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

Negative Resistance

In a negative resistance the current and   voltage are out of phase by 180.

The voltage drop across a negative resistance is negative and a power of $-I^2R$ is generated by the power supply.

i.e positive resistance absorbs power (passive devices) and negative resistances generates power (active devices).

Microwave Transistors and TEDs

Transistors operate with either junctions or gates but TEDs are bulk devices having no junctions or gates.

The majority of transistors are fabricated fr om Si or Ge whereas TEDs are fabricated f rom   GaAs, InP or CdTe.

Contd······

Transistors operate with "warm" electrons whose energy is not much greater than the thermal energy of the electrons in the semiconductors whereas TEDs operate with "hot" electrons whose energy is very much greater than the thermal energy.

Because of these fundamental differences, the theory and technology of transistors cannot be applied to TEDs
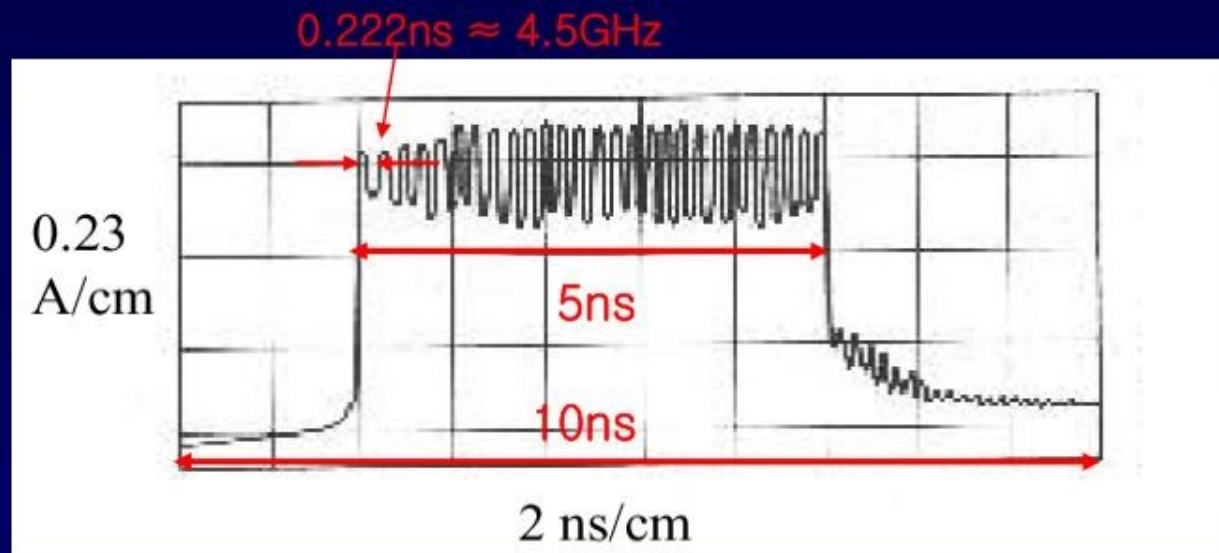
Gunn Effect

- 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 specimen (GaAs) became a

fluctuating function of time"

High-field domain

$\rightarrow v = 10^5$ m/s

Cathod −

+ Anode

Metal−coated contact
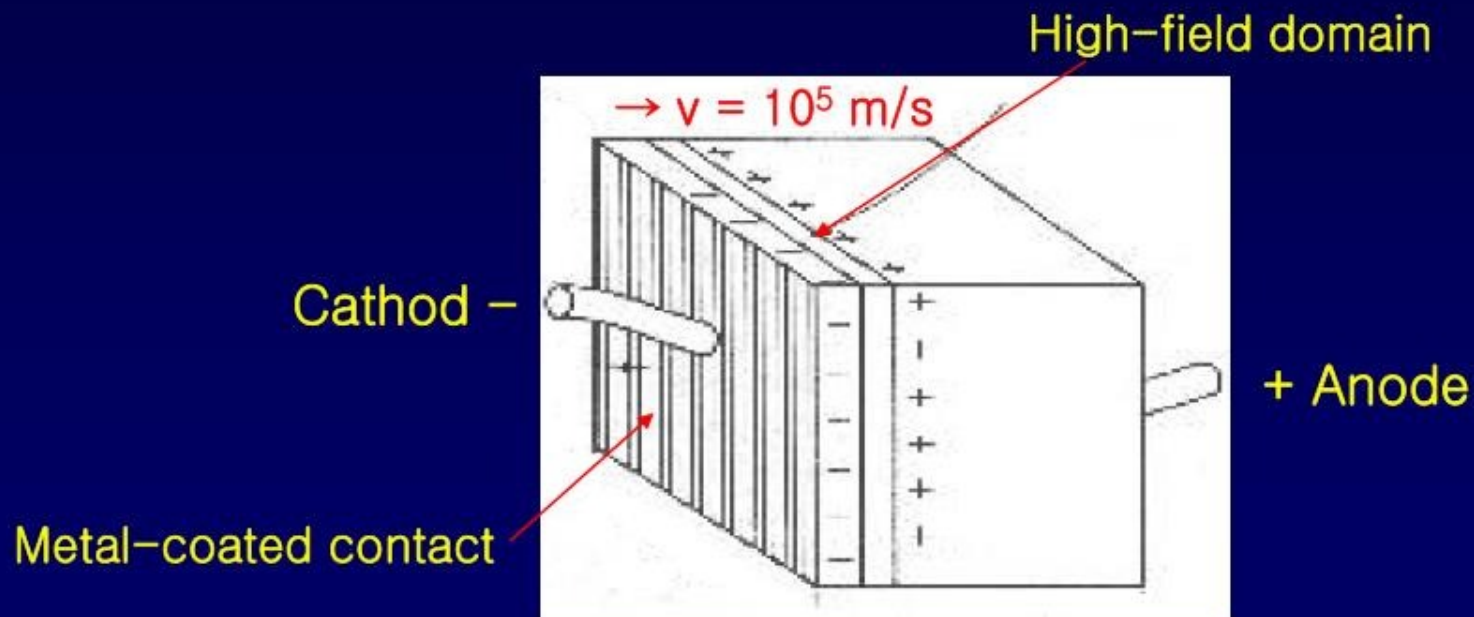
Schematic diagram for n−type GaAs diode

