16ECT72 - RF AND MICROWAVE ENGINEERING

Unit III – Microwave Solid State Devices

IMPATT Diode (Operation, Physical description and Applications)

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Course Outcome 3

CO3	Analyze the characteristics of microwave solid state devices with its application

Learning Outcome 1

LO1	Examine the construction and operation of microwave semiconductor devices

Avalanche Transit Time Devices

- IMPATTT Diode
- TRAPATT Diode
- BARITT Diode

Introduction

- Rely on the effect of voltage breakdown across a reverse biased p-n junction.
- The avalanche diode oscillator uses carrier impact ionization and drift in the high field region of a semiconductor junction to produce a negative resistance at microwave frequencies.

Negative Resistance Effect

1. The impact ionization avalanche effect, which causes the carrier current $I_0(t)$ and the ac voltage to be out of phase by 90°
2. The transit-time effect, which further delays the external current $I_e(t)$ relative to the ac voltage by 90°

Introduction

Two distinct modes of avalanche oscillator is observed

1) IMPATT (IMPact ionization Avalanche Transit Time operation)

   - DC-to-RF c.e. is 5 to 10%

2) TRAPPAT (Trapped Plasma Avalanche Triggered Transit operation)

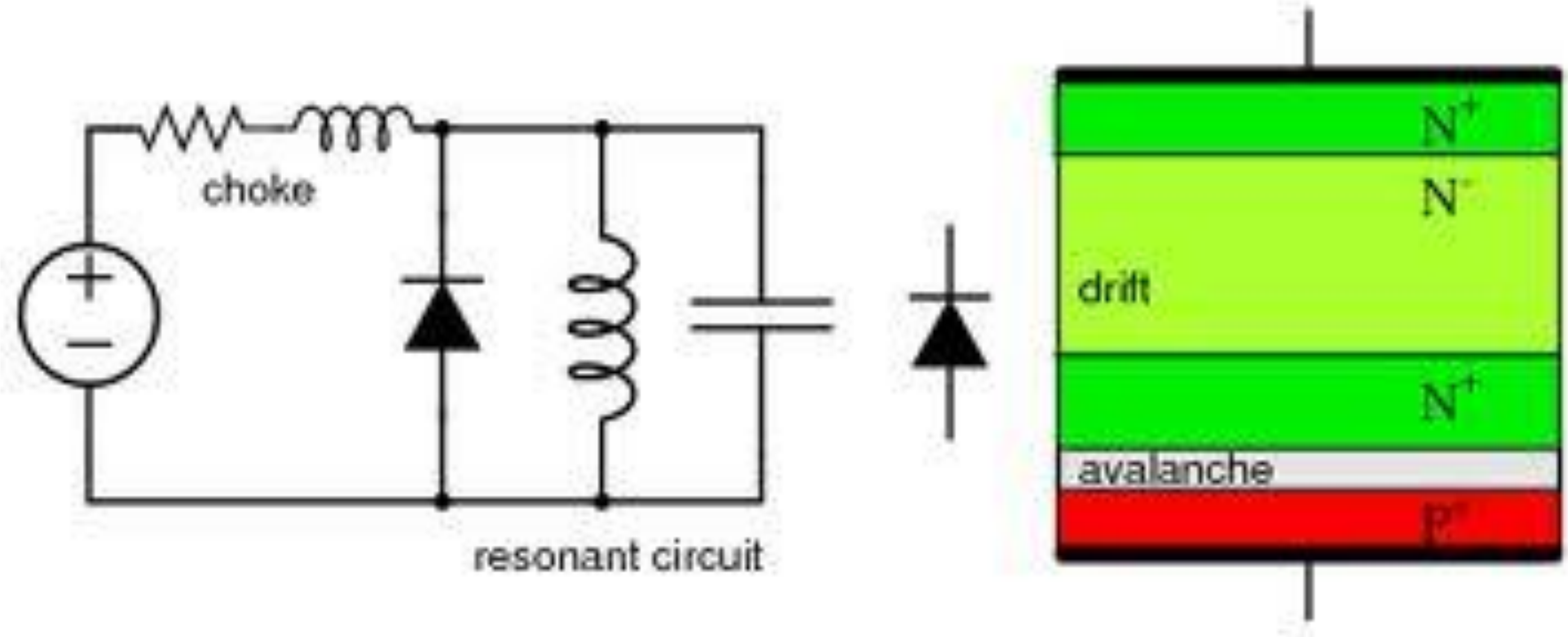
   - 20 to 60%

- Another type of active microwave device is BARITT (Barrier Injected Transit Time Diode)

Introduction

- Form of high power diode used in high frequency electronics and microwave devices
- Typically made from silicon carbides due to their high breakdown fields.
- Frequency - 3 to 100 GHz
- High power capability
- From low power radar systems to alarms
- Generate high level of phase noise – avalanche process

