4.6 IMPATT and TRAPATT

Module:4 Microwave Sources

Course: BECE305L – Antenna and Microwave Engineering

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Assistant Professor - SENSE

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Vellore Institute of Technology

(Deemed to be University under section 3 of UGC Act, 1956)

CHENNAI

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.

10.1 Avalanche Transit Time Devices (ATTD)

- Semiconductor junction structures with **highly doped p and n junctions**
- **Reverse bias of sufficient strength** – produces **large E field to create an avalanche of carriers**
- **Impact ionization with adjacent – highly doped p and n layers**

10.1 Avalanche Transit Time Devices (ATTD)

- Semiconductor junction structures with highly doped p and n junctions
- Reverse bias of sufficient strength – produces large E field to create an avalanche of carriers
- Impact ionization with adjacent – highly doped p and n layers
- **Generated carriers transit (travel through) a drift space** – **causes delay in collection at anode**
- **If delay causes current to be out of phase with voltage** across the device – **Negative resistance appears** across the structure’s terminals.

10.1 Avalanche Transit Time Devices (ATTD)

1) IMPATT: Impact Ionization Avalanche Transit Time

    Efficiency of 3% continuous wave power, 60% pulsed power

    Output power: 1W CW; 400W pulsed power

    From 500MHz to 100GHz

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   Low frequency (1-3GHz)

   Pulsed power output of several hundred watts and 20-60% efficiency

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   Pulsed power output of several hundred watts and 20-60% efficiency

3) BARITT: Barrier Injected Transit Time
   Low noise figures (<15dB) with low power and smaller bandwidth

10.2 IMPATT Diodes

- IMPATT: Impact Ionization Avalanche Transit Time
- **Produce differential negative resistance** ($n^{+} - p - i - p^{+}$ **junction**) at microwave frequencies by:

the effect of **carrier** impact **ionization breakdown** across a **reverse biased p-n junction** and

the **drift of carrier in the high field region of a semiconductor**

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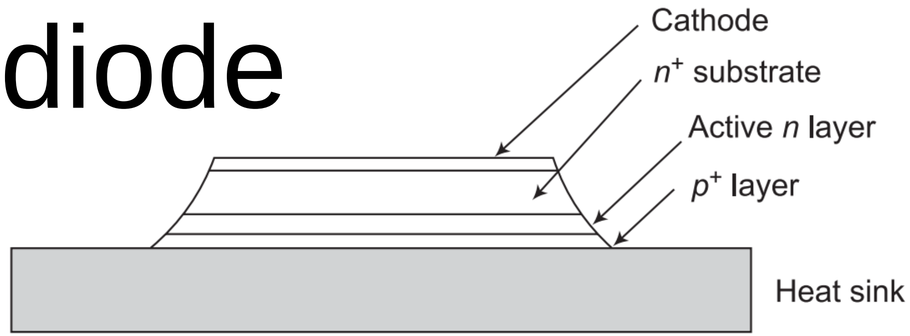
- **GaAs** (highest operating frequency, efficiency and least noise power), **Si** (upto 100GHz with typical dc to RF efficiency of 5-10%)

InP.

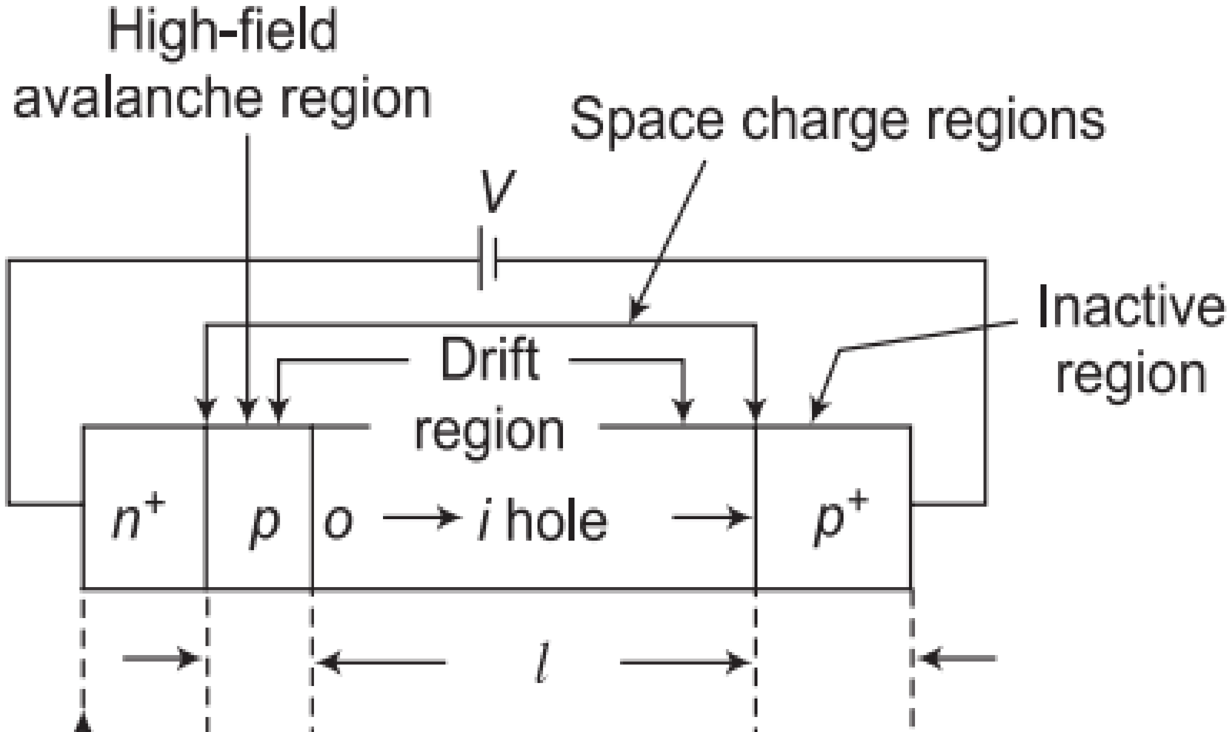
Applications: **Missile seekers**, **Oscillators** and **Amplifiers**

10.2 IMPATT Diodes: READ diode



- Doping profile: $\boldsymbol{n^+p\ i\ p^+}$
- n^+ and p^+ are <u>heavily doped regions</u>
- p: <u>moderately doped</u> i: <u>slightly $n-$type with doping</u> concentration of $10^{13}/\mathrm{cm}^3$

Si form



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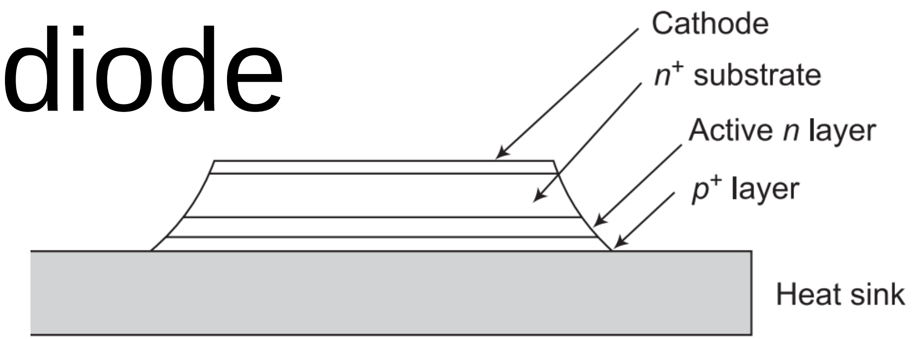
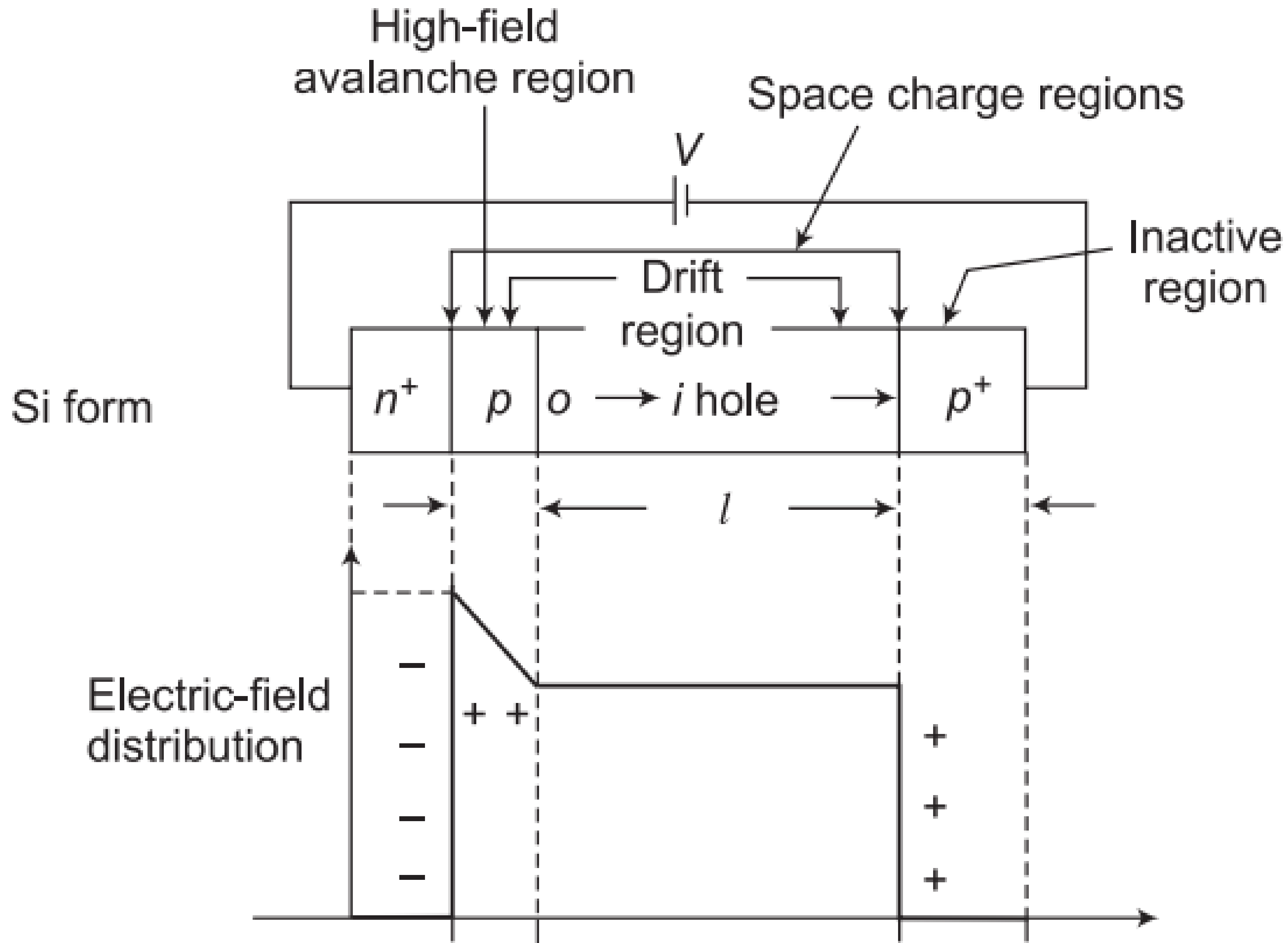
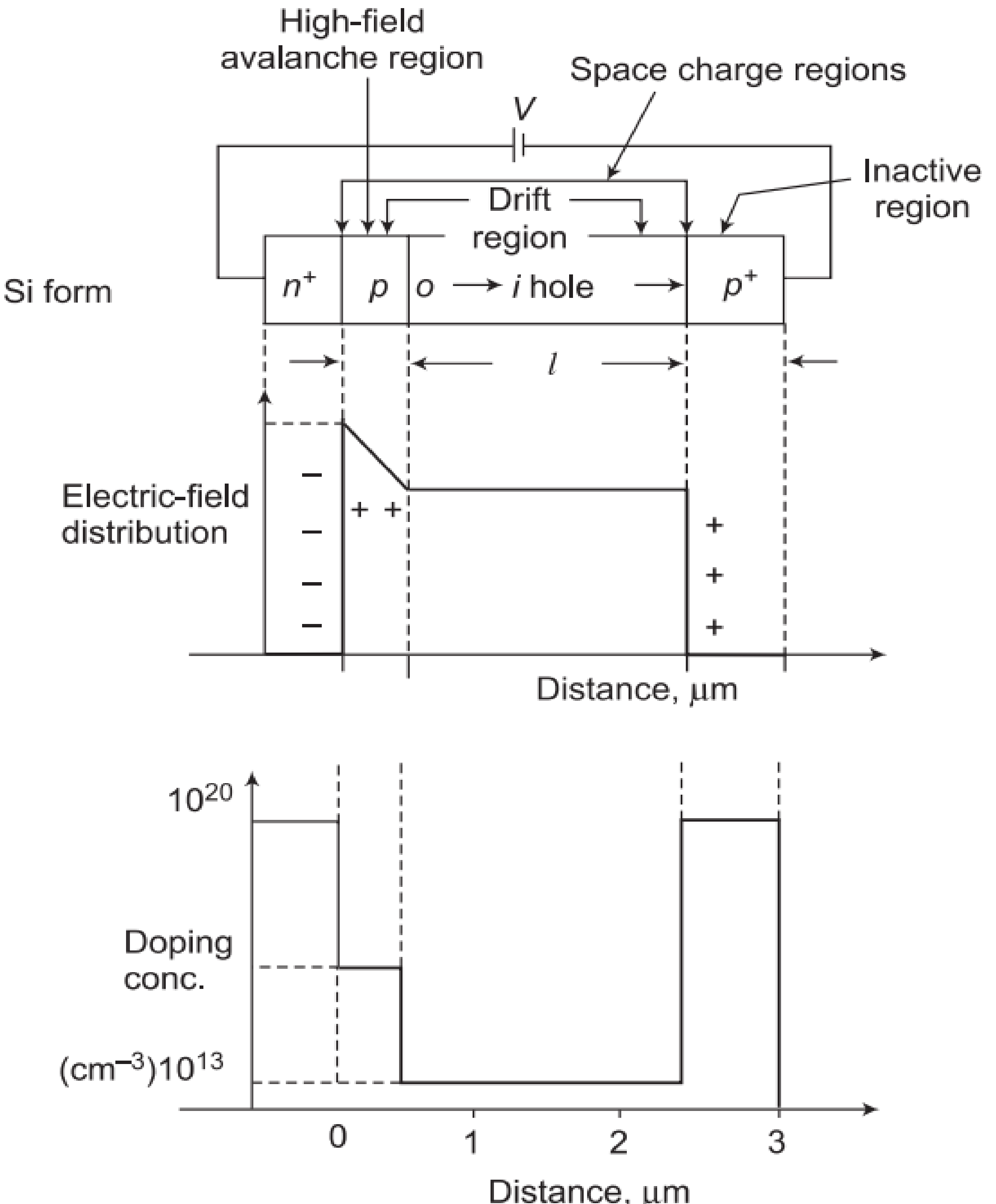
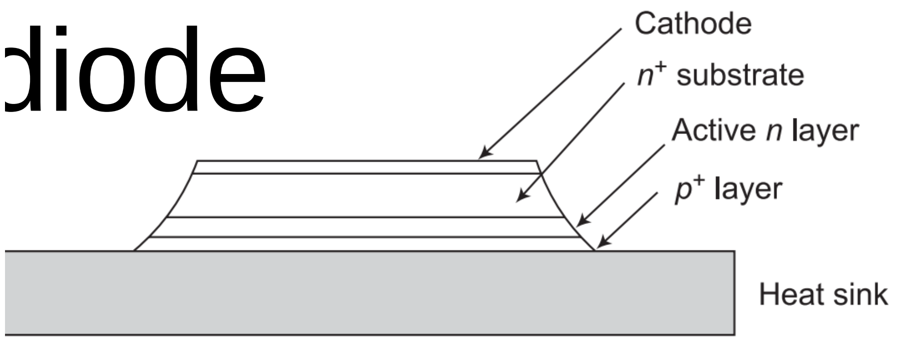




