Power Converters
Power Semiconductor Devices

Power Diodes

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Electronic History

- 1892-Mercury arc vacuum tube invented

- 1902-Mercury arc rectifier patented.
- 1906-Vacuum Diode invented.
- 1906~1950 electronics based on vacuum tubes.
- 1947-germanium BJT invented

- 1952-germanium diode manufactured
- 1954-Silicon transistor produced by TI .
- 1950~1960 vacuum tube to transistor migration.

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Power Semiconductors

- 1957 SCR developed
- 1960~1970 SCR in power control.

Since 1970, various types of power semiconductor devices were developed and become commercially available.

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Power Devices

Power Devices can be divided into following major types.

- Power Diodes
- Power BJTs
- Power MOSFETs
- IGBTs
- Thyristors:
  - ***SCR***
  - ***GTO***
  - ***DIAC***
  - ***TRIAC***

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Power Diode

- High current densities when ***'on'***
- Withstand high voltage when ***'off'.***
- When ***'on'*** the device drop is 2-3 volts.
- With large conducting current, the power dissipation is large.
- The power diode are much bigger in size and encapsulated in metal body to be mounted on metal heat sink for proper thermal design.

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Bipolar Diode

Reverse Biased

- The reverse bias voltage across a bipolar diode is limited because of high leakage current and avalanche breakdown.
- The *v-j* relation of a diode is given as

$$j = j_s(e^{qV_A/kT} - 1) \quad \text{--------(1)}$$

- Under reverse biased, VA <<0, J=Js

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Bipolar Diode

- J_s is called the leakage current density.
- At room temperature (25^OC) and under forward bias, J_s is very small compared to J.
- If V_A = 0.6 V, J is $2.6X10^{10}$ times greater than J_s.
- Such a small leakage current results in negligible power dissipation.

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Bipolar Diode

n_i^2 is a strong function of temperature as shown in following relation.

$$n_i^2 \propto T^3 e^{-E_g/kT} \quad \text{---------------- (2)}$$

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Bipolar Diode

$$n_i^{\ 2} = 2X10^{20} / cm^3 \ @ 25^o C$$
$$n_i^{\ 2} = 2X10^{27} / cm^3 \ @ 175^o C$$

7th order of magnitude increase gives a leakage current whose effect is no longer negligible.

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Bipolar Diode

- The diode equation (1) given above does not account for all the current under reverse bias,
- As we know, under thermal equilibrium

$$n_o \times p_o = n_i^{\ 2}$$

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Bipolar Diode

- However, under reverse bias, the device is no longer in thermal equilibrium.
- The excess carrier concentration in SCL and adjacent regions is substantially below than n_o and p_o.
- Therefore the thermal generation rate exceeds the recombination rate.

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Bipolar Diode

- The carrier concentrations do not built us because thermally generated carriers are swept out of SCL.
- These carrier flow give a component of measured leakage current that is not accounted for by equation (1)

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Conclusions

- Generation in wide SCL & adjacent regions of a power diode will yield substantially more leakage current at 25^{O}C than predicted by diode equation.
- To keep the leakage current in acceptably small, the minority carriers life time in the SCL should be as long as possible.

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Conclusions

- The component of leakage current resulting from thermal generation in the SCL, grows as n_i, which approximately doubles for every 11^{O}C increase in T between -50^{O}C to 200^{O}C. But J_s grows as n_i^2, so it eventually dominates at high temperature.
- This increase in reverse leakage current limits the maximum operating junction temperature of a power diode.

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PIN-Diode

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PIN Diode

- The transient performance of diodes tends to deteriorate as the thickness of silicon wafer is increased in attaining higher reverse voltage.
- The asymmetric doping concentration is preferred in Power Diodes fabrication.

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PIN Diode

- Under reverse bias, nearly all the voltage is supported by the SCL in the lightly doped region.
- Power diode are vertical in structure and fabricated by simply diffusing P^+ region into n^- substrate.

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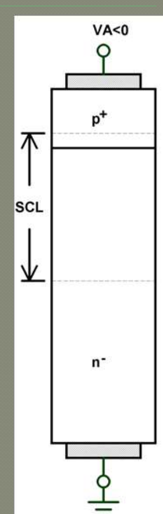
PIN Diode

- The substrate thickness is usually about 500um to maintain mechanical strength.
- A long n^- region results in a large resistive component of the diode drop under forward bias.