IMPATT Diode as oscillator



IMPATT Diode

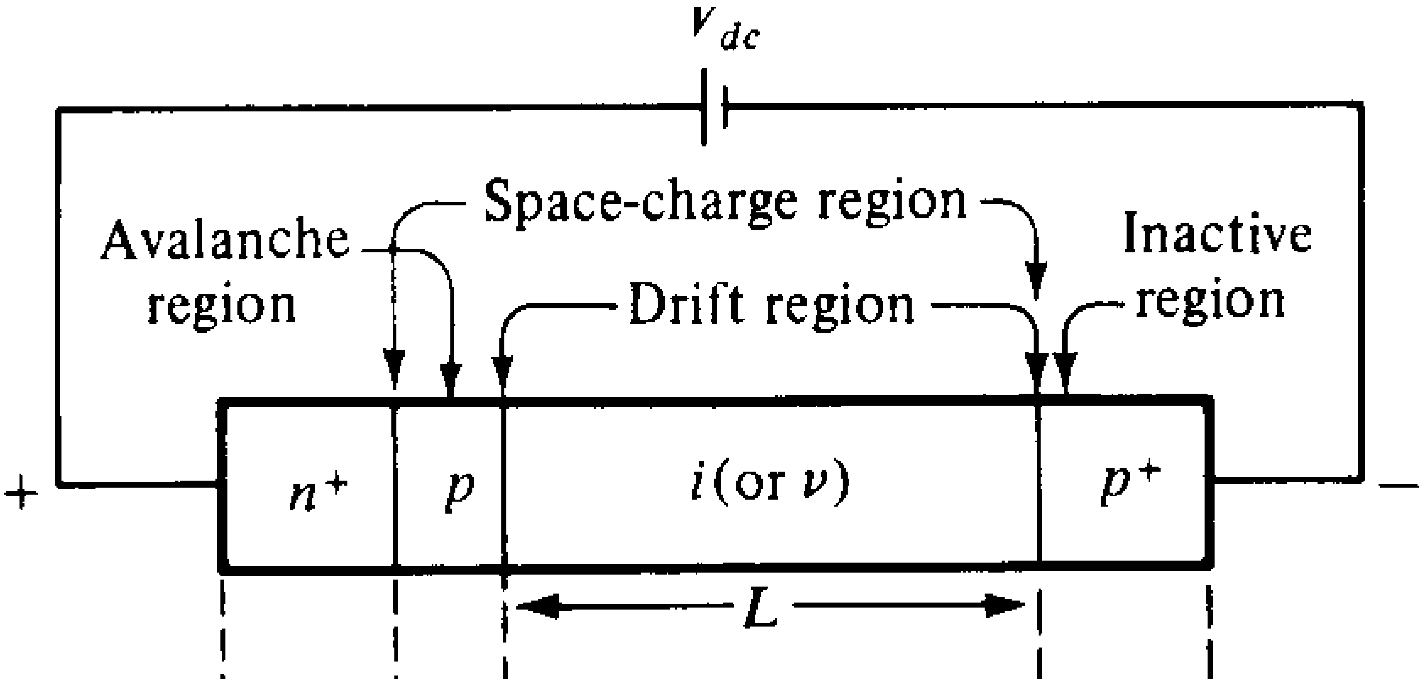
- The IMPATT diode family includes many different junctions and metal semiconductor devices.
- The first IMPATT oscillation was obtained from a simple silicon p-n junction diode biased into a reverse avalanche break down and mounted in a microwave cavity.

Avalanche Effect and Transit Time Effect

- Electron–hole pairs are generated in the high field region. The generated electron immediately moves into the N region, while the generated holes drift across the P region.

- The time required for the hole to reach the contact constitutes the transit time delay.