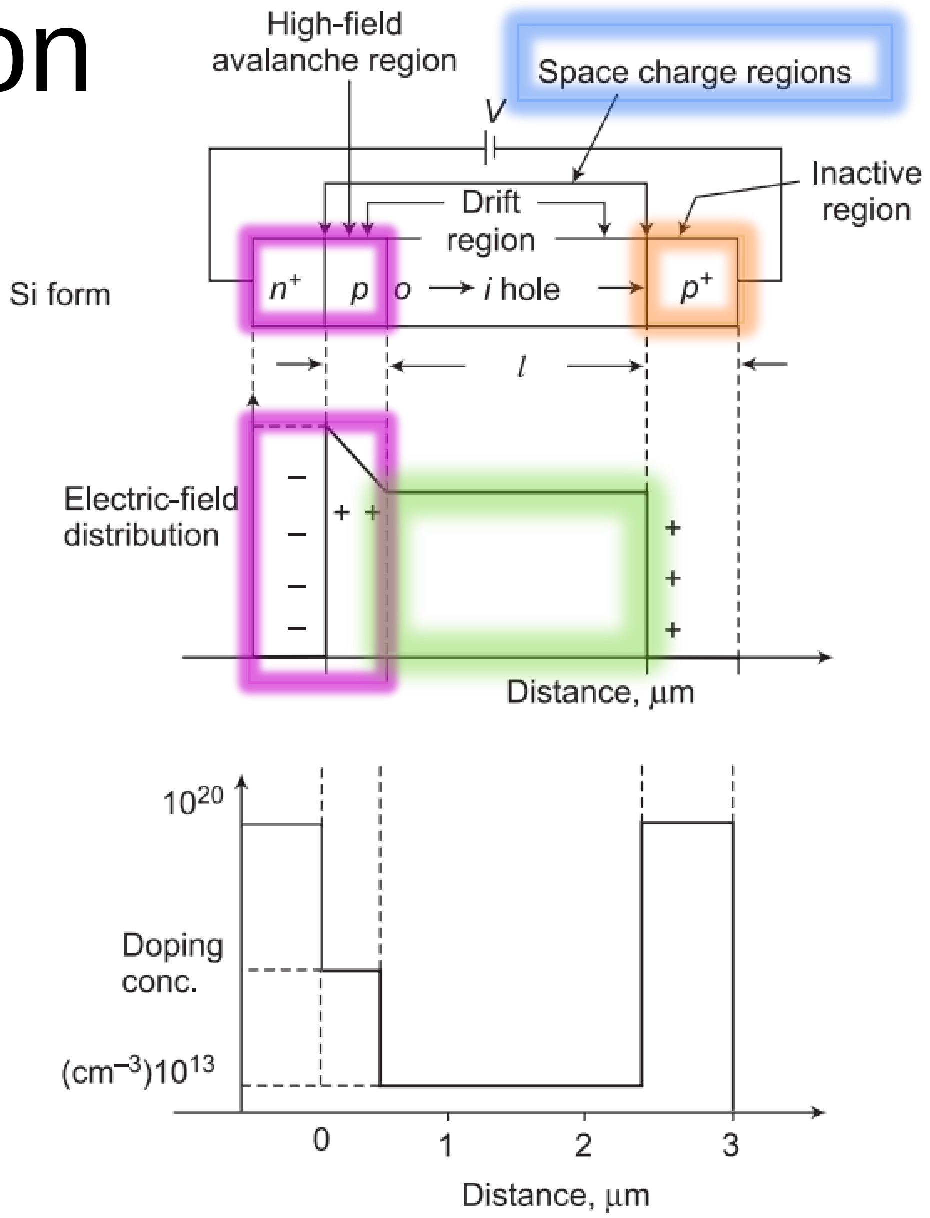
10.2 IM... diode


High-field
avalanche region
Space charge regions
V
Drift
region
Inactive
region
Si form
n^+
p
o → i hole →
p^+
l
Electric-field
distribution
Distance, µm
10^{20}
Doping
conc.
$(cm^{-3})10^{13}$
0
1
2
3
Distance, µm


Cathode
n^+ substrate
Active n layer
p^+ layer
Heat sink

10.2.1 READ diode: Operation

- When reverse bias exceeds breakdown voltage V_B, **maximum electric field** of very high value (MV/m) appears at n^+p junction
- E field in intrinsic region (i-region) remains below breakdown



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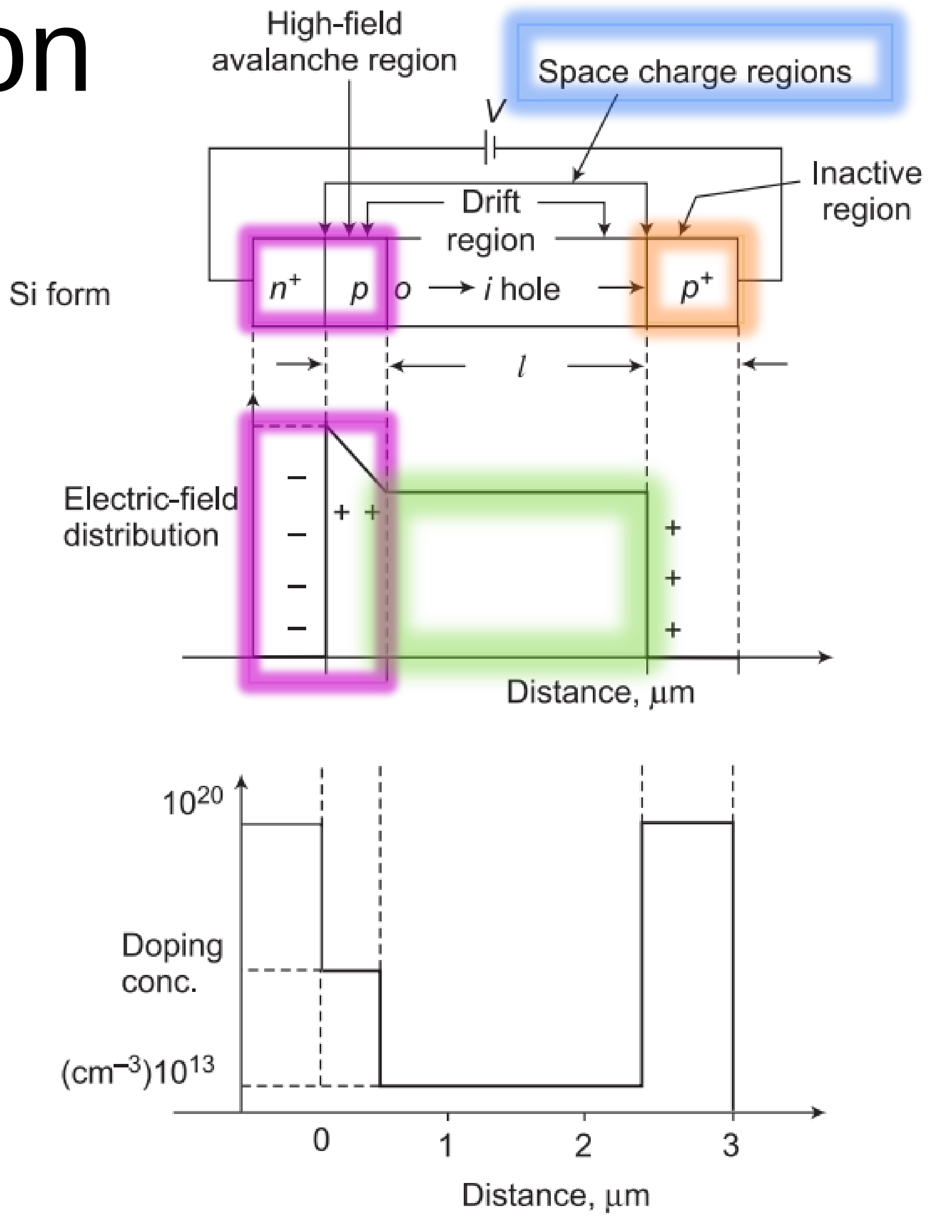
- Space between $n^+ - p$ junction and $i - p^+$ junction is called space charge region



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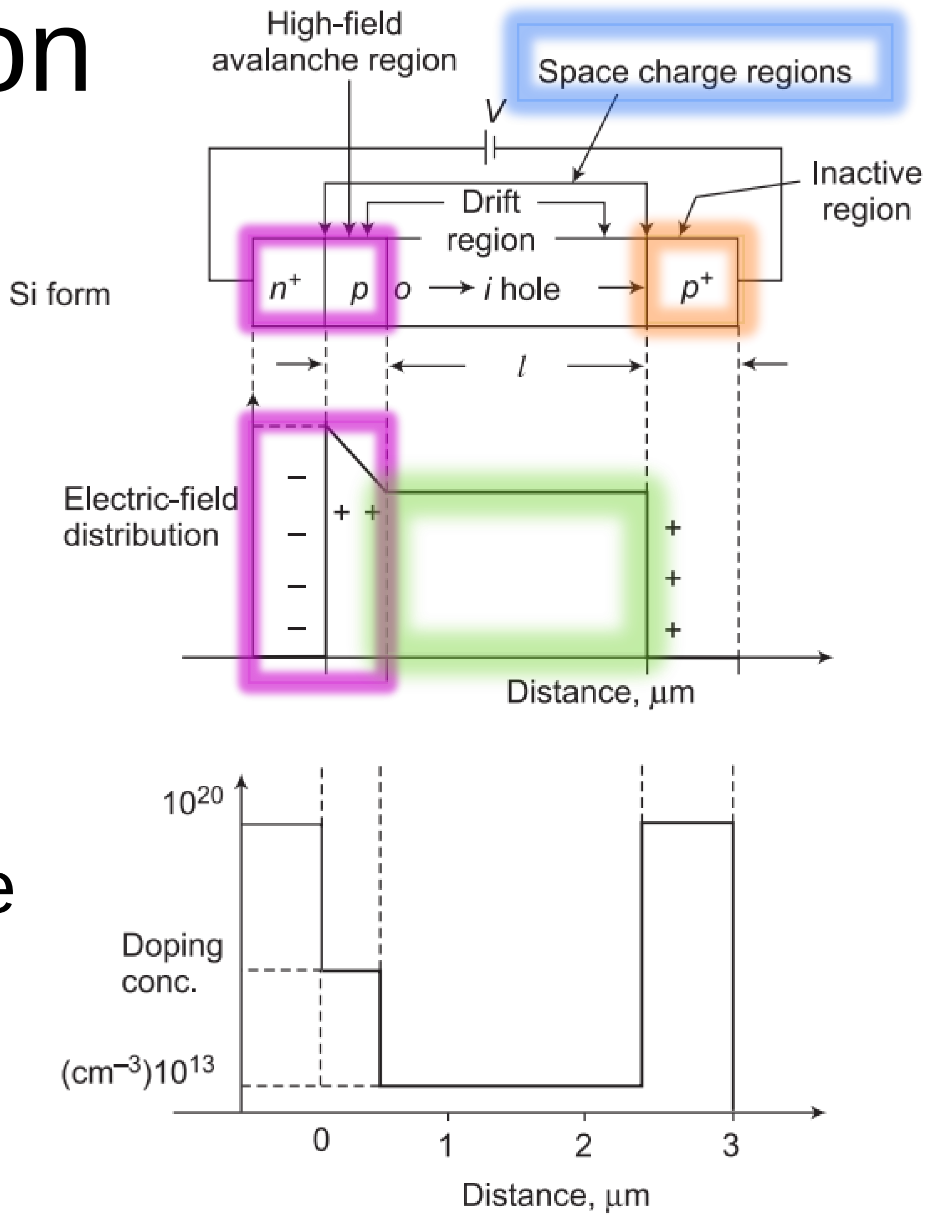
- Space between $n^+ - p$ junction and $i - p^+$ junction is called space charge region
- Generated electrons due to electric field move through the i region with **saturated drift velocity** and are collected at p^+ region.