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   Negative Differential Resistance
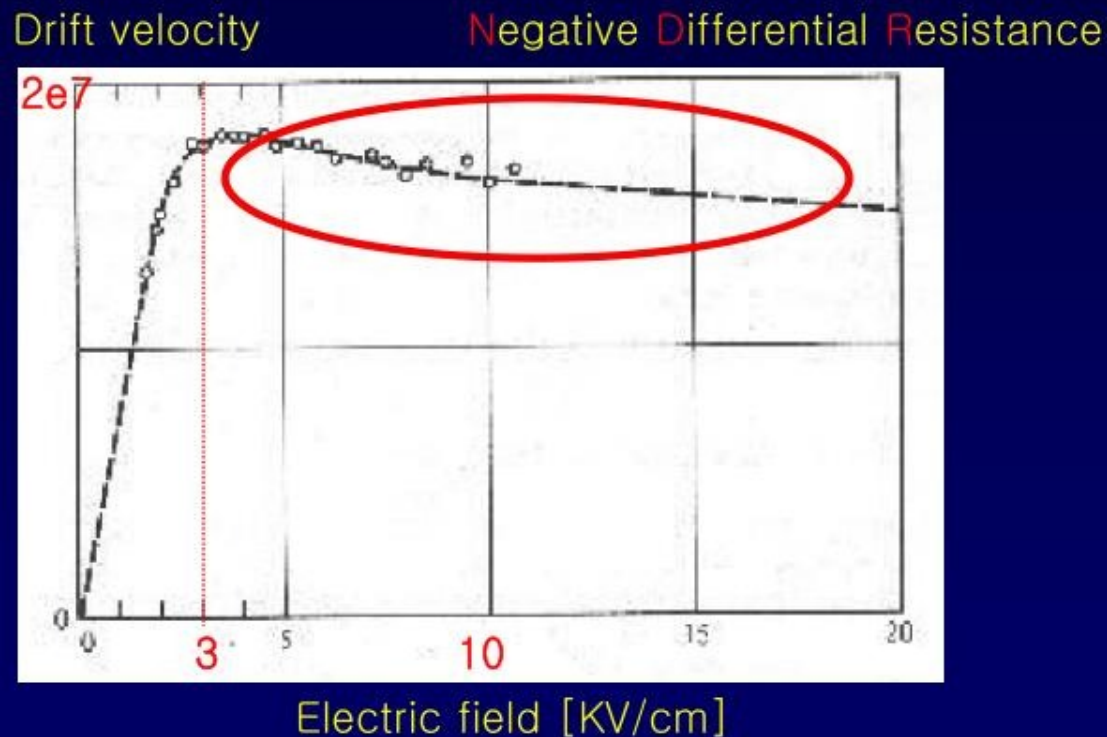
Drift velocity of electrons in GaAs bulk Vs electric field

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:

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

Rate of change of the valley curves slope

Upper valley
(Satellite valley)

Lower valley
(Central valley)