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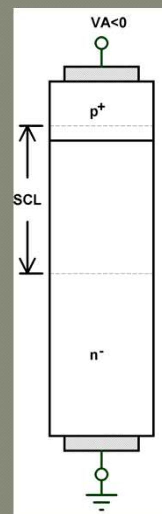
PIN Diode

- The SCL width is approximately between 10 to 200um and most of it is in the ***n^-*** region.



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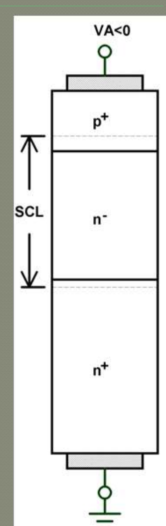
PIN Diode

- The lower part of the substrate can be heavily doped to lower the resistive component of the forward voltage drop as shown in the diagram.
- Performance can be further improved by doping the ***n^-*** region so lightly that is nearly intrinsic.



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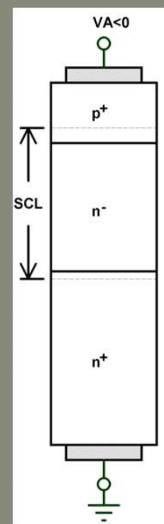
PIN Diode

- Resulting diode is called a ***PIN*** diode.
- Almost all power diodes have ***PIN*** type of structure.



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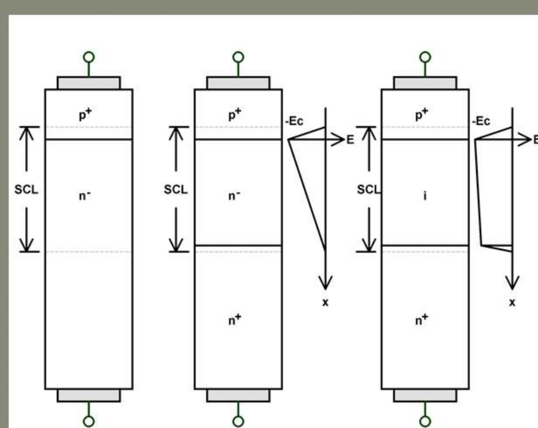
PIN Diode



Evolution of PIN structure

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PIN Diode
under Forward Bias

- Analysis of ***PN*** diode is based on the assumption that both sides are in low-level injection.
- Low level injection means minority carrier concentration remains small compared to majority carrier concentration even if the diode may not be in thermal equilibrium.

PIN Diode
under Forward Bias

- This is not valid for the i-region of ***PIN*** diode.
- i-region is in high level injection.
- Consequently ***n*** is nearly equal to ***p*** in the neutral region.

PIN Diode
under Forward Bias

- High level injection is also called

  "Conductivity Modulation".
- Under conductivity modulation, the conductivity of the material is no longer determined by the majority doping level.
- It is now a function of injection level.

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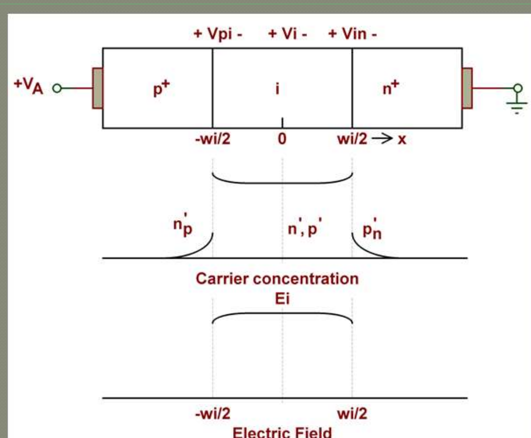
PIN Diode
under Forward Bias



One dimensional PIN structure

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PIN Diode
under Forward Bias

- In PN diode, the minority current flows only by diffusion.
- There is also a drift component of current in the intrinsic region and drift field gives rise to a voltage drop V_i which adds to the on state voltage drop of the diode.

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PIN Diode
under Forward Bias

- All the current flowing through the diode results from recombination within the i-region therefore, E_i & V_i are dependent only on physical parameters and length of i-region.
- Because n_i increases rapidly with increasing temperature, J increases with temperature and the forward drop decreases with temperature if the forward current is fixed.