Physical Description – Read Diode



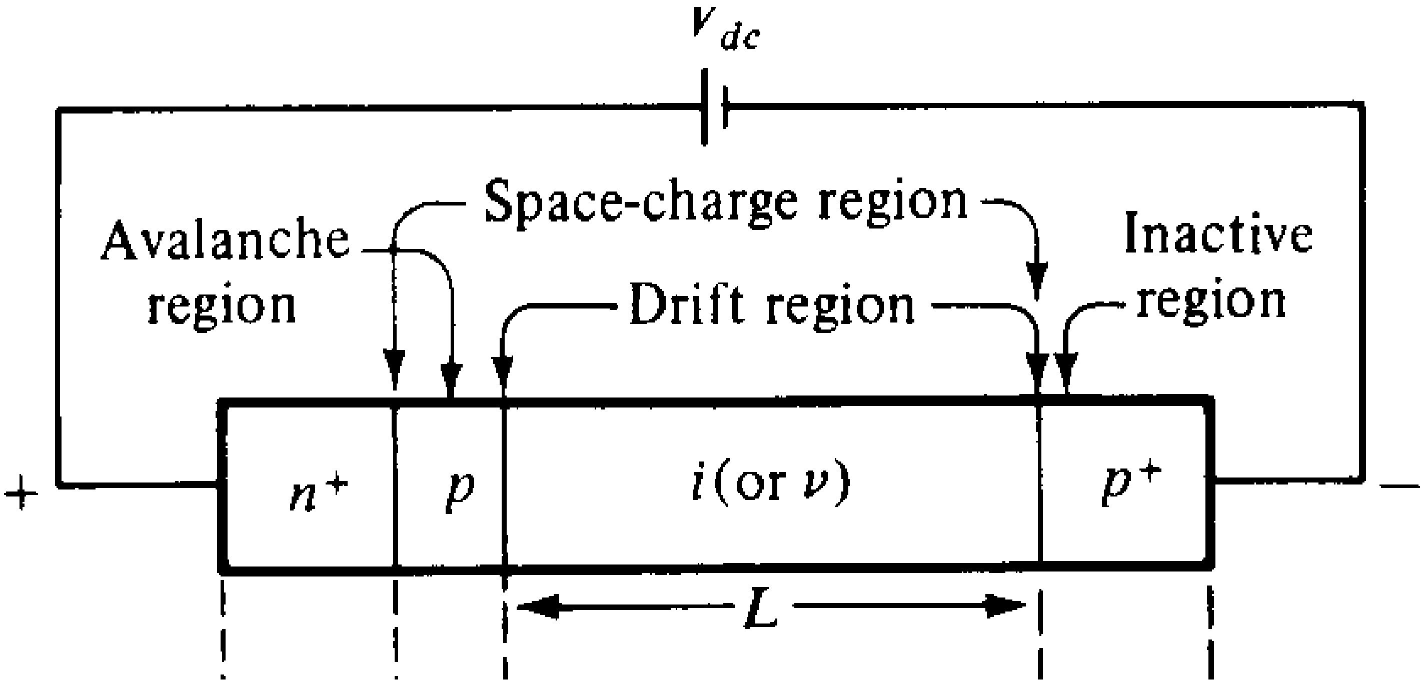
Physical Description – Read Diode

- The original proposal for a microwave device of the IMPATT type was made by **Read.** Read diode is the basic type in the IMPATT diode family

The Read diode consists of two regions:

1) The Avalanche region (a region with relatively high doping and high field) in which avalanche multiplication occurs and
2) the drift region (a region with essentially intrinsic doping and constant field) in which the generated holes drift towards the contact.

Physical Description – Read Diode



Physical Description

n^+-p-i-p^+

- + very high doping
- i or v intrinsic material
- Two regions:

1) Thin p region (High field/Avalanche region) – avalanche multiplication occurs

2) Intrinsic region (Drift region) – generated holes must drift towards the p+ contact

Impact Ionization

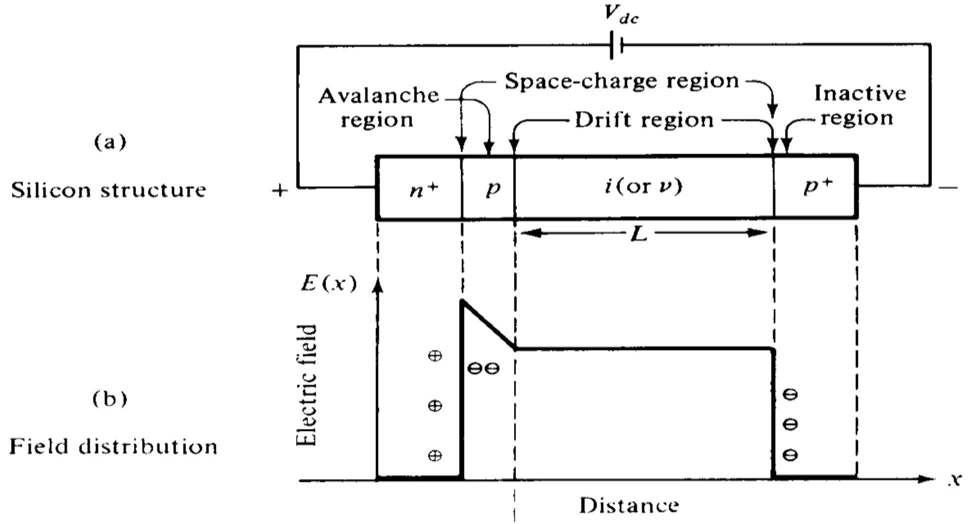
- If a free electron with sufficient energy strikes a silicon atom, it can break the covalent bond of silicon and liberate an electron from the covalent bond.
- If the electron liberated gains energy by being in an electric field and liberates other electrons from other covalent bonds then this process can cascade very quickly into a chain reaction producing a large number of electrons and a large current flow.
- This phenomenon is called impact avalanche.