Central valley Satellite valley

$E_g = 0.36$ eV

$E_g = 1.43$ eV

Energetic electron can transfer from lower to upper valley

$K = 0$
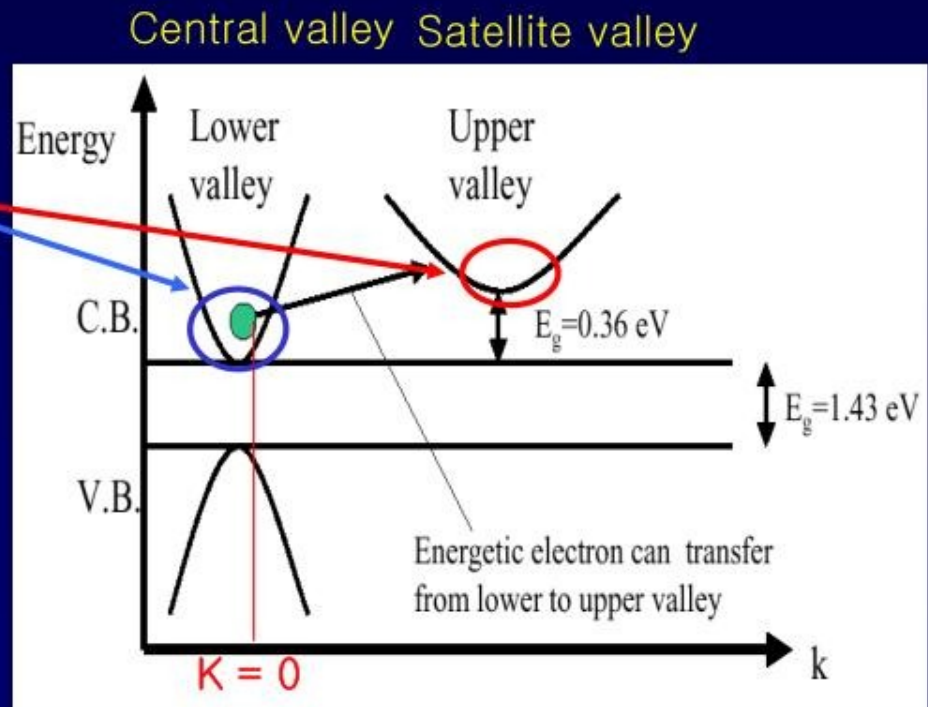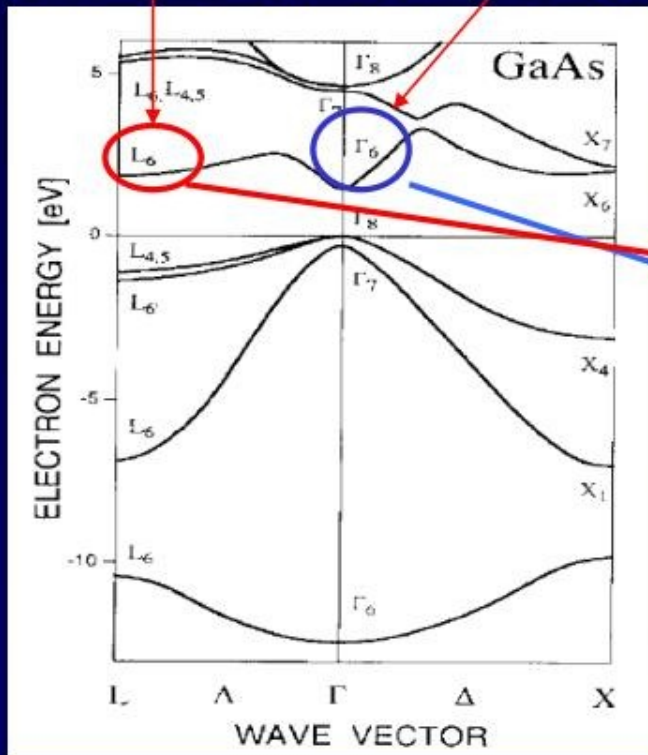
Two-Valley Model Theory

- 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 than the one in upper valley, thus electron effective mass in lower valley is higher than that in upper valley

- So that, the mobility of electron in upper valley is less due to the higher effective mass
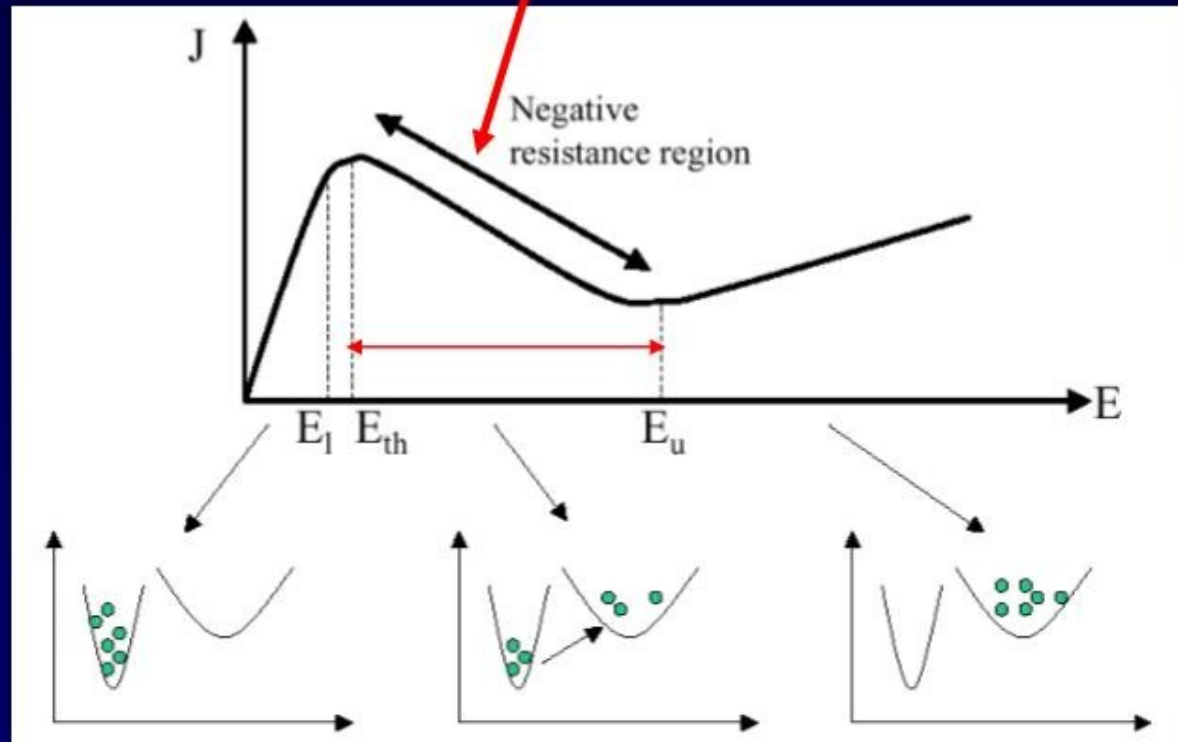
$$\mu_n = \frac{e\tau}{m_n*}$$