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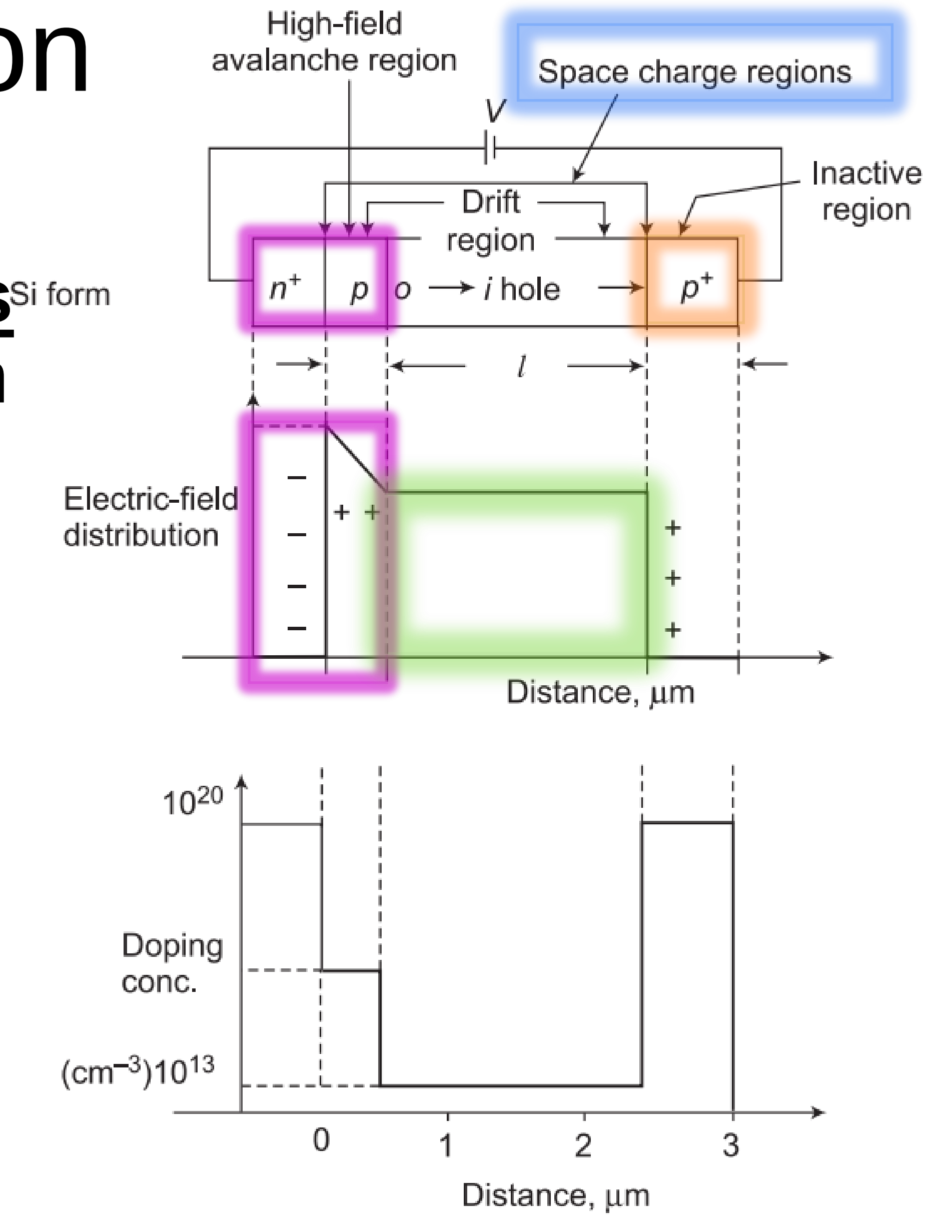
- **Holes** move to high field region acquire **sufficient energy to excite valence electrons of the atom into conduction band** resulting in **avalanche multiplication of electron hole pairs**.



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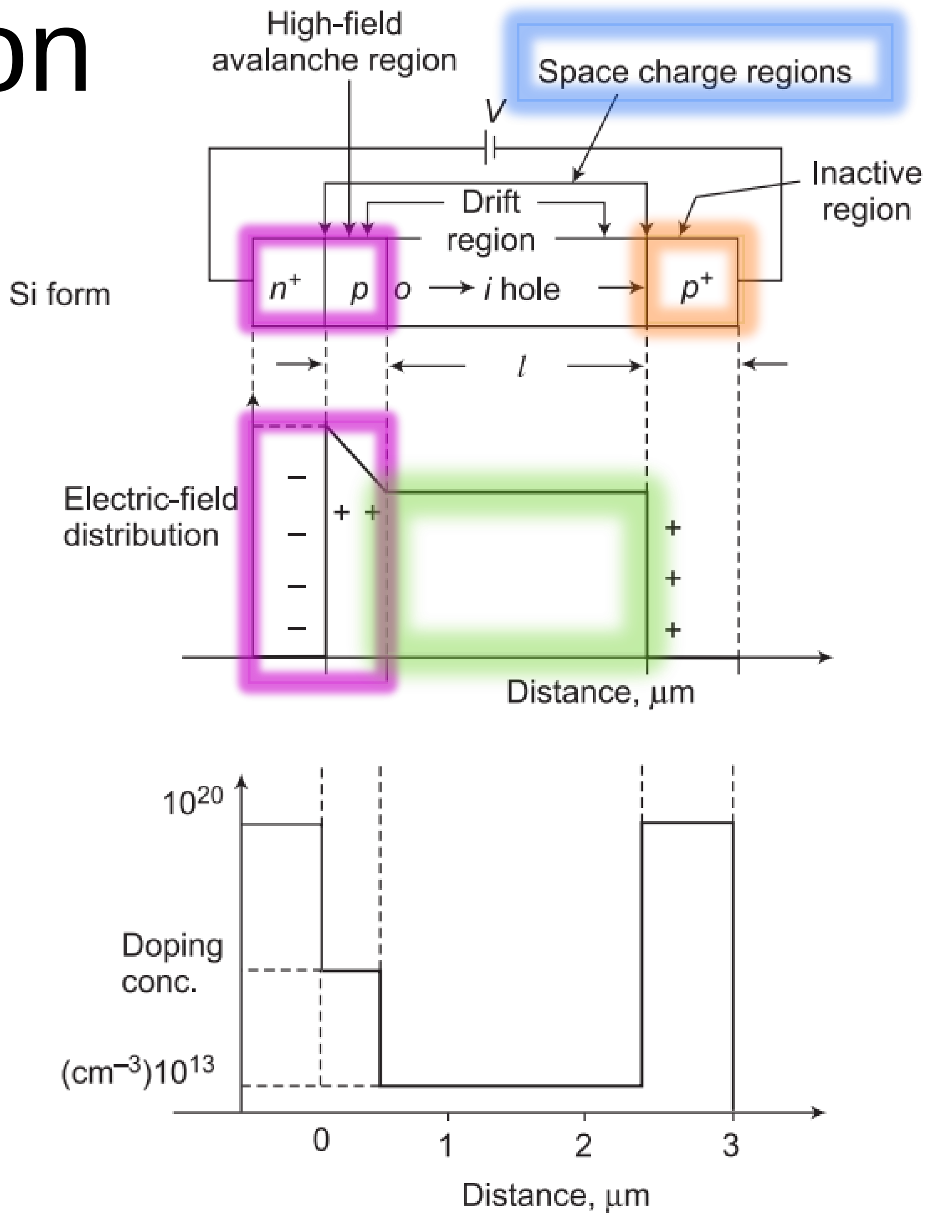
- Doping profile designed to peak E field
- Impact avalanche effect occurs only near junction of n^+ and p
- Carriers increase rapidly



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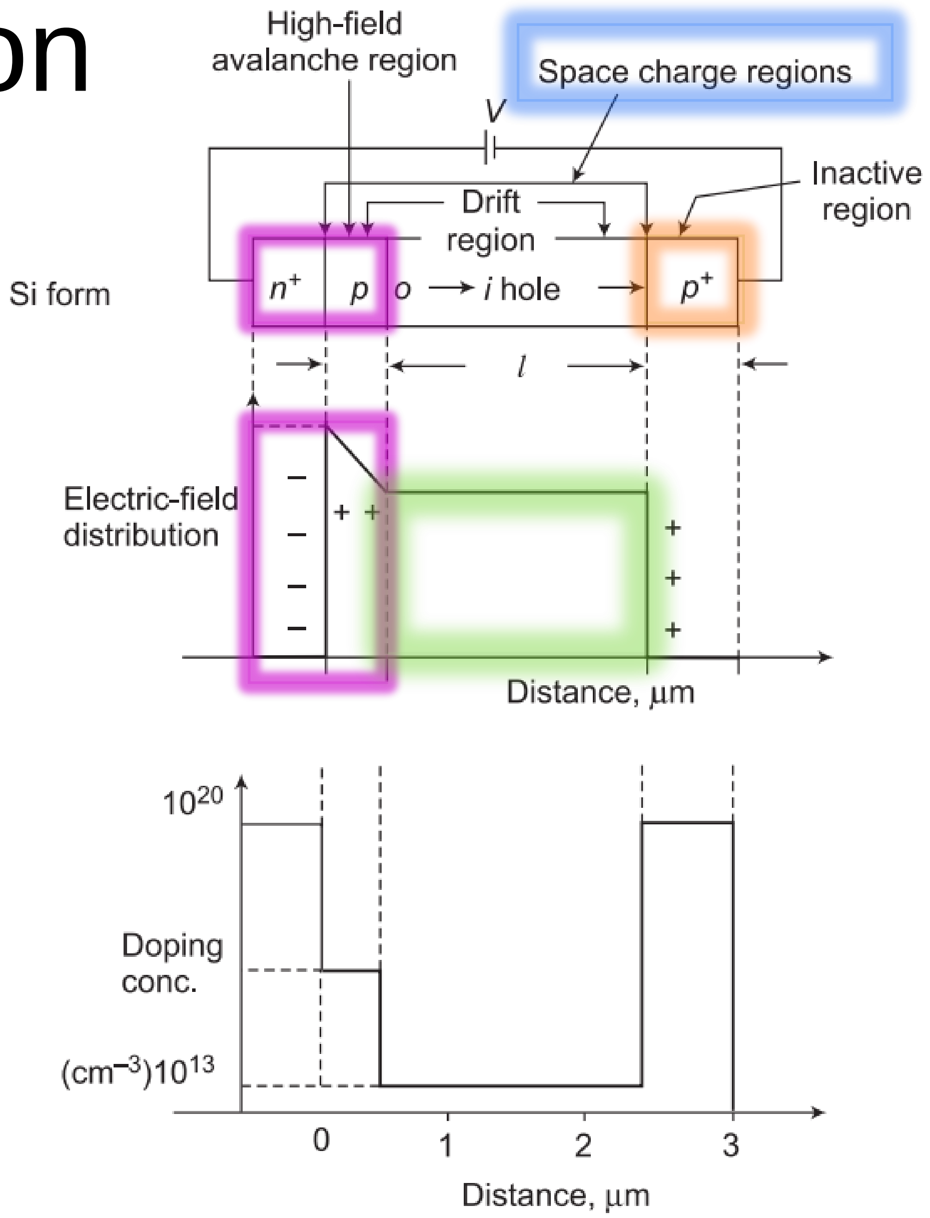

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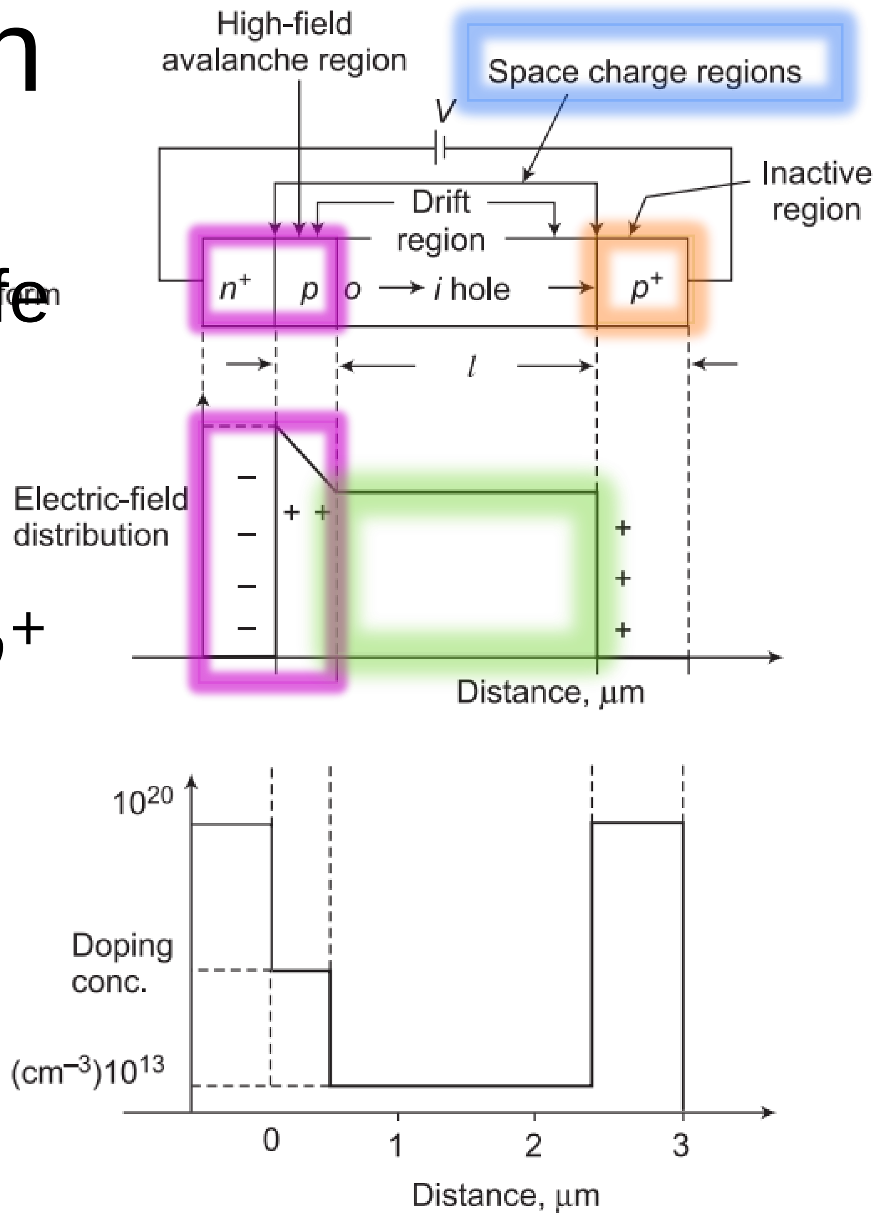