Impact Ionization

- The space between n+ -p junction and the i –p+ junction is called the space charge region
- The diode is reverse biased and mounted in a microwave cavity. The impedance of the cavity is mainly inductive which is matched with the capacitive impedance of the diode to form a resonant circuit.
- Such device can produce a negative ac resistance that in turns delivers power from the dc bias to the oscillation

Avalanche Multiplication

- When the reverse bias voltage is above the breakdown voltage, the space charge region always extends from n+ -p junction to the i –p+ junction through the p and the i regions.



Avalanche Multiplication

- A positive charge moves from left to right and gives a rising field.
- The maximum field which is at the n+ -p junction is about several hundred kilovolt/cm
- Carriers (holes) in the high field region near the n+ -p junction acquire energy to knock down the valence electrons in the conduction band and hence electron hole pairs are generated.
- This is avalanche multiplication.

Avalanche Multiplication

- The electrons move into the n+ region and the holes drift through the space charge region to the p+ region with a constant velocity V_d.
- The field throughout the space charge is about 5 kV/cm.

Avalanche Multiplication

The transit time of a hole across the drift i-region L is given by

$$\tau = \frac{L}{v_d}$$

And the avalanche multiplication factor is

$$M = \frac{1}{1 - (V/V_b)^n}$$

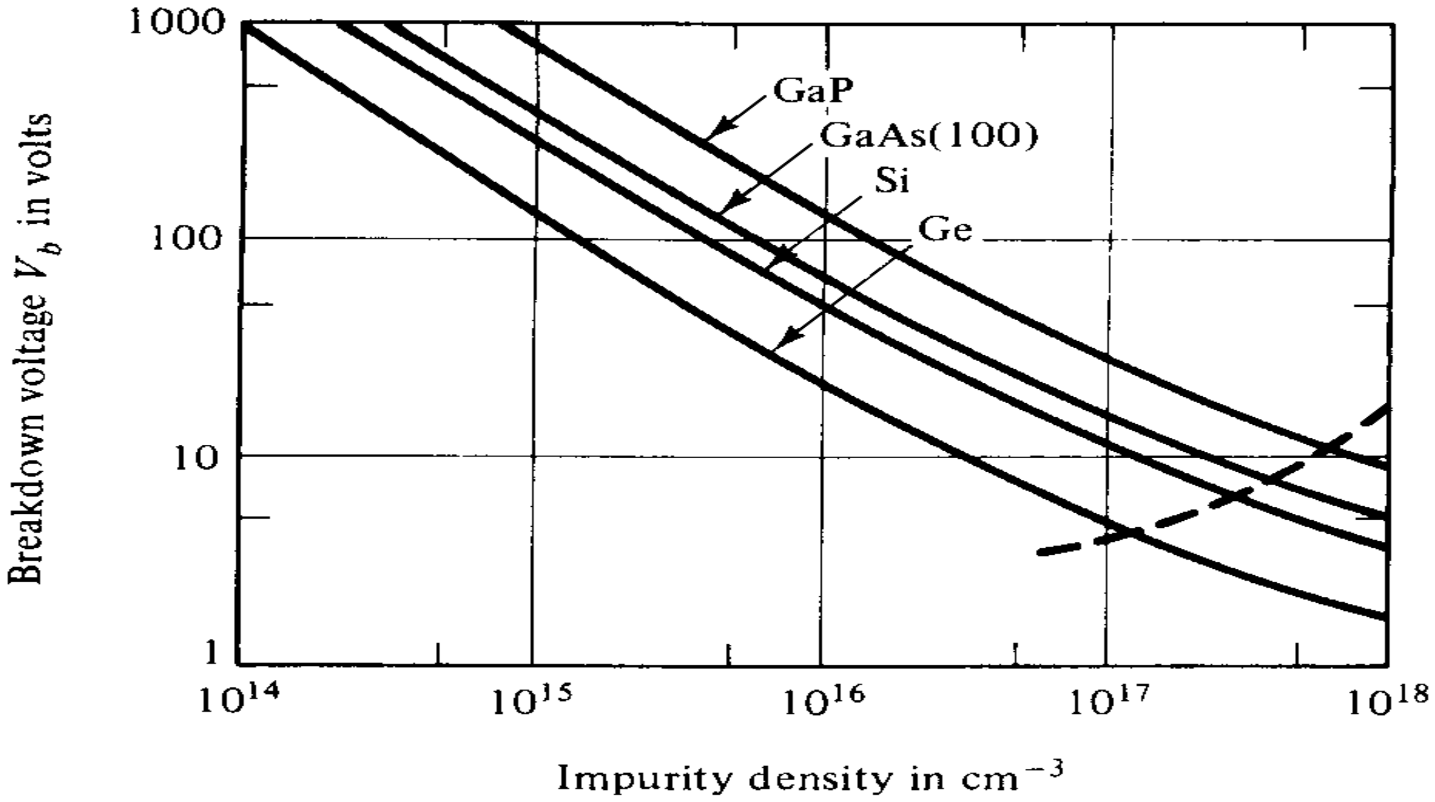
where V = applied voltage
V_b = avalanche breakdown voltage
n = 3–6 for silicon is a numerical factor depending on the doping of p^+-n or n^+-p junction