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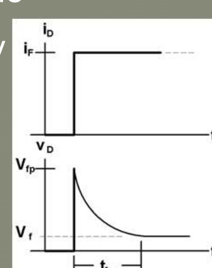
PIN Diode
Transient Operation

- For simplicity, let us ignore the SCL capacitance and focus on the excess stored charge in the neutral regions outside the SCL.

PIN Diode
Transient Operation

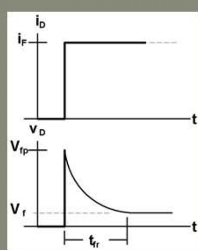
Forward Recovery

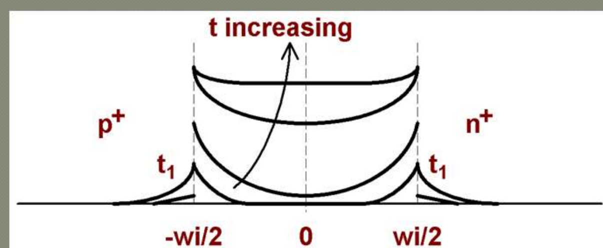
- Let us consider turn-on transient, The diode current steps from zero to I_f, the terminal voltage first rises to V_{fp} and then decay to steady state value of V_f.
- This process is called forward recovery of the diode. V_{fp} is known as the Forward recovery voltage
- The duration of forward recovery is called Forward recovery time t_{fr}.



PIN Diode
Transient Operation

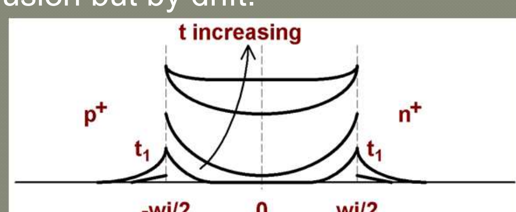
- As forward current I_F flows, holes drift through p^+ region and injected into i-region. Similarly electrons drift through n^+ region and injected into i-region.
- The carrier concentration builds up with time as indicated below





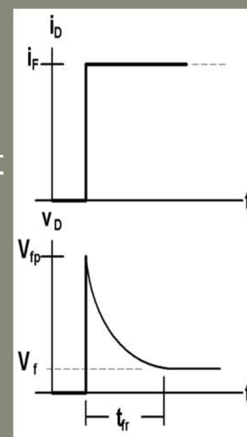
PIN Diode
Transient Operation

- At t_1 just after the forward current starts, the carrier builds up near the junctions but not in the middle of the i-region.
- In most of the i-region at t_1, there is no gradient to the carrier profile.
- Therefore, the injected carriers flows across the i-region not by diffusion but by drift.



PIN Diode
Transient Operation

- The voltage that results from this drift is very large.
- i-region is not in high level injection at this time so that conductivity is very low and the region is carrying the full current ***I_F***.



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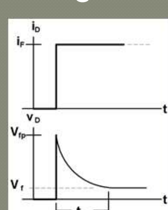
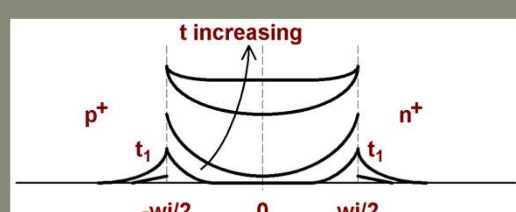
PIN Diode
Transient Operation

- The high resistance is the source of the peak transient voltage ***V_{fp}***.
- As time passes, the carrier concentration grows in the middle of the i-region modulating the conductivity and reducing the resistance.





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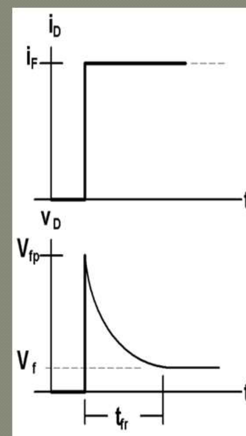
PIN Diode
Transient Operation

- As a result, the voltage across the middle region drops.
- The change in the middle region at steady state is proportional to the forward current I_f.
- The duration of forward recovery transient is called "Forward Recovery Time", t_{fr}.