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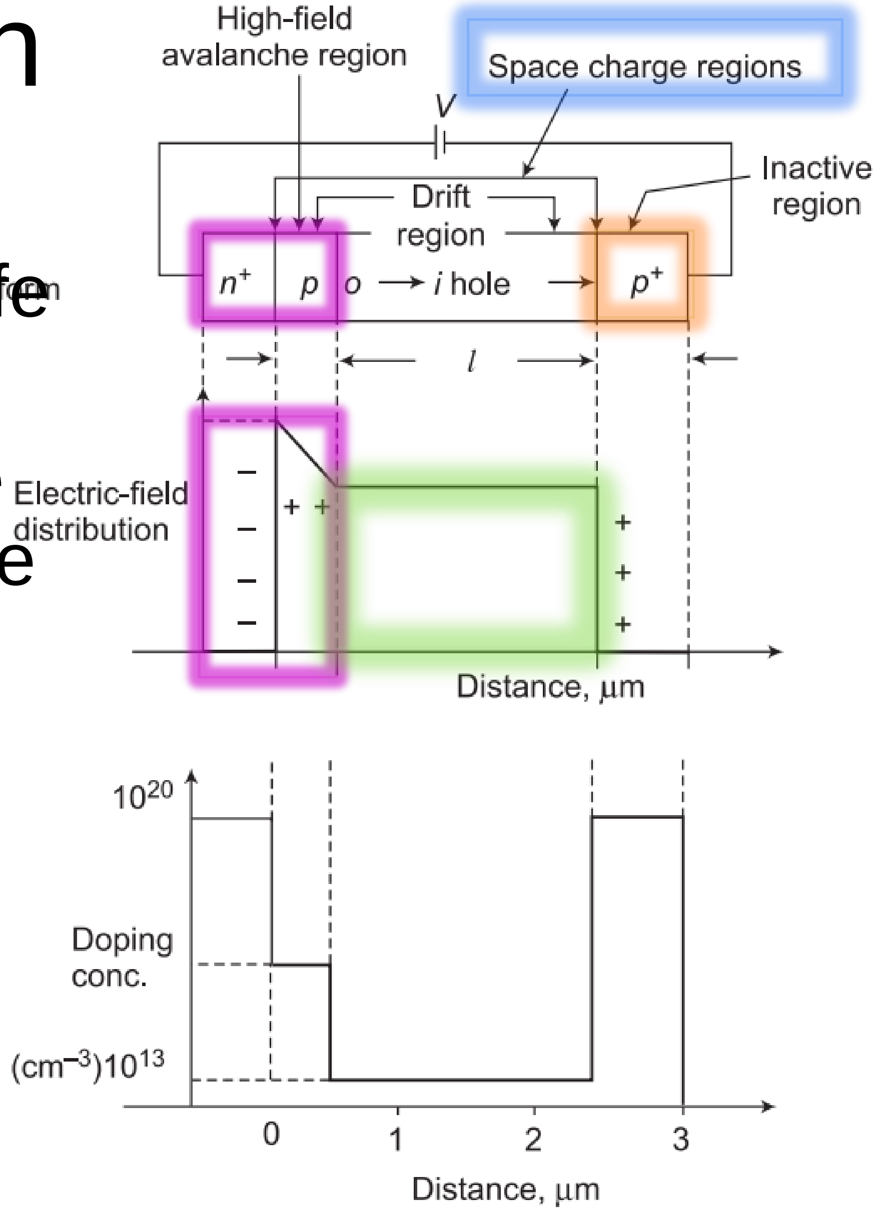
- Drift time: $t_d = l/v_d$
- v_d: Drift velocity of holes (~ 10^5 m/s for $E \sim 0.5MV/m$)
- $l = 2mm,\ t_d = 20ps$



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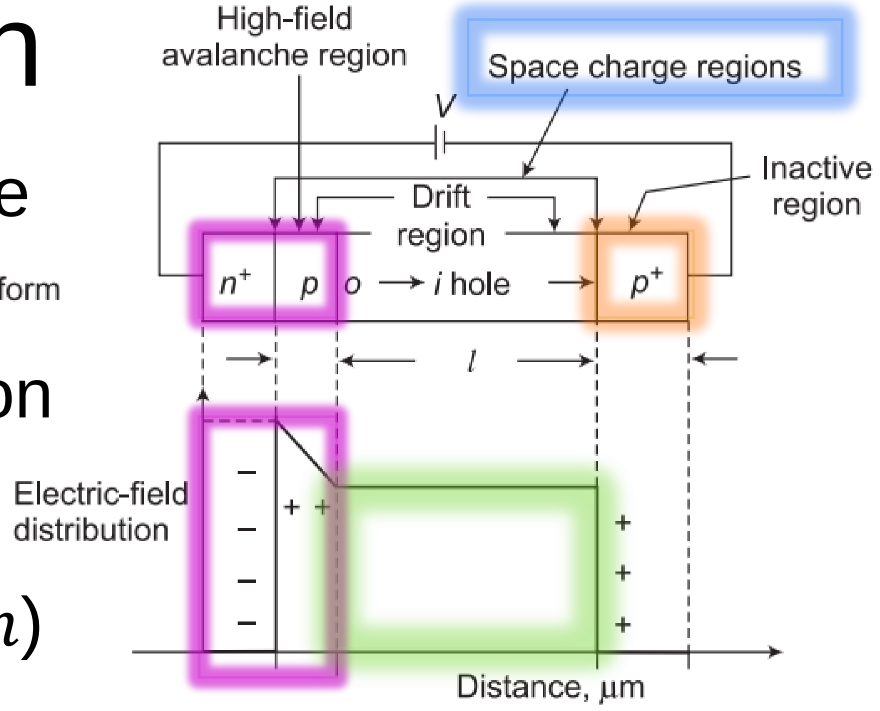
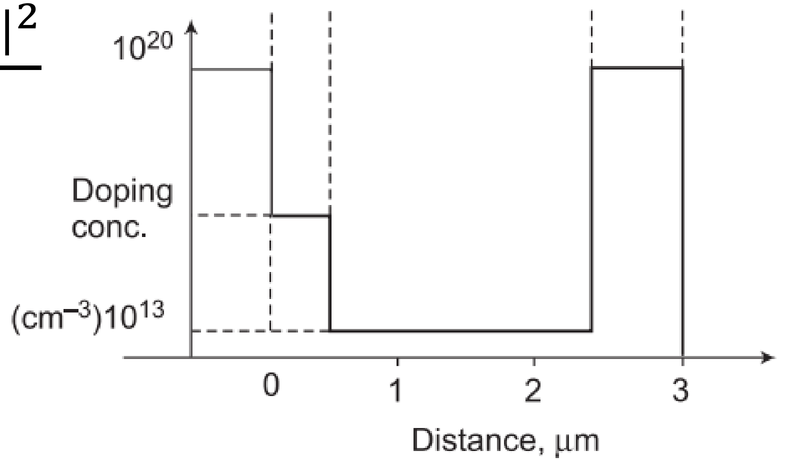
- $l = 2mm$, $t_d = 20ps$
- Breakdown voltage for silicon p^+n: $|V_B| = \frac{\rho_n \mu_n \varepsilon |E_{max}|^2}{2}$
- ρ_n: resistivity of the semiconductor
- μ_n: electron mobility ε: permittivity
- E_{max}: Max breakdown electric field at n^+p junction

Si form





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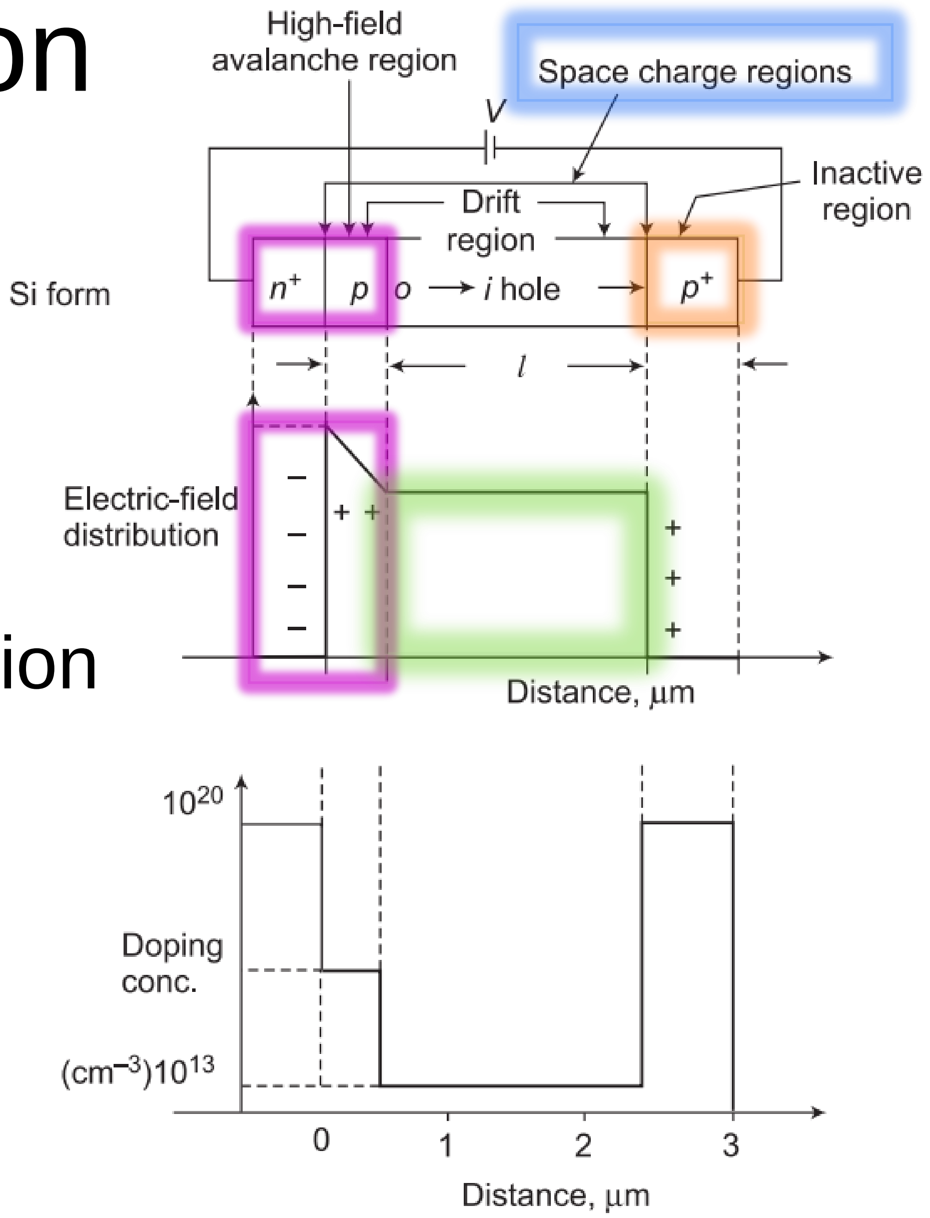
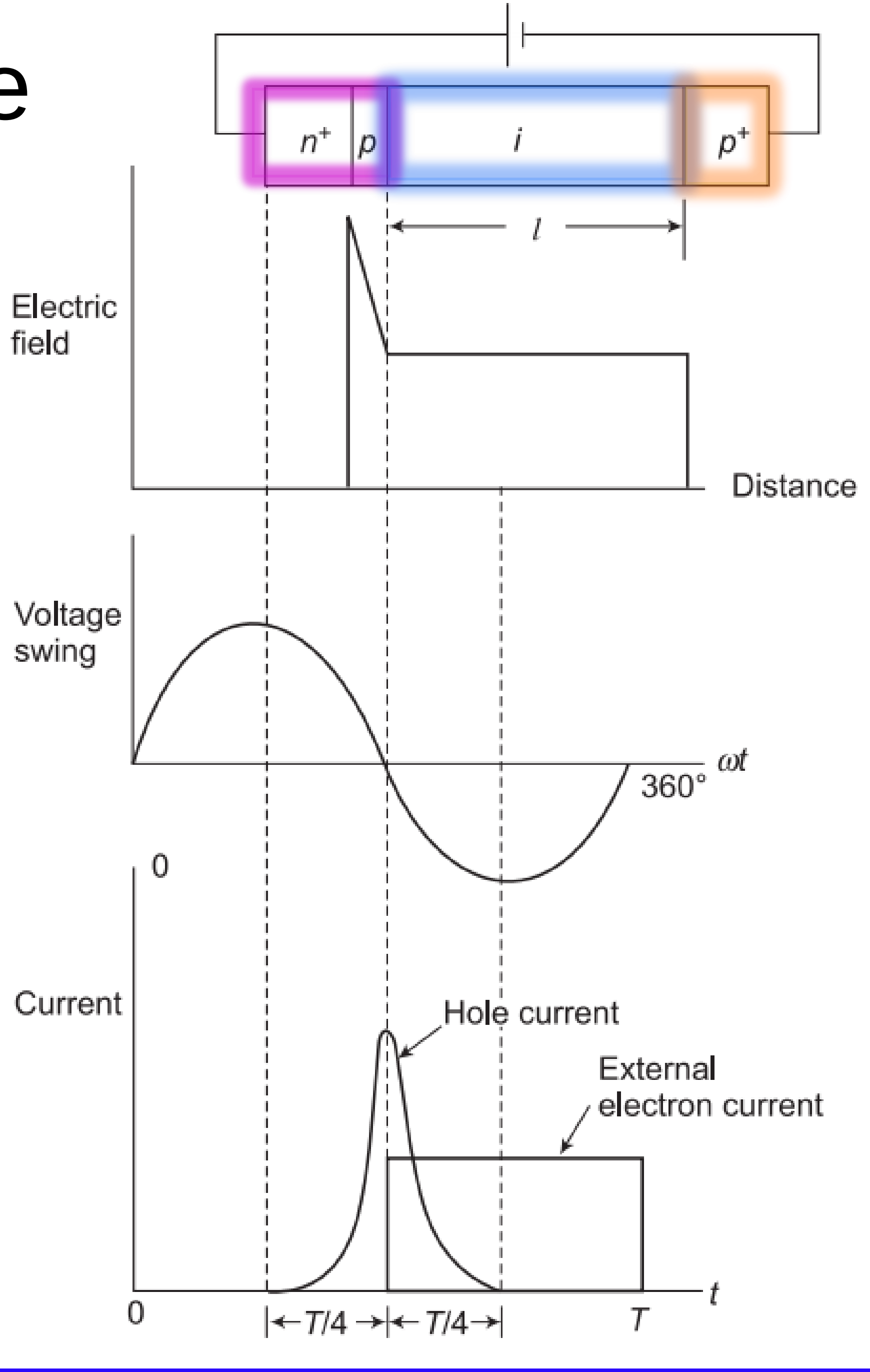
- E_{max}: Max breakdown electric field at n^+p junction
- $V_B \sim 50V$ doping concentration $10^{16}/cm^3$
- $V_B \sim 10V$ for doping order of $10^{17}/cm^3$