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

$$J = e(\mu_l n_l + \mu_u n_u)E \qquad \mu_l > \mu_u$$

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

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

Two–Valley Model Theory

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

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

- rewrite equation 2:

$$\frac{1}{\sigma}\frac{dJ}{dE} = 1 + \frac{\dfrac{d\sigma}{dE}}{\dfrac{\sigma}{E}} \qquad (3)$$
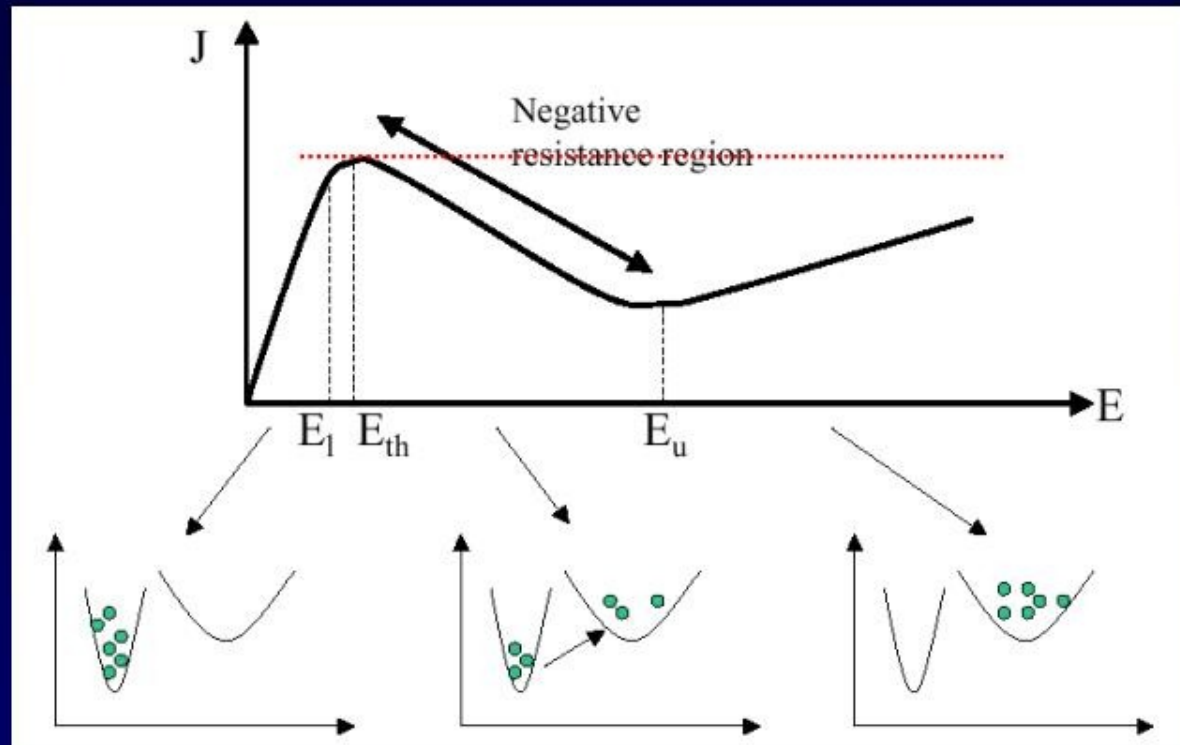
- Current density J must decrease with increasing field E
- Negative resistance occurs when

$$-\frac{\dfrac{d\sigma}{dE}}{\dfrac{\sigma}{E}} > 1 \qquad (4)$$

-

Two-Valley Model Theory

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

Two-Valley Model Theory

According to Ridley-Watkins-Hilsum thoery, the band structure of a semiconductor must satisfy 3 criteria in order to exhibit negative resistance.

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 gap energy between the valence and the conduction band.

3. Electron in lower valley must have a higher mobility and smaller effective mass than that of in upper valley

Gunn-Oscillation (High field domain)

- 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

·

Modes of operation

1. Gunn Oscillation: $fL = 10^7$ cm/s

 $n_0L = 10^{12}$ cm/s^2

Device is unstable because of the cyclic formation of either the accumulation layer or high field domain

2. Stable Amplification: $fL = 10^7$ cm/s

$n_0L = 10^{11}$ cm/s^2 to 10^{12} cm/s^2

3. LSA Oscillation: $fL > 10^7$ cm/s

Quotient of doping divided by frequency is between 2×10^4 to 2×10^5.