- The breakdown voltage for a silicon p+ -n junction can be expressed as

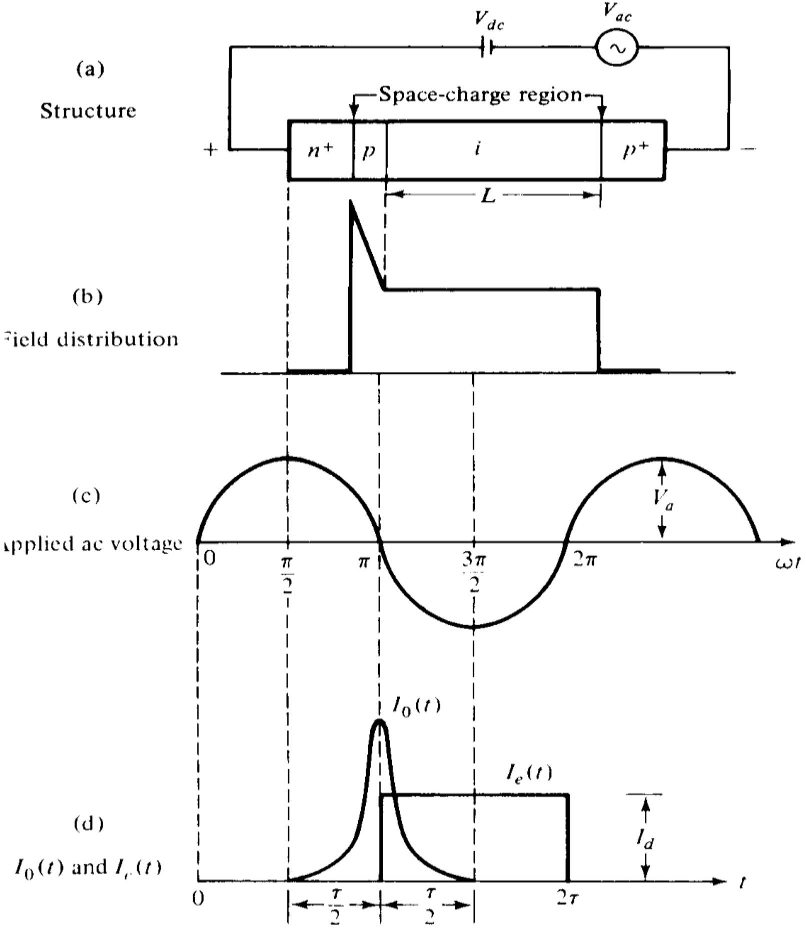
$$|V_b| = \frac{\rho_n \mu_n \epsilon_s |E_{\max}|_b^2}{2}$$

where ρ_n = resistivity
μ_n = electron mobility
ϵ_s = semiconductor permittivity
$E_{\max}$ = maximum breakdown of the electric field

Breakdown voltage Vs impurity doping



Carrier Current Io(t) and External Current Ie(t)



Carrier Current Io(t) and External Current Ie(t)

- The diode can be mounted in a microwave resonant circuit
- An ac voltage can be maintained at a given frequency in the circuit, and the total field across the diode is the sum of ac and dc fields which causes breakdown at the n+ -p junction during the positive half cycle of the ac voltage cycle if the field is above the breakdown voltage.
- The carrier current (hole current in this case) Io(t) generated at the n+ -p junction by the avalanche multiplication grows exponentially with time while the field is above critical voltage.

Carrier Current Io(t) and External Current Ie(t)

- During the negative half cycle, when the field is below breakdown voltage, the carrier current decays exponentially.
- Io(t) is in the form a pulse of very short duration and it reaches its maximum in the middle of the ac voltage cycle or one quarter of the cycle later than the voltage.

Carrier Current Io(t) and External Current Ie(t)

- Under the influence of electric field the generated holes are injected into the space region towards the negative terminal.