10.2.2 READ diode: negative resistance

- Biased below V_B (breakdown voltage)
- AC voltage superimposed over dc voltage
- Bias voltage is near V_B, total voltage (dc+ac)>V_B in positive half of ac cycle



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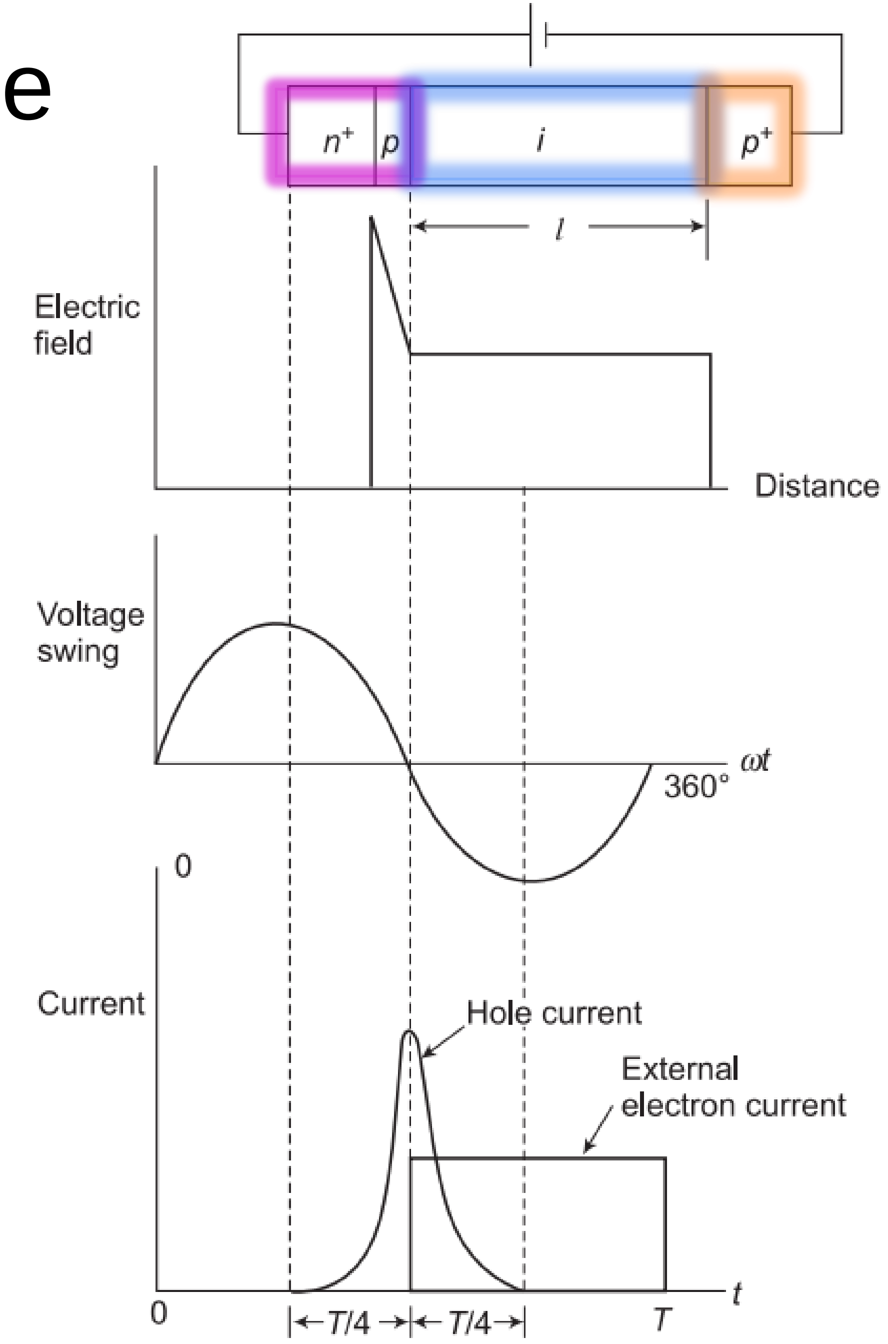
- Injected junction current or carriers at junction due to avalanche: peak at $t = T/2$



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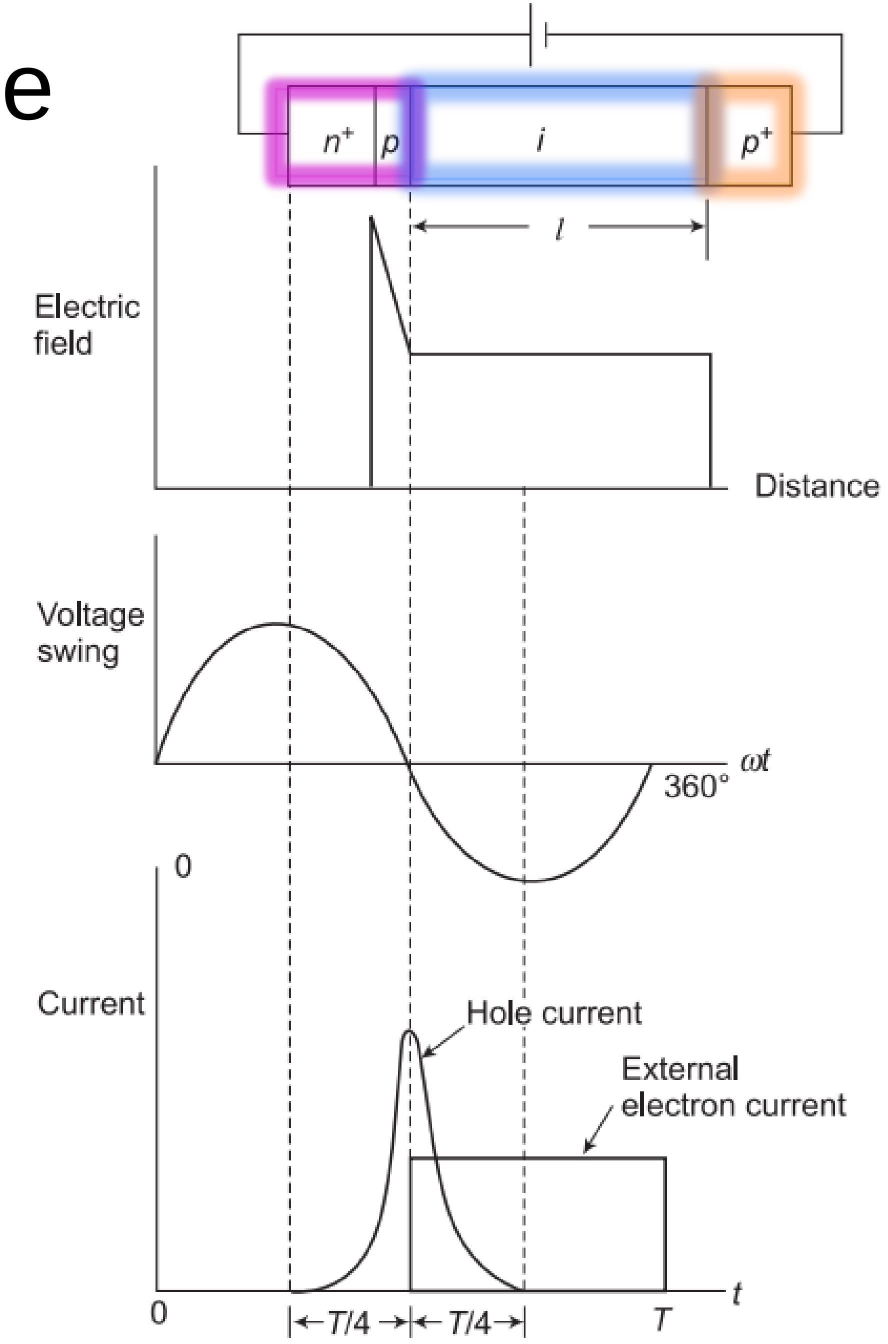
- **t>T/2**: generated carriers decay rapidly
- Injected carrier current at $n^+ - p$ junctions is short duration pulse delayed by $T/4$ ($\pi/2$ phase)
- Injected holes traverse through drift space (i-region).



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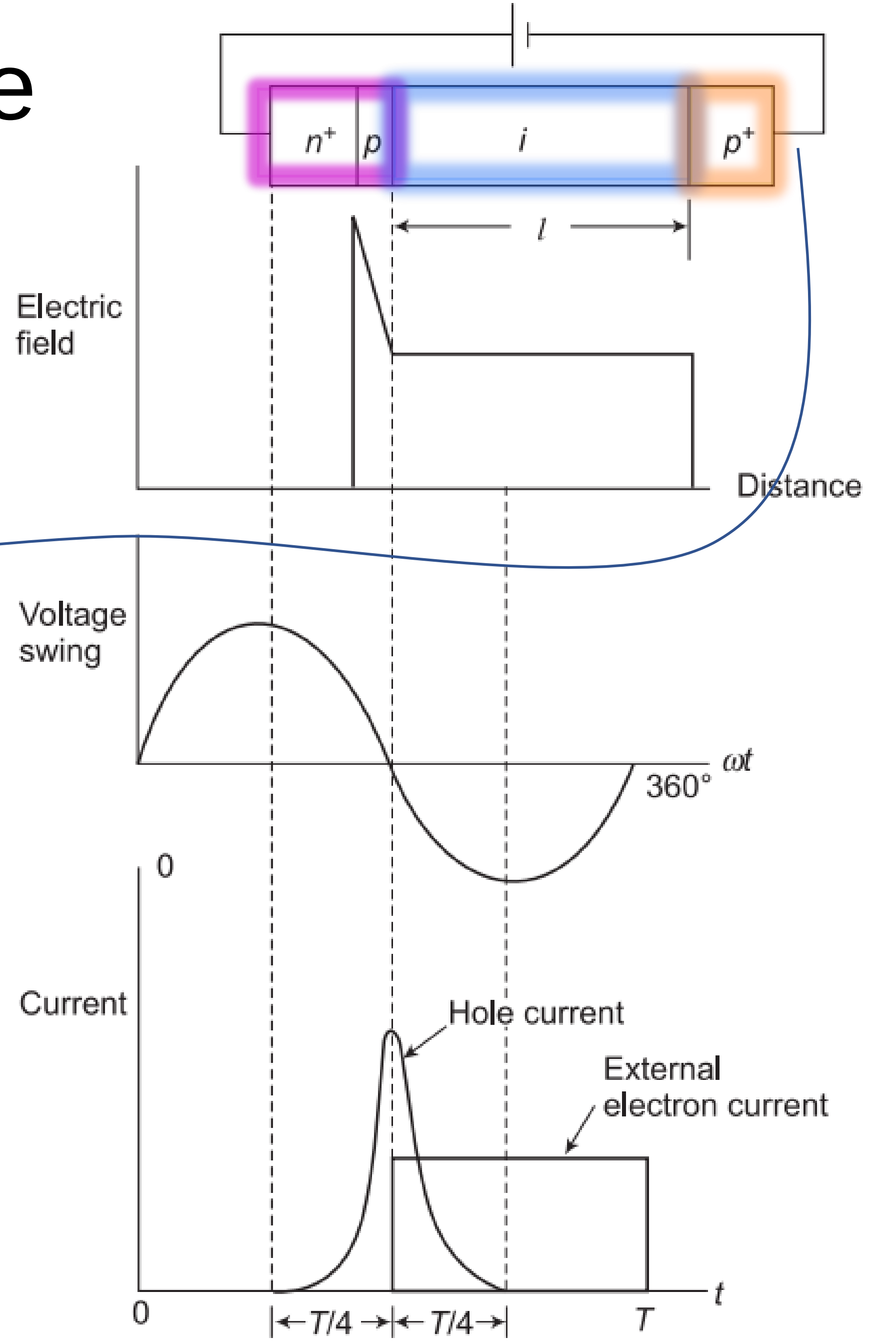
- **Holes move with constant saturated drift velocity through drift zone** and **current in external circuit with constant saturated drift velocity through the drift zone.**
- **Current in external circuit remains constant till time the carriers reach cathode contact**.



