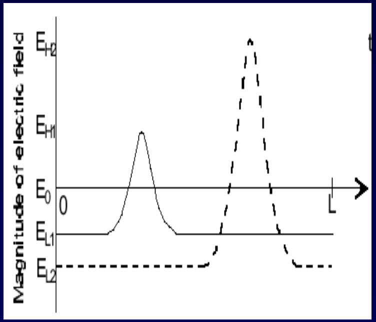
1. Stable domain mode(Without resonant circuit)

$\varepsilon > \varepsilon_{th}$ (Low efficiency less than 10%)

$$f = \frac{v_s}{L}$$



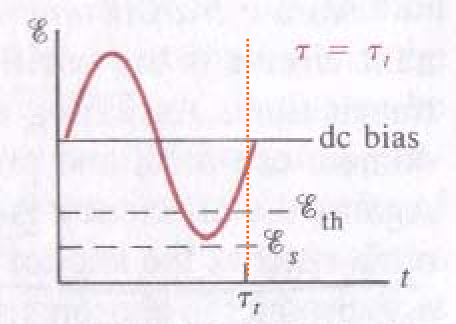


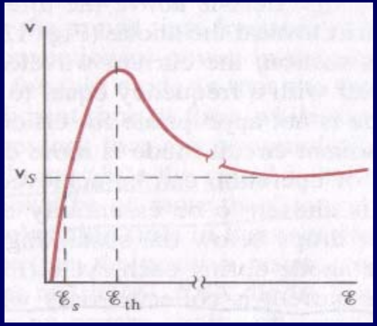


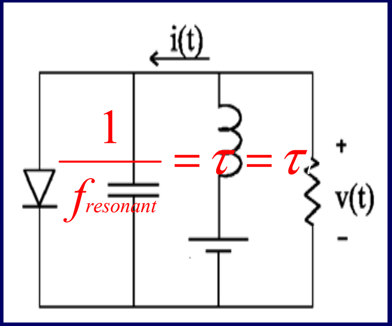
2. Resonant Gunn mode

$\varepsilon > \varepsilon_s$ $\frac{1}{f_{resonant}} = \tau = \tau_T$ (Low efficiency less than 10%)

$$f = \frac{v_s}{L}$$





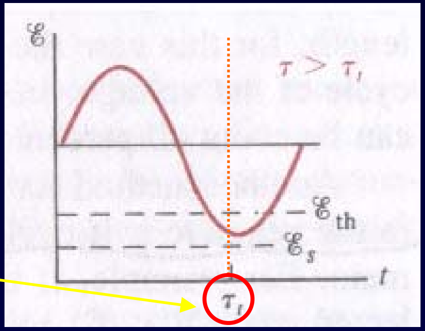


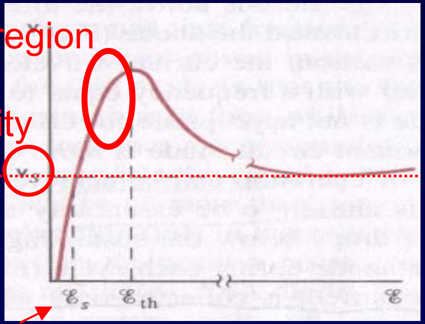
$\frac{1}{f_{resonant}} = \tau = \tau_t$

Gunn Oscillation Modes

3. Delayed mode :

- $\tau = \tau_t$(High efficiency up to 20%)
  - There is an ohmic currents higher than domain currents.
  - f_{osc} is determined by the resonant circuit



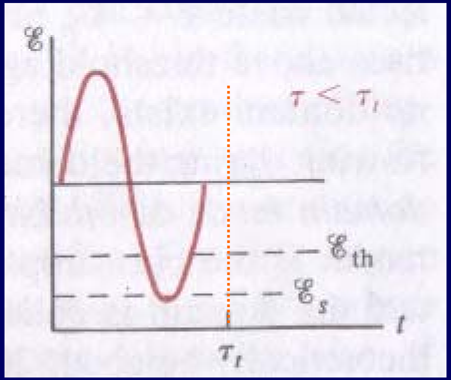


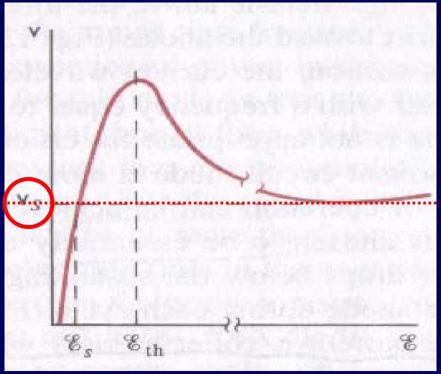
Positive resistance region

The sustaining drift velocity

4. Quenched mode

- $\tau > \tau_t$(Efficiency up to 13%)
  - The domain can be quenched before it is collected
  - So that, f_{osc} is determined by the resonant circuit





Gunn Oscillation Modes

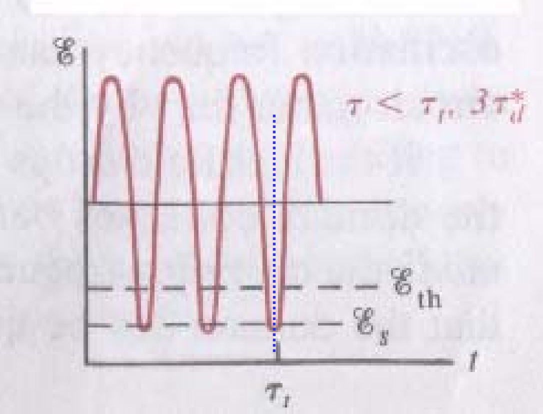
- The Operation in Resonant Circuit (Continue)