- As the injected holes traverse the drift space,

  a. They induce a current Ie(t) in the external circuit.

  b. Cause a reduction of the field

Carrier Current Io(t) and External Current Ie(t)

- Since the velocity of the holes in the space charge is constant

$$I_e(t) = \frac{Q}{\tau} = \frac{v_d Q}{L}$$

where Q = total charge of the moving holes

v_d = hole drift velocity

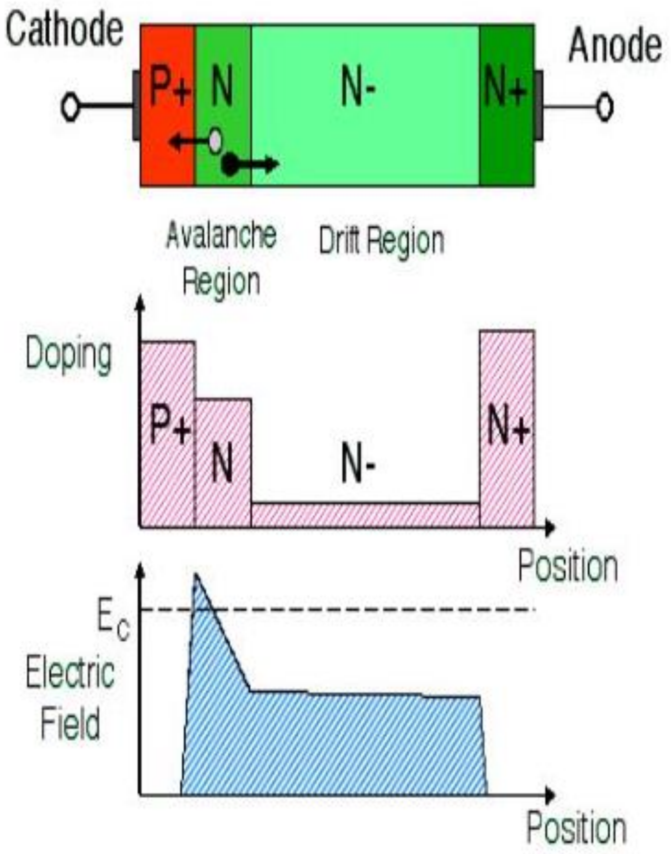
L = length of the drift i region

Carrier Current Io(t) and External Current Ie(t)

- The external current Ie(t) because of the moving holes is delayed by 90 degree relative to the pulsed Io(t).
- Since the carrier current Io(t) is delayed by one quarter cycle or 90 degree relative to the ac voltage, Ie(t) is then delayed by 180 degree relative to the voltage.
- Hence negative conductance occurs and the diode can be used for microwave oscillation and amplification.

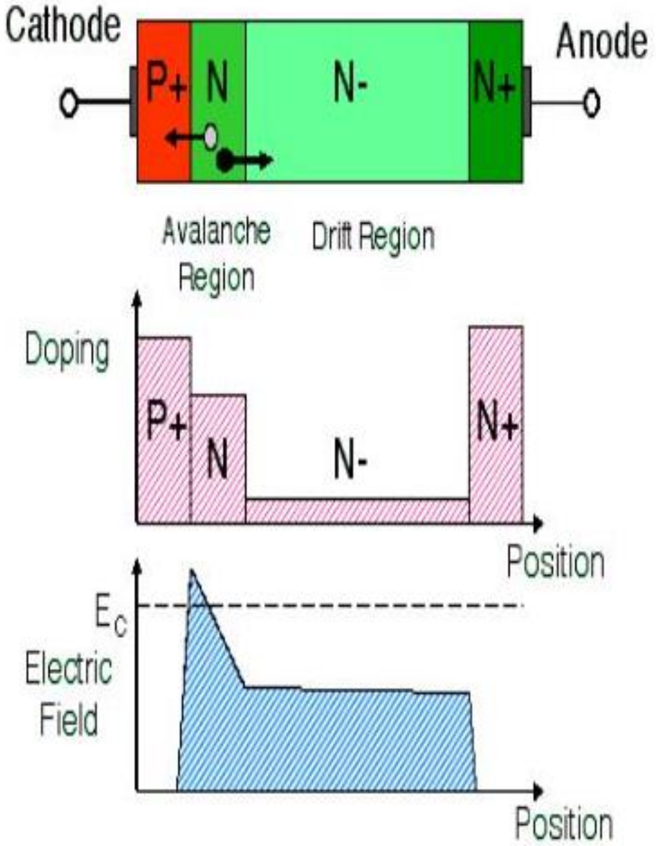
IMPATT Diode - Operation

- Diode is operated in reverse bias near breakdown, and both the N and N- regions are completely depleted
- Electric field is highly peaked in the avalanche region and nearly flat in drift region