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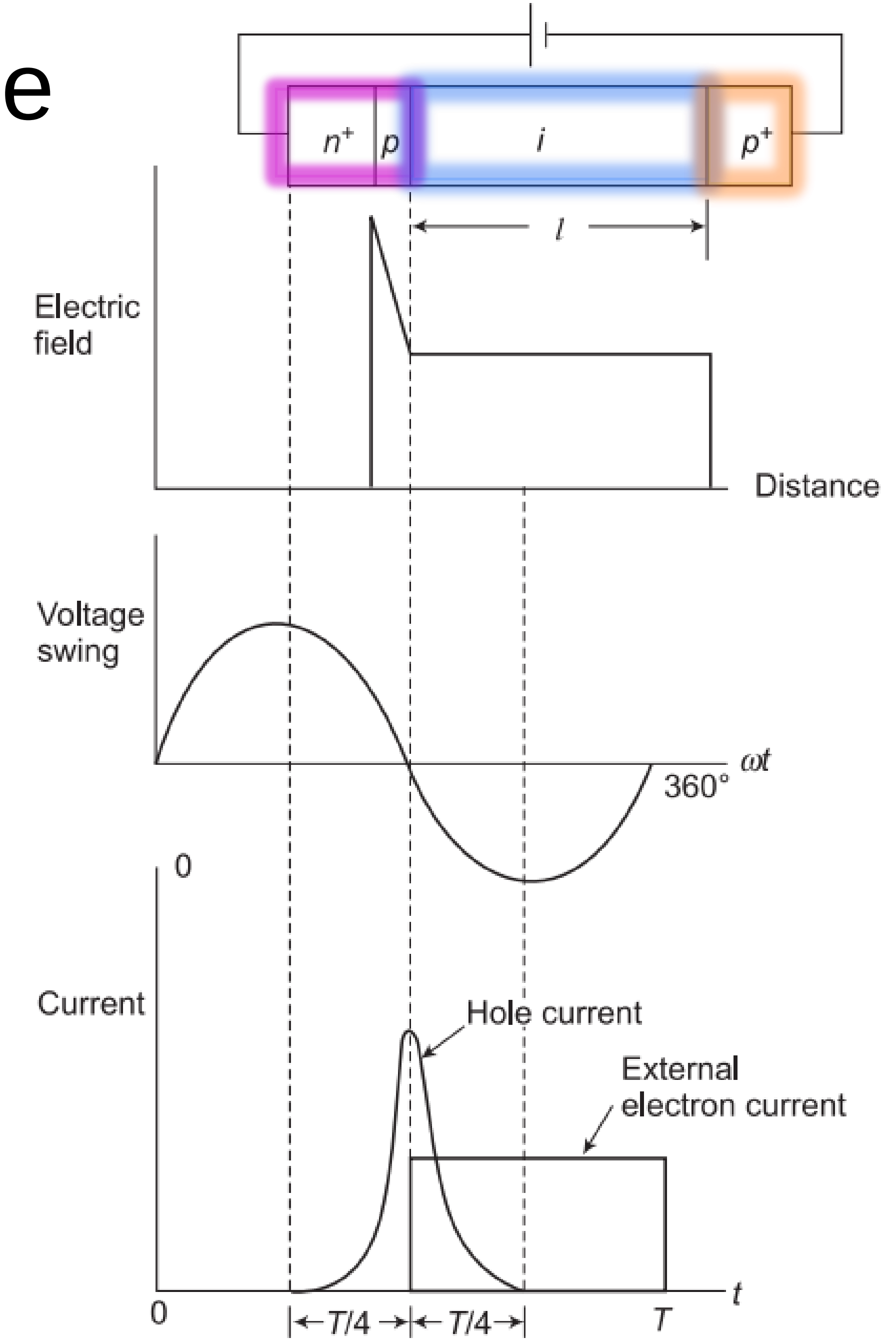
- $t_d = T/2$, duration for external current is from $t = \frac{T}{2}$ to $t = T$
- External current during –ve half cycle of AC



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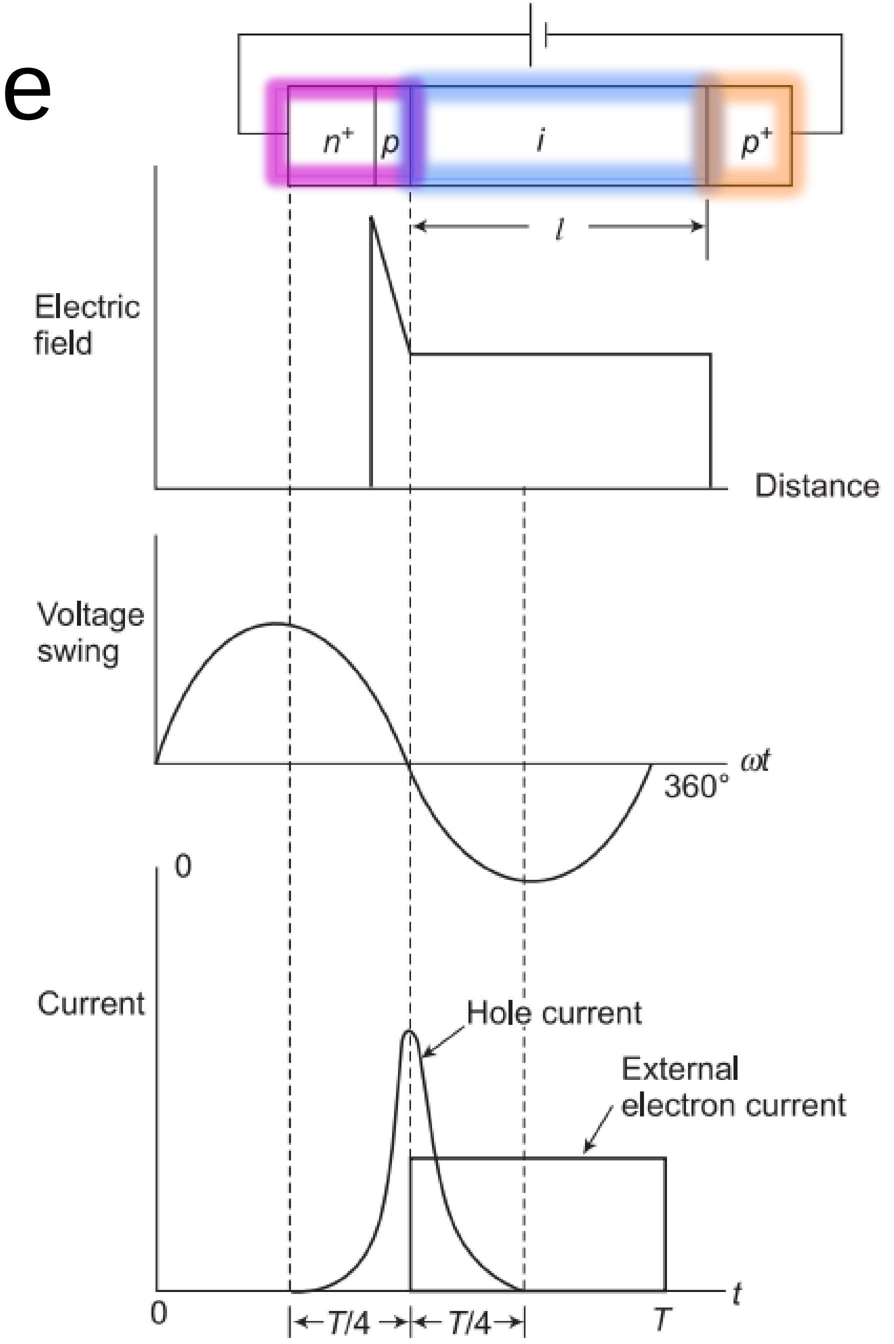
- External current during –ve half cycle of AC
- **Incremental terminal resistance of IMPATT device is negative**
- Effective transit time of carriers must be equal to half the time period of oscillator voltage



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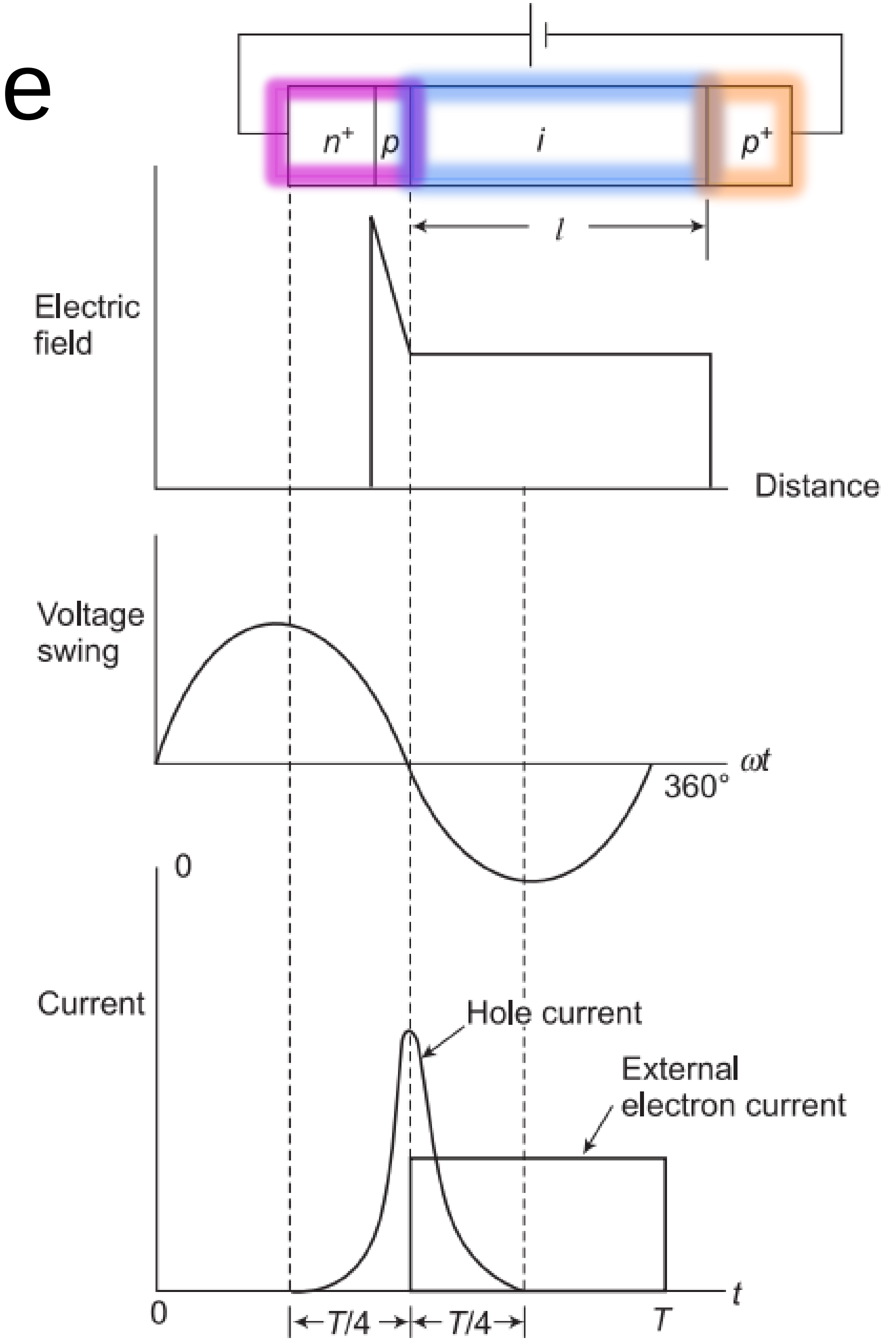