4. Bias-circuit oscillation mode: This mode occurs only when there is either Gunn or LSA oscillation, and it is usually at the region where the product of frequency times length is too small in the figure to appear.
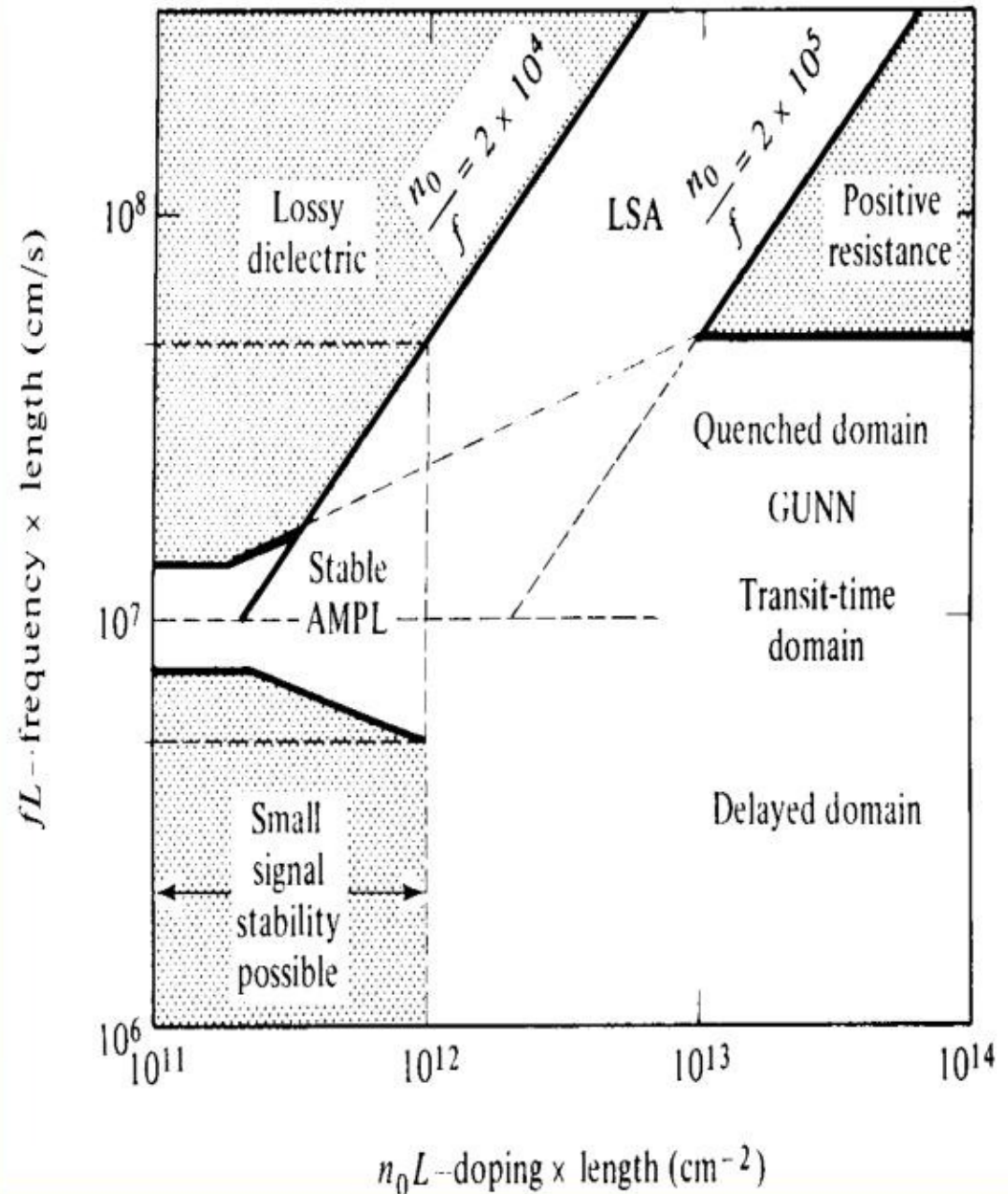
Gunn Oscillation Modes

$\varepsilon > \varepsilon_{th}$. The high field domain drifts along the specimen until it reaches the anode or until the low-field value drops below the sustaining field ε_s requuired to maintain Vs as shown in the figure

Since the electron drift velocity v varies with E, there are 3 possible modes

1. Transit time domain mode:

$$v_d = v_s = fL \approx 10^7 \text{ cm/s}$$

Oscillation period is equal to transit time $\tau_0 = \tau_t$

efficiency $(10^6 \text{ cm/s} < fL < 10^7 \text{ cm/s})$

$E < E_{th}$ $\tau_0 > \tau_t$

2. Delayed domain mode:

. In $(fL > 2 \times 10^7 \text{ cm/s})$

de.

Low efficiency less than 20%.

3. Quenched domain mode:

If $E < \varepsilon_s$ domain collapses before it reaches the anode. When the bias field swings back above the threshold, a new domain is nucleated and the process repeats. Thus oscillation occurs at the frequency of resonant circuit rather than at the transit time frequency. efficiency can reach 13%.
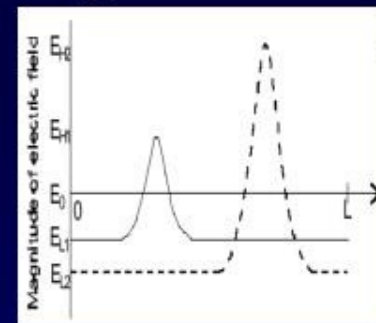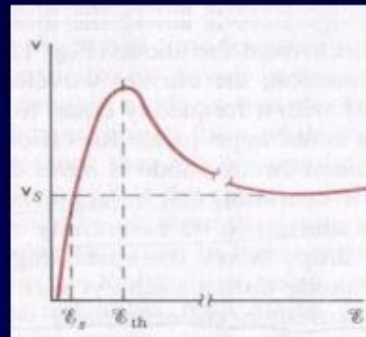