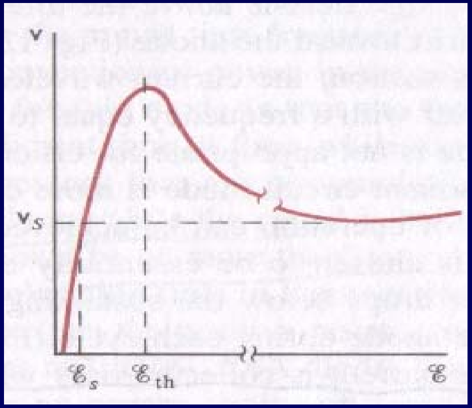
5. LSA mode(Limited Space charge Accumulation)

$\tau < \tau_t$ (The most efficiency mode more than 20%)

The frequency is so high that domains have insufficient time to form while the field is above threshold. As a results, domains do not form.

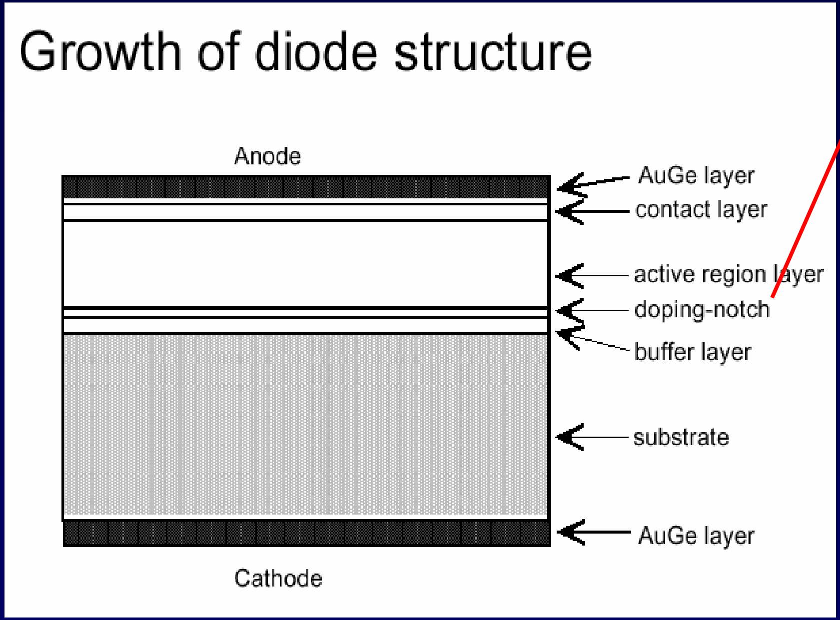
f_{osc} determined by the resonant circuits, is much higher than the transit time frequency





Fabrication

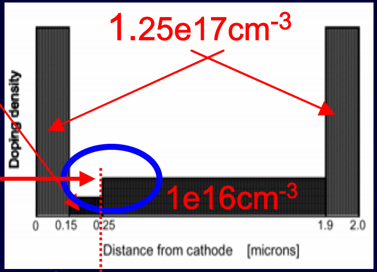
- Structure



Doping density

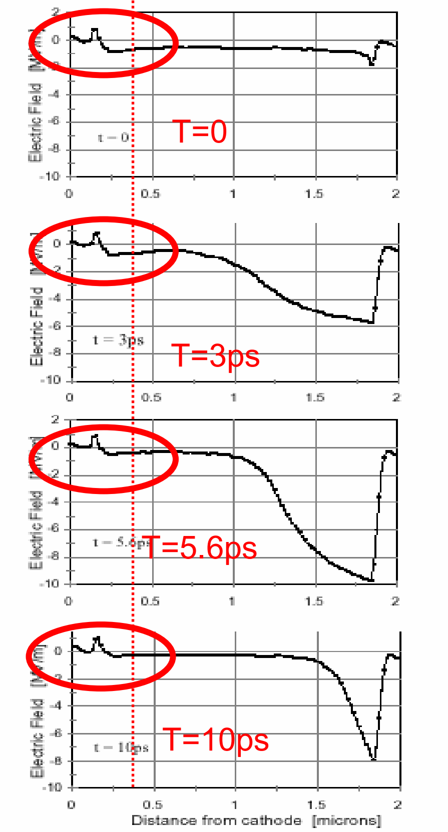
Active region : $5e15cm^{-3}$

The doping-notch



Electric field

Dead zone



Distance from the cathode

Summary

- Gunn diode is mainly used as a local oscillator covering the microwave frequency range of 1 to 100GHz
- By means of the transferred electron mechanism, the negative resistance characteristic can be obtained. This mechanism provides low noise, high frequency operation and Medium RF Power characteristic
- The LSA mode is particularly suitable for microwave power generation because of its relatively high efficiency and operating frequency

Reference

- “Solid State Electronic Devices”, 3rd Ed, Streetman
- “Microwave device & Circuits” 3rd Ed, Samuel Y.Liao
- “The Gunn-diode: Fundamentals and Fabrication”, Robert van Zyl, William perold, Reinhardt Botha
- “PPM KLYSTRON SIMULATION” http://www.slac.stanford.edu/grp/kly/