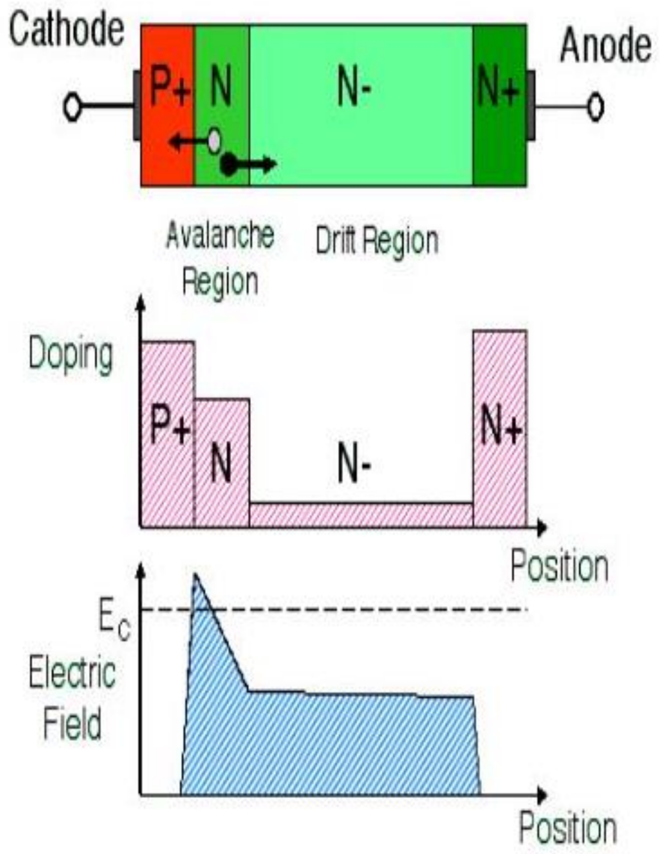
IMPATT Diode - Operation

- Avalanche breakdown occurs at the point of highest electric field, and this generates a large number of hole-electron pairs by impact ionization
- Holes swept into the cathode – electrons travel across drift region toward anode

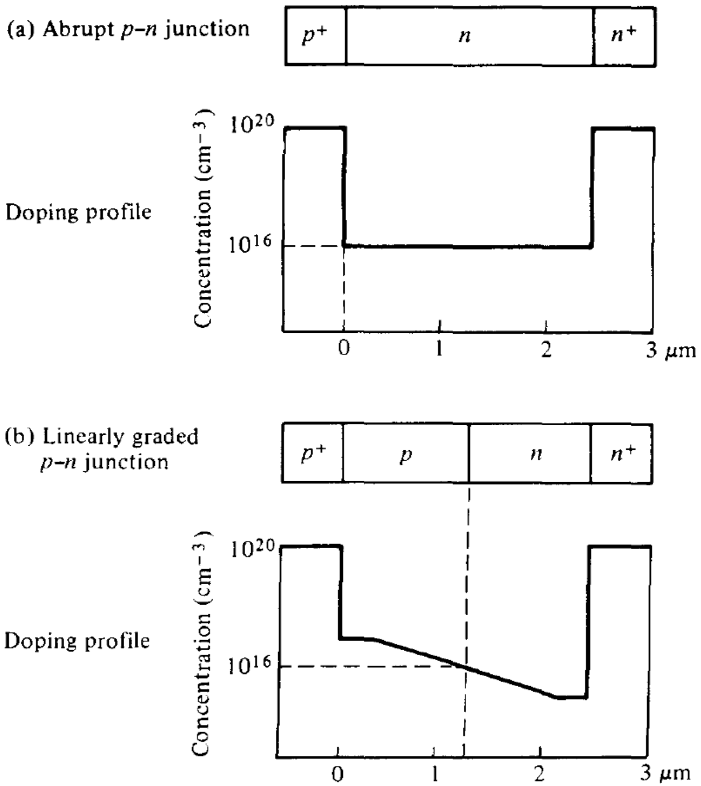


IMPATT Diode - Operation

- As they drift, they induce image charges on the anode, giving rise to a displacement current in the external circuit that is 180 degree out of phase with the nearly sinusoidal voltage waveform