(a) Transit-time mode $\tau_0 = \tau_t$

(b) Delayed mode $\tau_0 > \tau_t$

(c) Quenched mode $\tau_0 < \tau_t$
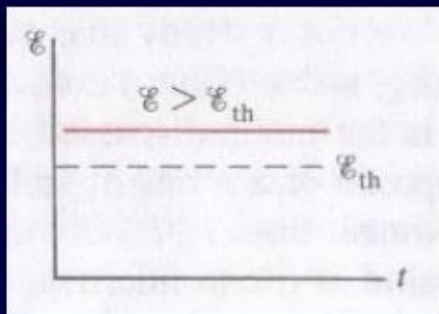
(d) LSA mode $\tau_0 < \tau_t$, $\tau_0 = 3\tau_d$
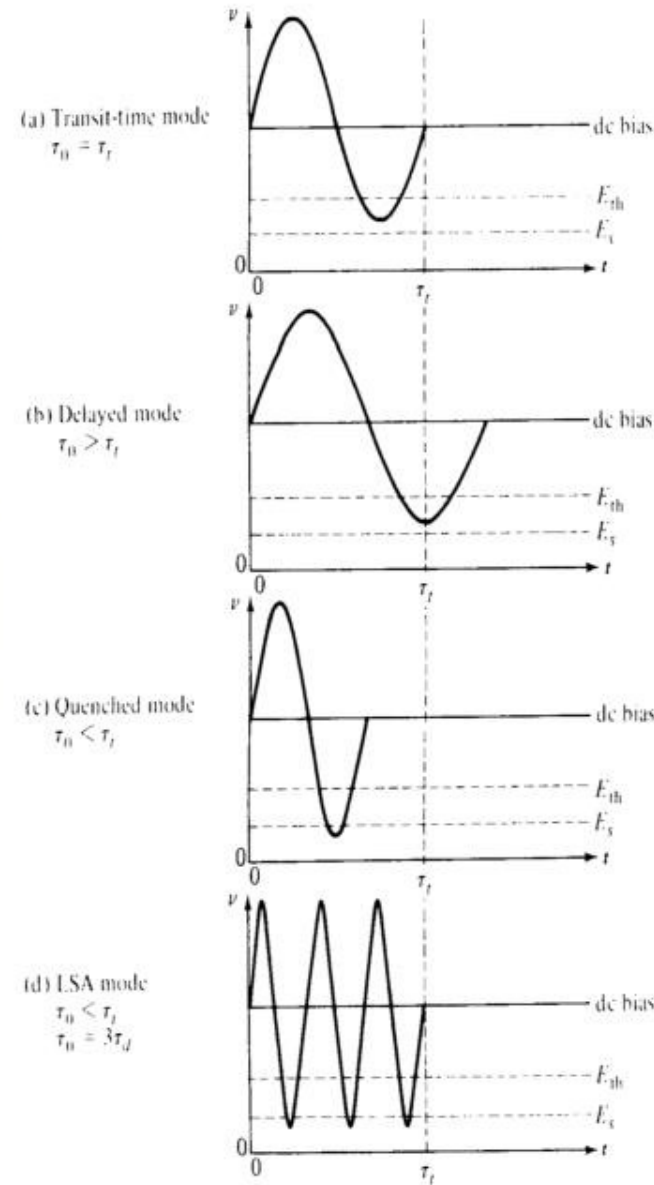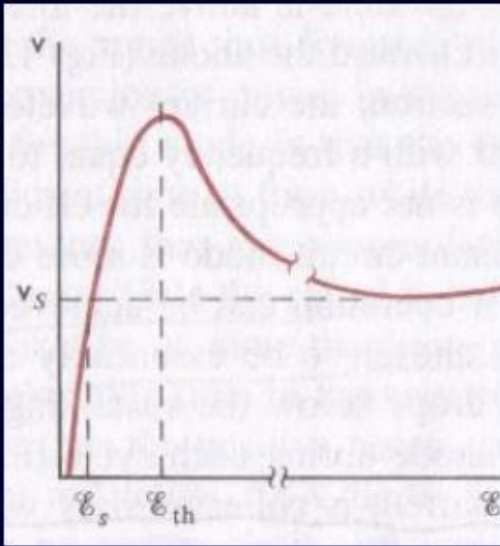
Figure 7-3-4 Gunn domain modes.

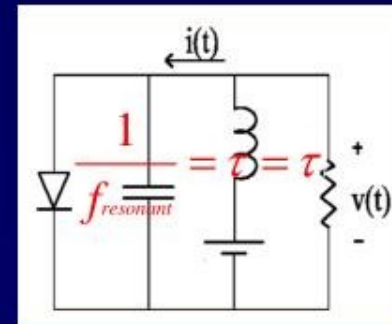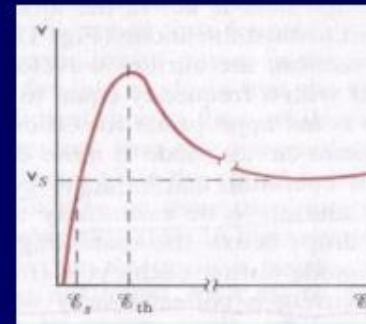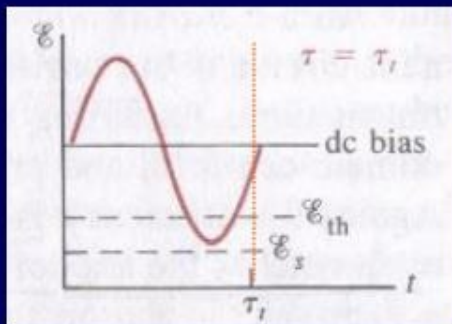# Gunn Oscillation Modes

- The Operation in Resonant Circuit

  1. Stable domain mode(Without resonant circuit)

     $\varepsilon > \varepsilon_{th}$ (Low efficiency less than 10%) $f = \dfrac{v_s}{L}$

  2. Resonant Gunn mode

     $\varepsilon > \varepsilon_s$ $\dfrac{1}{f_{resonant}} = \tau = \tau_t$ (Low efficiency less than 10%) $f = \dfrac{v_s}{L}$