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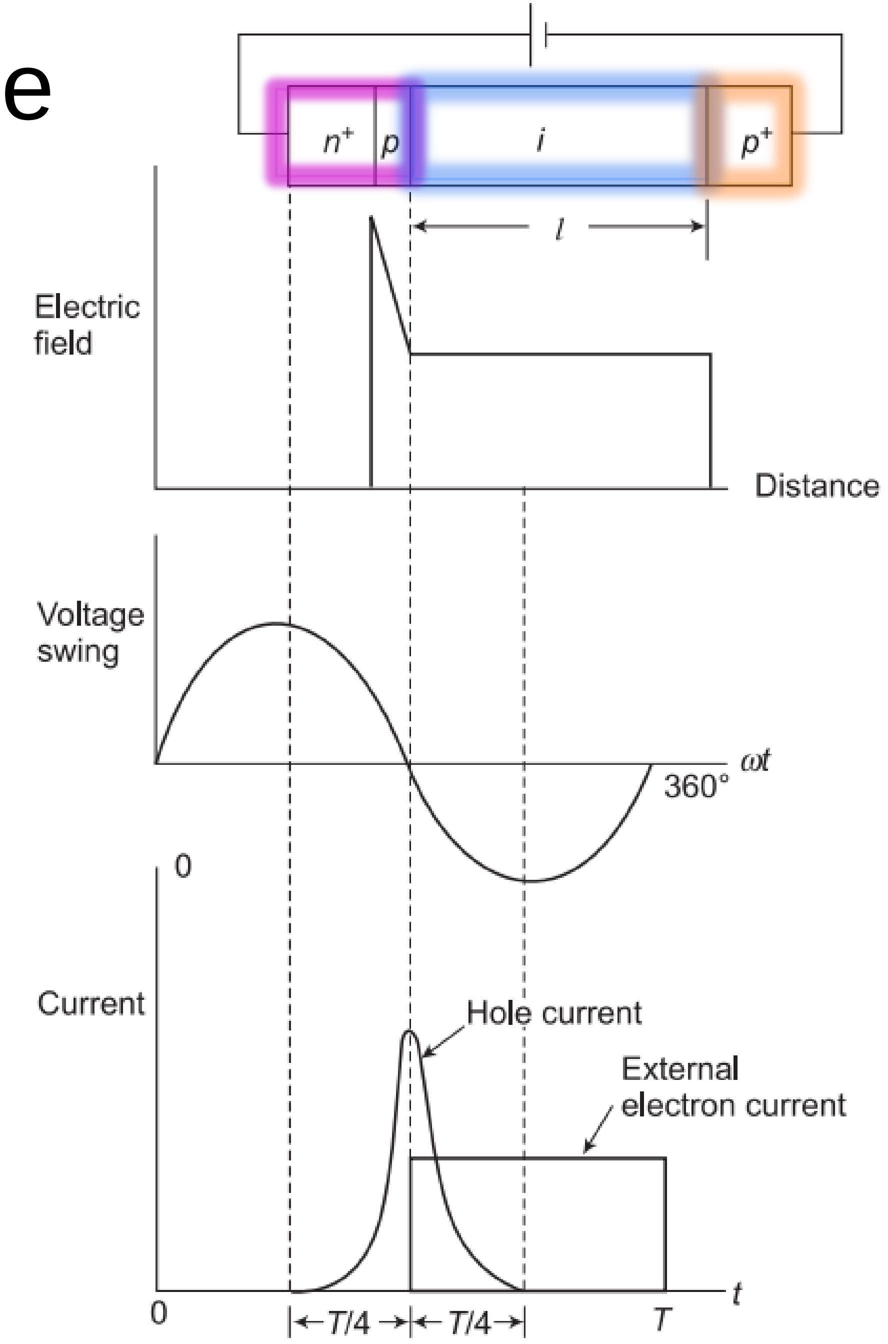
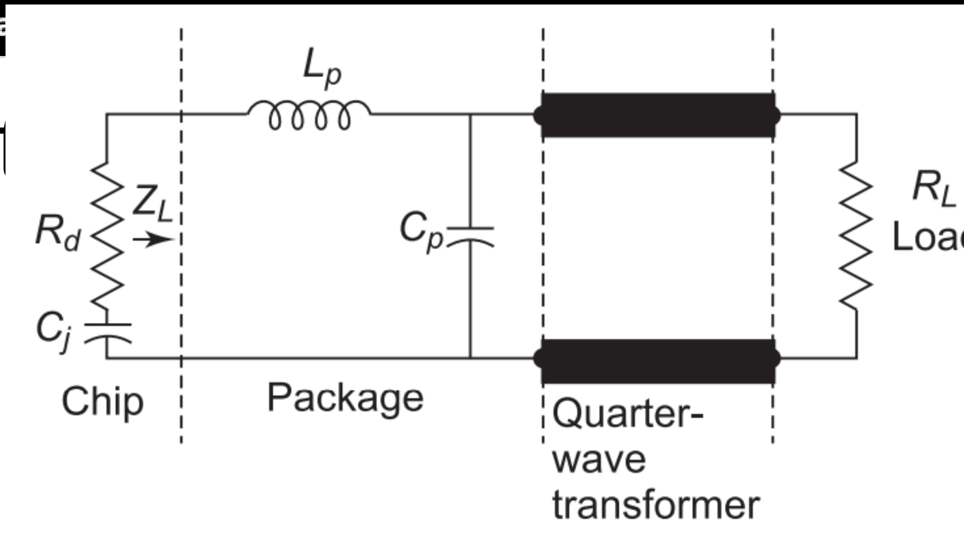
- $t_d = \frac{T}{2} = \frac{1}{2f}$
- $f = \frac{1}{2t_d} = \frac{v_d}{2l}$ is frequency of oscillation



10.2.3 READ diode: Equivalent circuit



- R_d: diode negative resistance (series lead resistance R_S and negative resistance $-R_j$)

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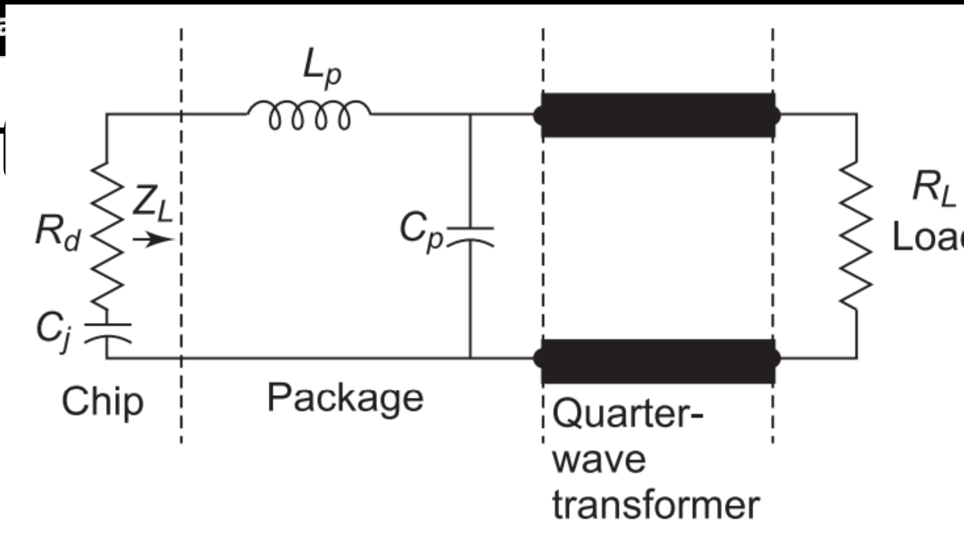

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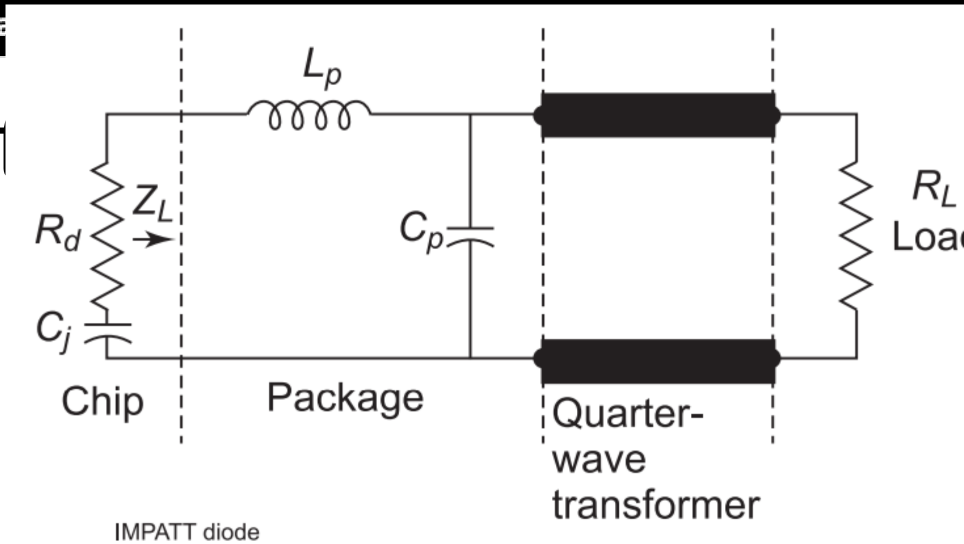
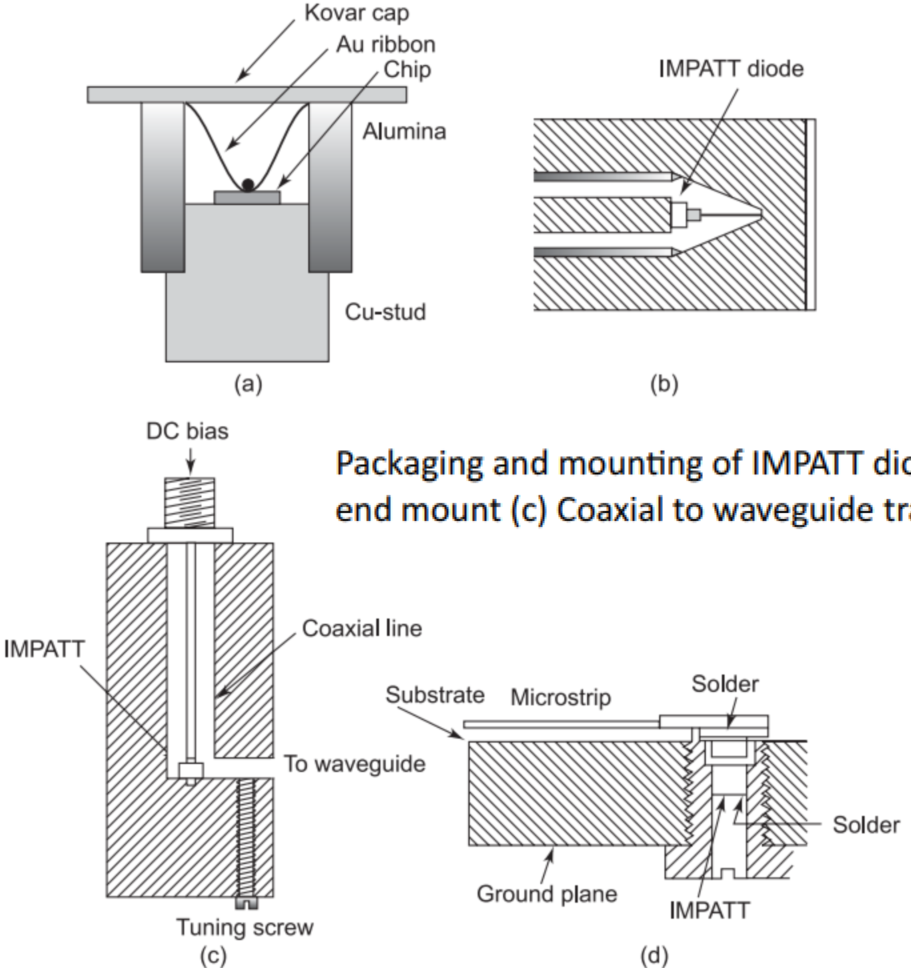


- R_d: diode negative resistance (series lead resistance R_S and negative resistance $-R_j$)
- C_j: Junction capacitance at break-down voltage
- L_p, C_p: Package lead inductance and capacitance
- Diode is mounted in coaxial lines, waveguides or microstrip lines



Packaging and mounting of IMPATT diode: (a) IMP diode packages (b) Coaxial end mount (c) Coaxial to waveguide transition mount (d) Microstrip mount

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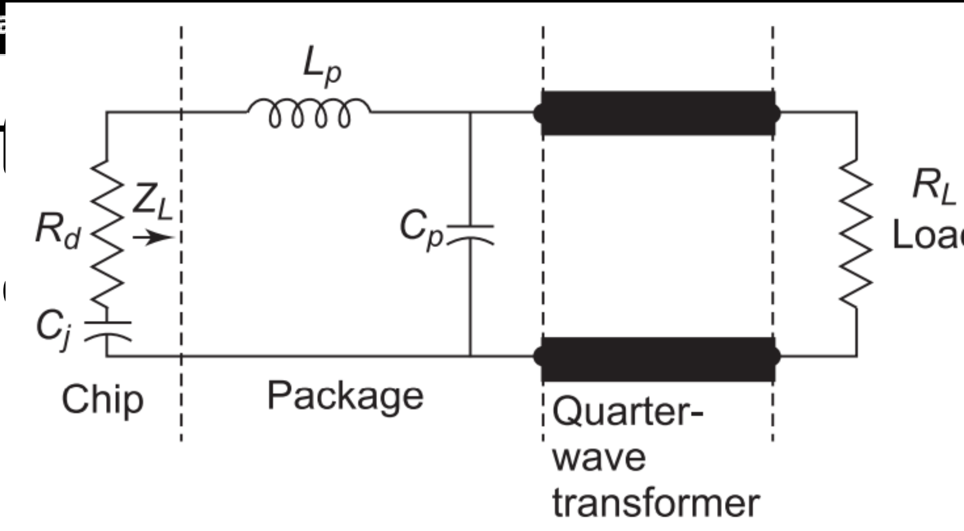

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- **Power extracted by ac field from dc field** compensates for power dissipation in positive resistance of circuit, Total resistance R_d=0.

Peak RF current determines the load power. Impedance matching – due to low negative resistance.