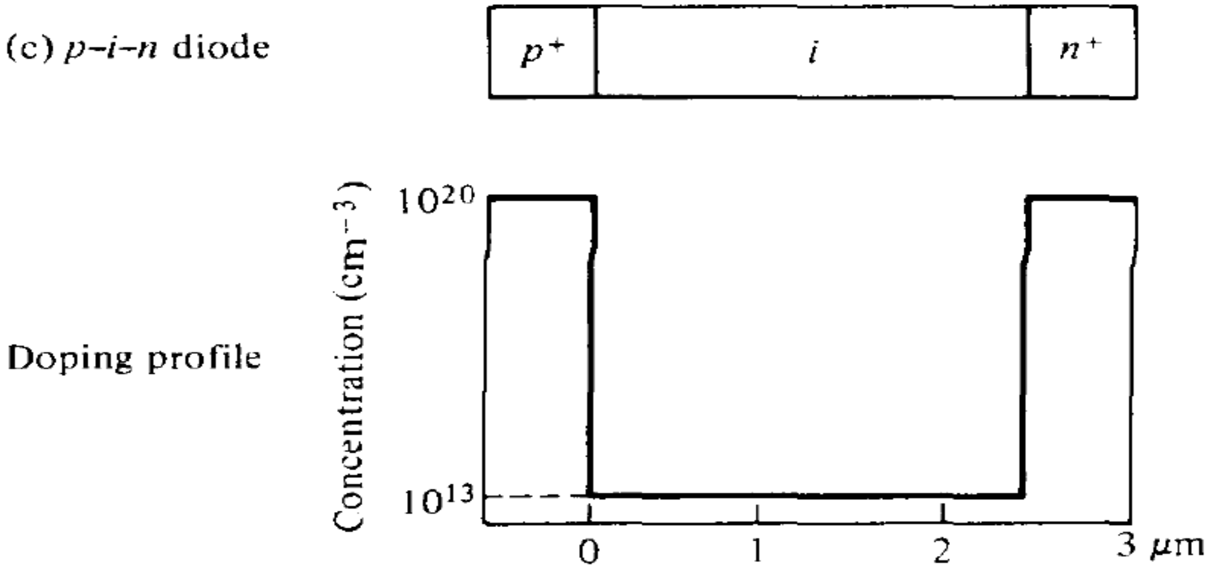


IMPATT Diode Physical Structure



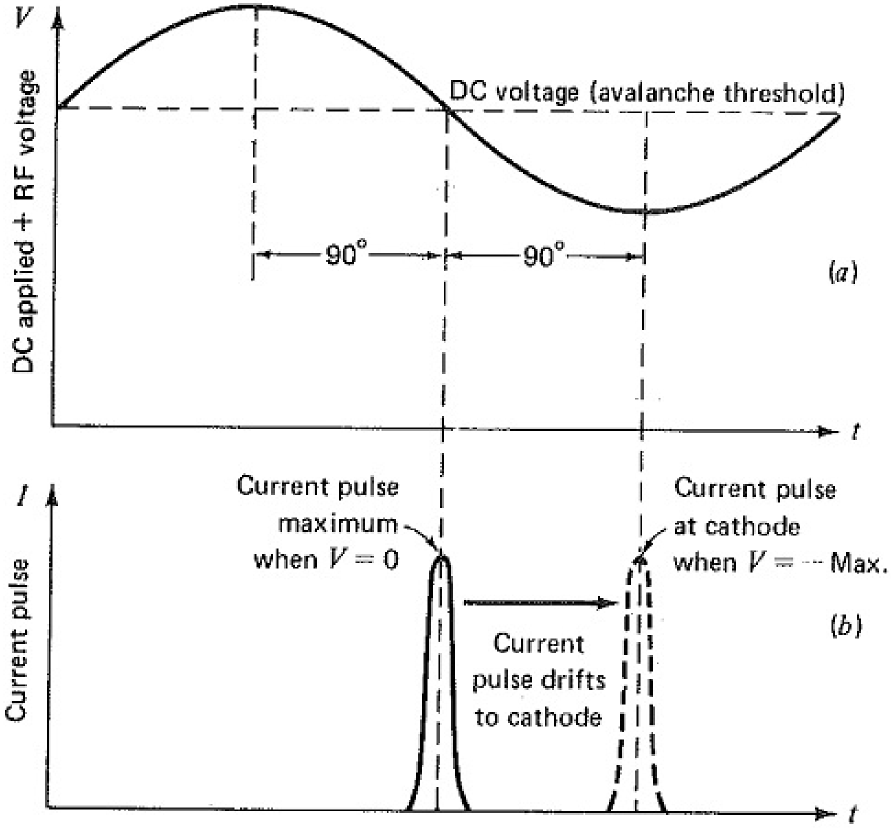
Three typical silicon IMPATT diodes

IMPATT Diode Physical Structure



Three typical silicon IMPATT diodes

IMPATT Diode



(a) Applied and RF voltage

(b) Resulting current pulse and its drift across diode

IMPATT Diode – Negative Resistance

$$R = R_s + \frac{2L^2}{v_d \epsilon_s A} \frac{1}{1 - \omega^2/\omega_r^2} \frac{1 - \cos\theta}{\theta}$$

where R_s = passive resistance of the inactive region
v_d = carrier drift velocity
L = length of the drift space-charge region
A = diode cross section
e_s = semiconductor dielectric permittivity

Applications of IMPATT diode

- Used in a variety of applications from low power radar systems to alarms
- In view of its high levels of phase noise, it is used in transmitters more frequently than as a local oscillator in receivers where the phase noise performance is generally more important

Applications of IMPATT diode

The following products are available as examples of IMPATT diode application:

1. Cavity stabilized IMPATT diode oscillator CIDO series
2. Pulsed IMPATT power sources IPSP series
3. IMPATT active frequency multipliers IAFM series
4. Pulsed and CW IMPATT injection-locked amplifiers IILAP and IILA series
5. Voltage controlled IMPATT oscillators VCIO series

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- Liao, S.Y., “Microwave Devices and Circuits”, Prentice Hall of India, 2006
- Annapurna Das and Sisir K Das, “Microwave Engineering”, Tata McGraw Hill Inc., 2009
- David M Pozar, “Microwave Engineering”, 3rd Edition John Wiley and Sons, Inc., 2005

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