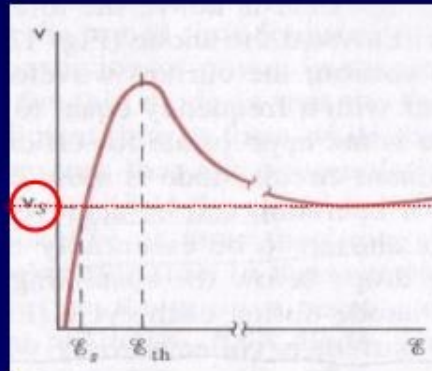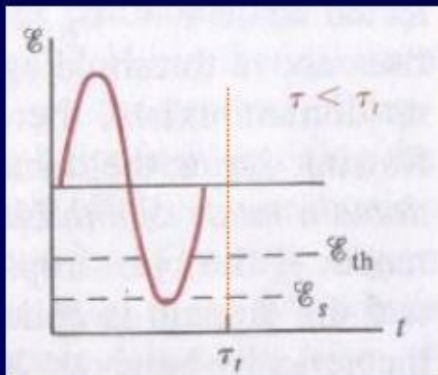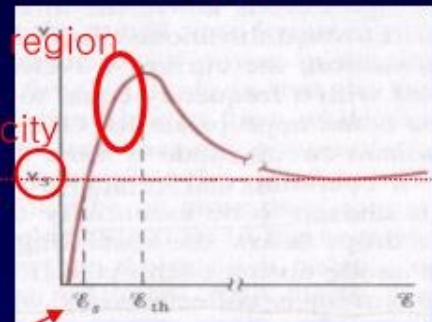# Gunn Oscillation Modes

3. Delayed mode :

- $\tau = \tau_I$ (High efficiency up to 20%)

- There is an ohmic currents higher than domain currents.

- f_{osc} is determined by the resonant circuit
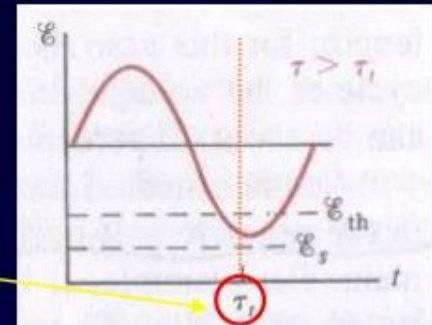
4. Quenched mode

- $\tau > \tau_I$ (Efficiency up to 13%)

- The domain can be quenched before it is collected

- So that, f_{osc} is determined by the resonant circuit

Positive resistance region

The sustaining drift velocity

Gunn Oscillation Modes

LSA mode(Limited Space charge Accumulation)

(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.

$$\tau < \tau_t$$

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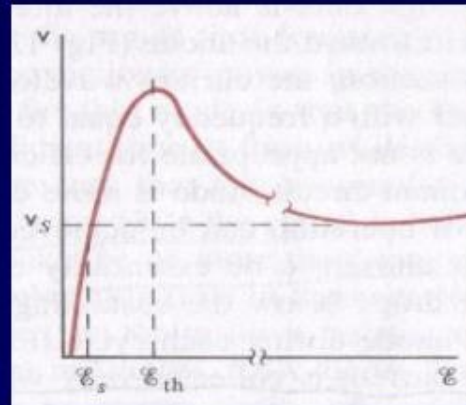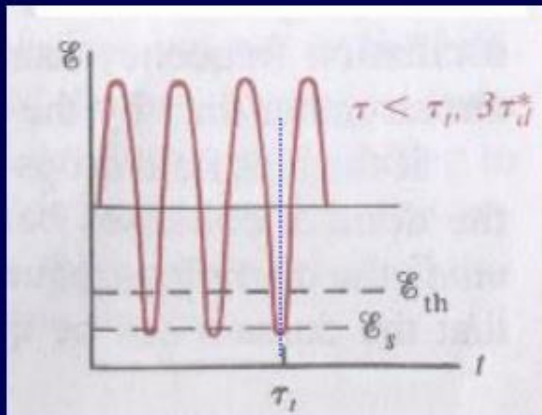
Stable amplification mode

When $n_0L < 10^{12}/cm^2$ the device exhibits amplification at the transit time frequency rather than spontaneous oscillation.

This situation occurs because the negative conductance is utilized without domain formation.