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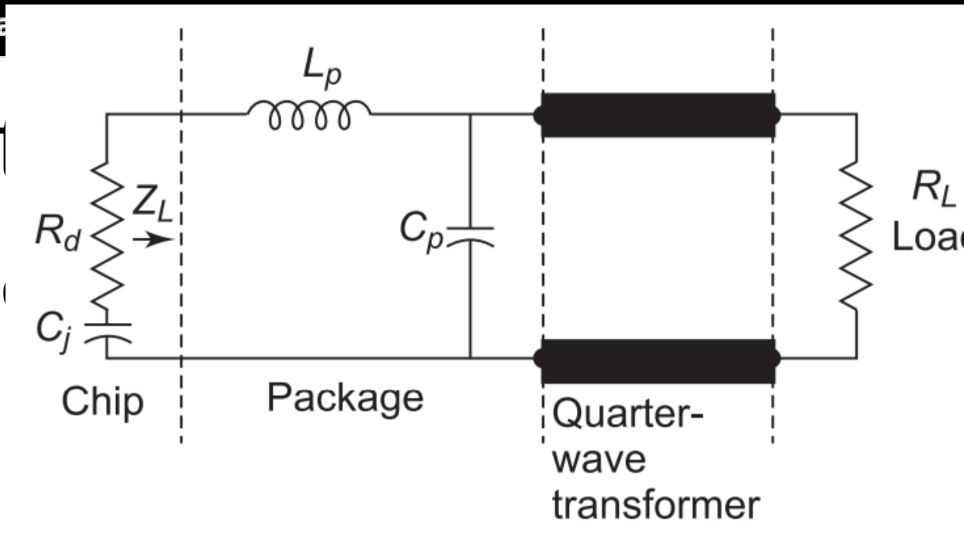

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- Diode chip resistance:

$$Z_d = -|R_d| - \frac{j}{\omega C_j}$$

- Load impedance $Z_L = -Z_d$ or $R_L = |R_d|$ and $X_L = \frac{1}{\omega C_j}$

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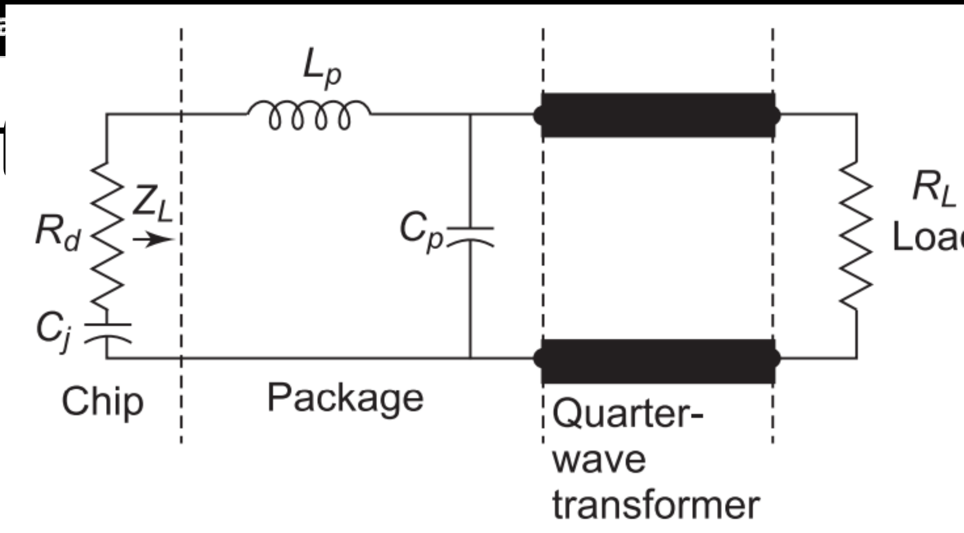
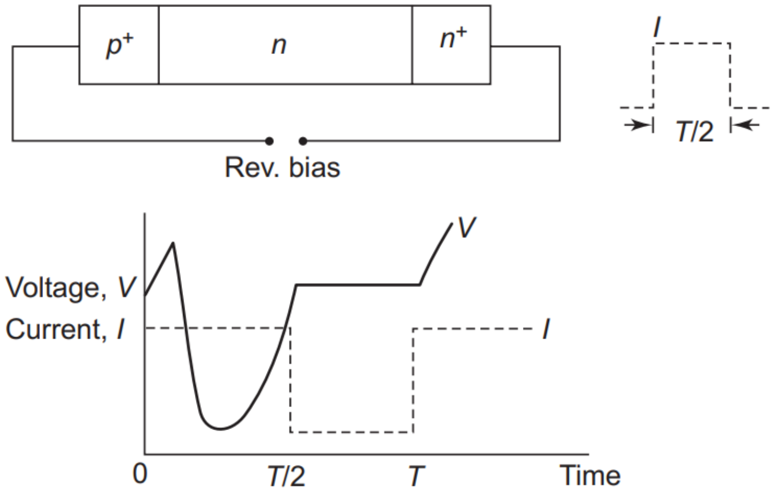


- Power $P_{dc} = V_m I_m$ max output voltage and current
- Efficiency η

- Output power $P = \eta P_{dc}$

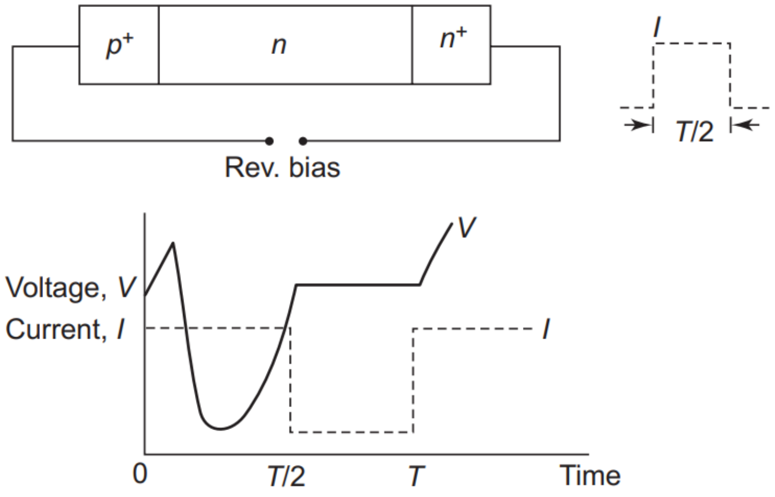
Peak RF current determines the load power. Impedance matching – due to low negative resistance.

10.3 TRAPATT Diode



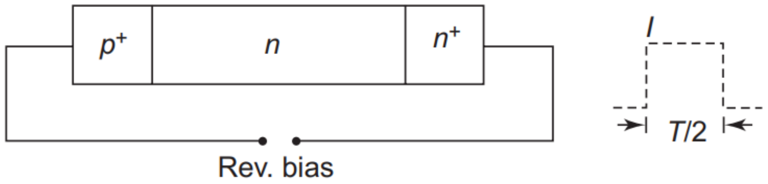
- $p^{+}n\,n^{+}$ or $(n^{+}p\,p^{+}$) configuration
- PN junction is reverse biased beyond breakdown

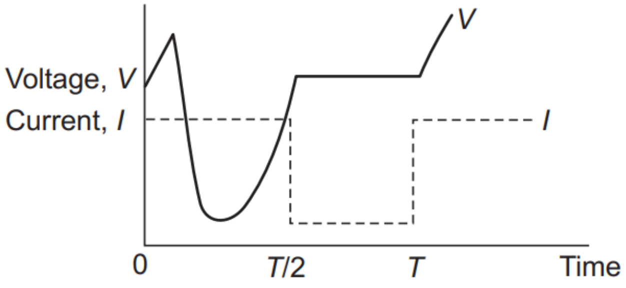
10.3 TRAPATT Diode



- $p^+n\,n^+$ or $(n^+p\,p^+)$ configuration
- PN junction is reverse biased beyond breakdown
- **Current density is higher**
- Electric field in space charge region is **decreased** and carrier transit time is **increased**

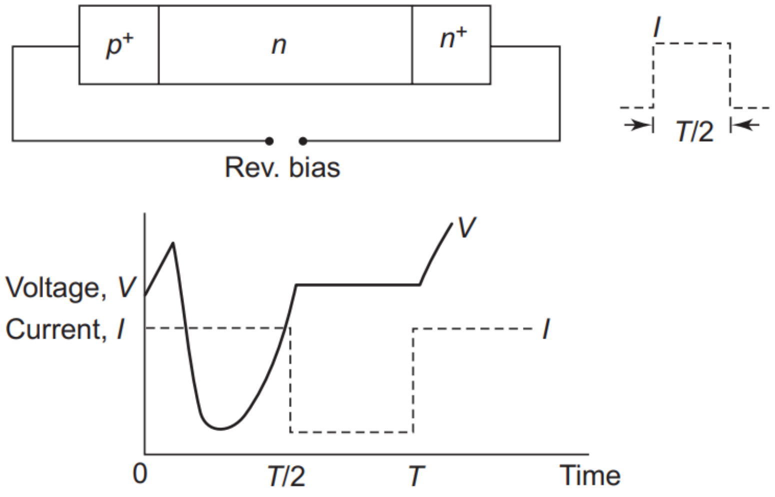
10.3 TRAPATT Diode





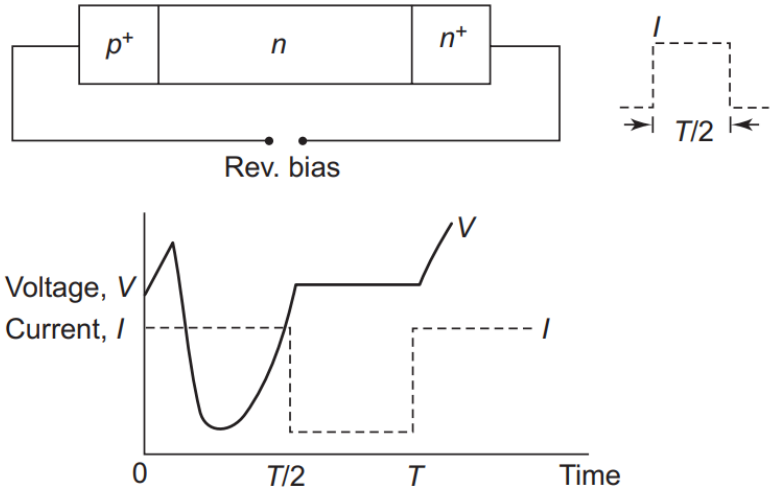
- $p^+n\,n^+$ or ($n^+p\,p^+$) configuration
- PN junction is reverse biased beyond breakdown
- Current density is higher
- Electric field in space charge region is decreased and carrier transit time is increased
- **Frequency of operation becomes lower** and is limited to below 10GHz
- **Efficiency increases due to low power dissipation**.

10.3 TRAPATT Diode



- TRAPATT diode is mounted inside coax resonator
- at max RF voltage swing **DC reverse bias+RF swing causes potential to exceed** beyond threshold of breakdown: : avalanche occurs

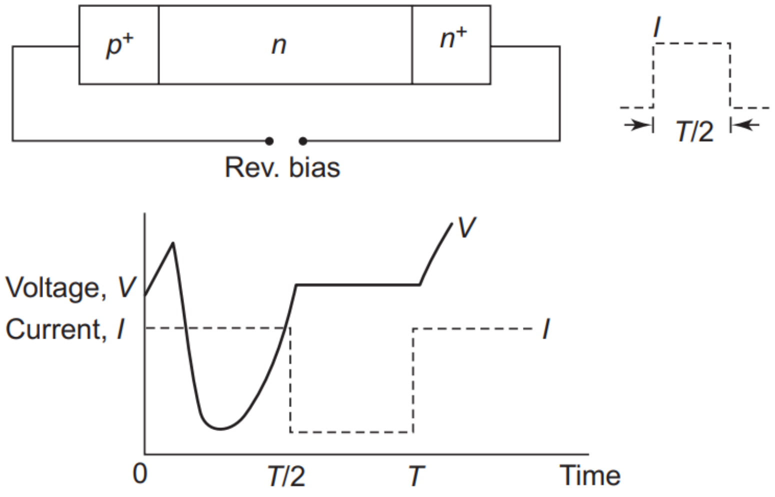
10.3 TRAPATT Diode



- TRAPATT diode is mounted inside coax resonator at max RF voltage swing
- DC reverse bias+RF swing beyond threshold of breakdown: : avalanche occurs
- A **plasma of holes and electrons are generated**
- **Plasma density results in high potential difference across junction - Opposite to dc reverse bias**

Plasma is typically an **electrically quasineutral medium** of **unbound positive and negative particles** (i.e. the overall charge of a plasma is **roughly zero**). Although these particles are unbound, **they are not "free"** in the sense of not experiencing forces.

10.3 TRAPATT Diode



- TRAPATT diode is mounted inside coax resonator at max RF voltage swing
- DC reverse bias+RF swing beyond threshold of breakdown: : avalanche occurs
- A plasma of holes and electrons are generated
- Plasma density results in high potential difference across junction - Opposite to dc reverse bias
- **Plasma gets trapped**
- **External circuit current flow causes voltage to rise, trapped plasma is released producing current pulse across drift space.**

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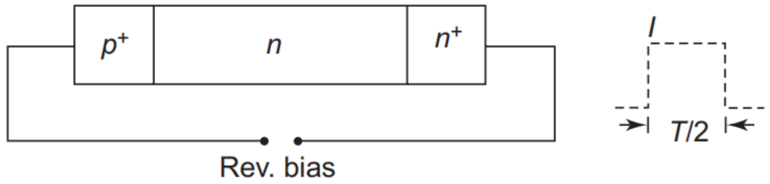

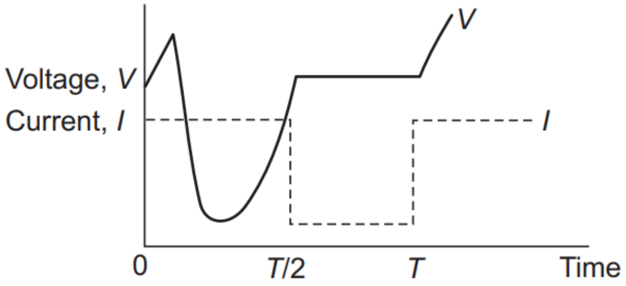

$$Total\ transit\ time \\ = delay\ time\ in\ releasing\ plasma \\ + drift\ time$$

Operating frequency is limited to 10GHz

Current pulse is associated with low voltage.
Power dissipation is low