There are too few carriers for domain formation within the transit time. Therefore amplification of signals near the transit time frequency can be accomplished.
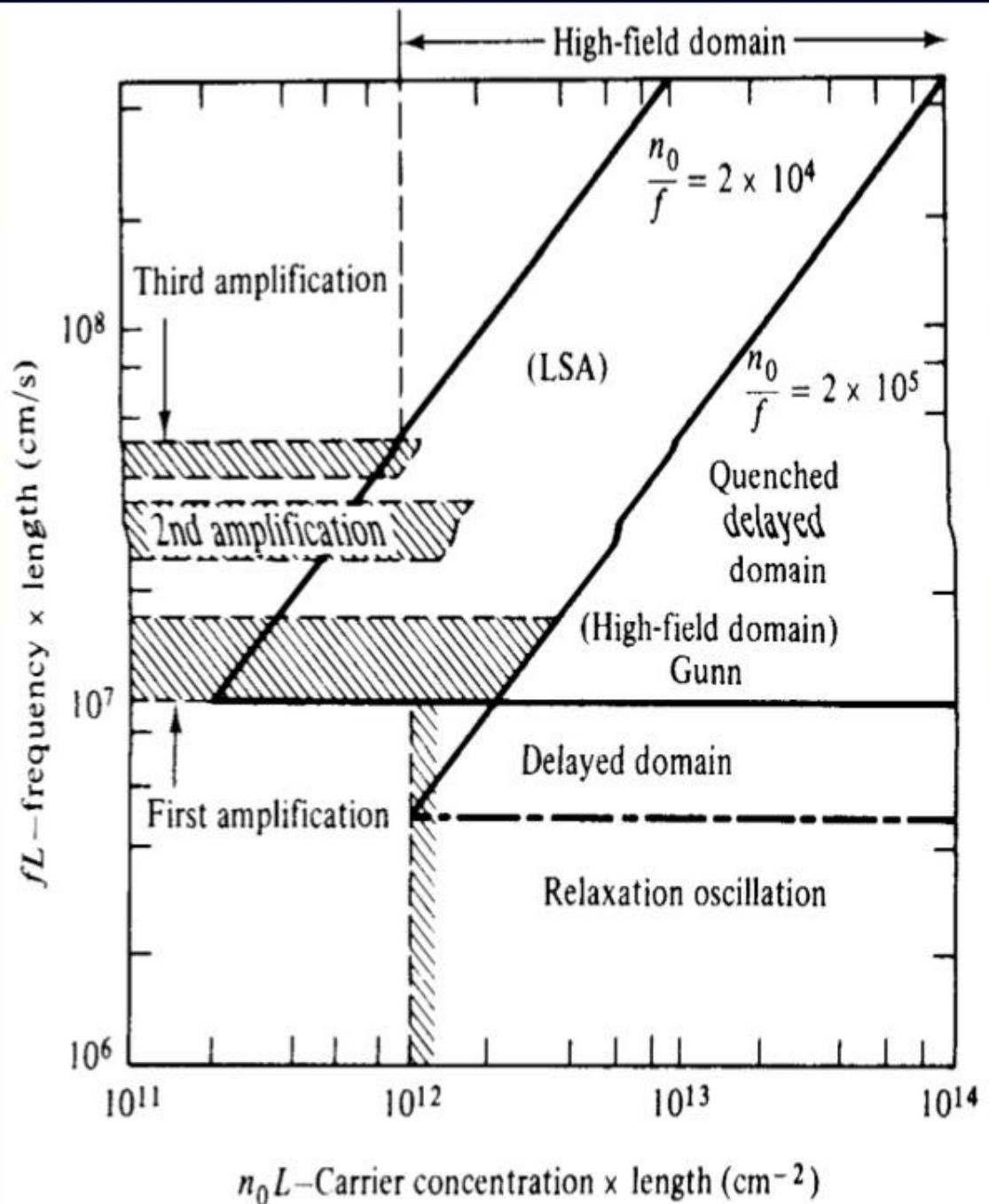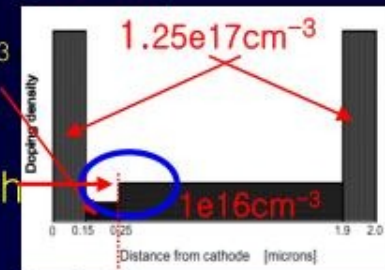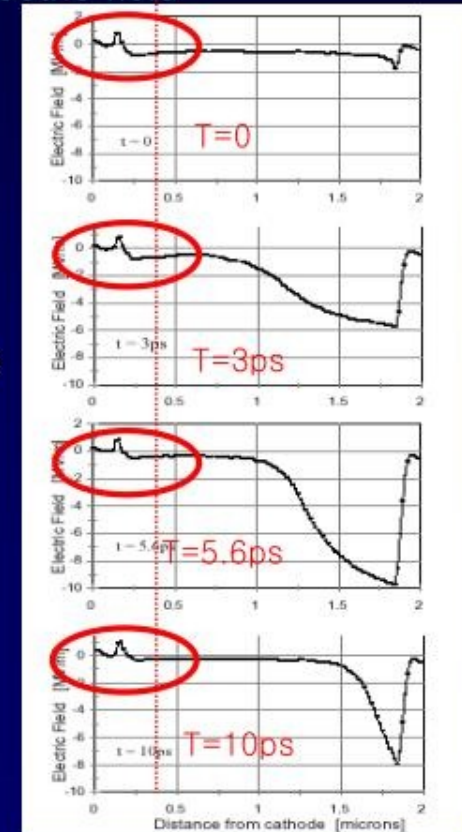
Fabrication

- ## Structure

Doping density

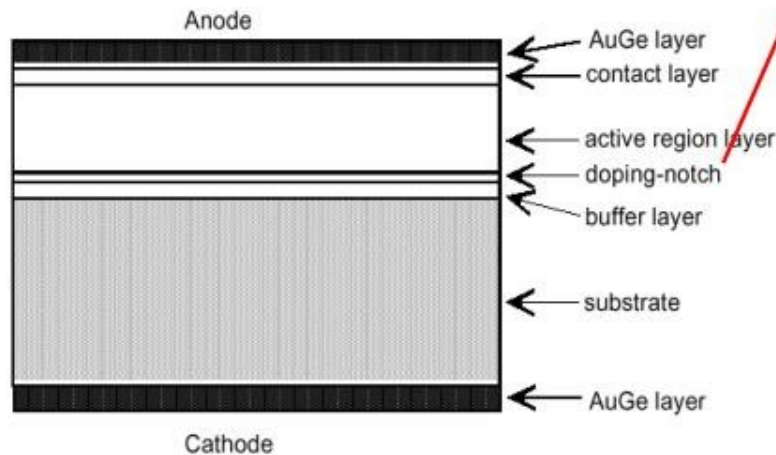Active region : 5e15cm^{-3}

1.25e17cm^{-3}

The doping-notch

1e16cm^{-3}

Distance from cathode [microns]

Electric field

Growth of diode structure

Anode

AuGe layer

contact layer

active region layer

doping-notch

buffer layer

Dead zone

substrate

AuGe layer

Cathode

T=0

T=3ps

T=5.6ps

T=10ps

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