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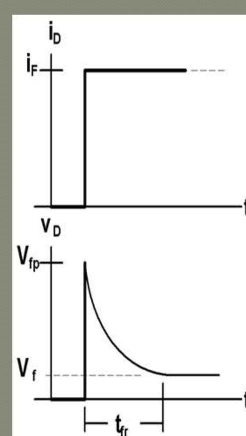
PIN Diode
Transient Operation

Reverse Recovery

- Consider that that PIN diode is carrying a forward current of I_F.
- At t = 0, the diode is connected to reverse voltage V_R.
- Because the excess charge in the i-region and diffusion regions of the diode can not change instantaneously, the p^+-i and i-n^+ junctions remain forward biased for some time even after t = 0.
- As the diode voltage is zero during this time, the diode current is negative.



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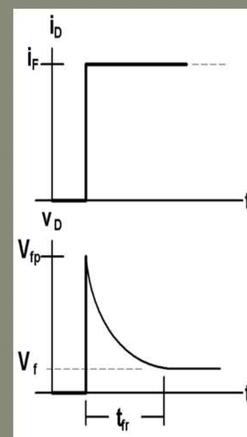
PIN Diode
Transient Operation

Reverse Recovery

- This reverse current adds the removal of excess charge, until the concentrations at the SCL edges become negative and the junction can begin to support a reverse voltage.
- This process is called reverse recovery.



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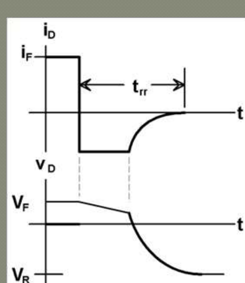
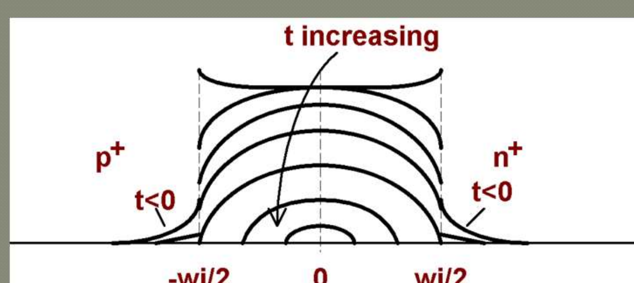
PIN Diode
Transient Operation

- Following figure shows the carrier profile in the i-region as the reverse recovery current flows.
- Just after t = 0, the excess carrier concentrations at the junction edges are still positive, therefore the junction voltages are also positive.





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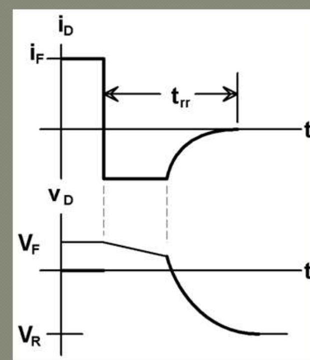
PIN Diode
Transient Operation

- To support the negative current, the excess carrier distribution develop a negative slope near the junction edges.
- Continuing recover current flow eliminates the excess carrier concentrations in the i-region.



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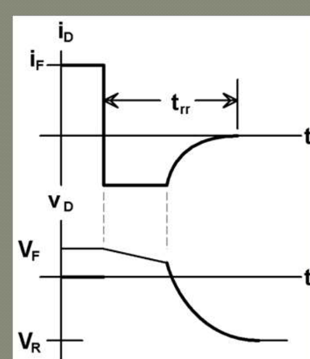
PIN Diode
Transient Operation

- When the excess carrier concentrations at the junction edges reach zero, the concentration gradients decreases and the diode current can no longer be maintained.



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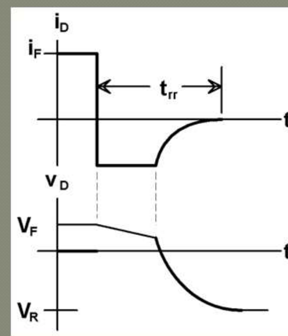
PIN Diode
Transient Operation

- The dynamics of this process produce an exponential rise of i_D to zero and fall of V_D to $-V_R$ as shown in the Figure.
- During the initial phase of reverse recovery, the diode voltage changes only slightly this is due to the change in sign of vi.



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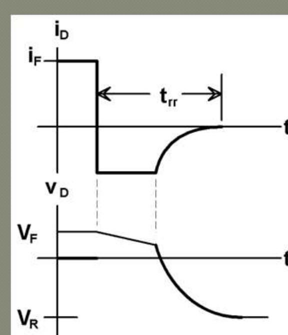
PIN Diode
Transient Operation

- The duration of reverse current flow in the diode is t_{rr}, the *reverse recovery time*.
- Based on the above discussion, t_{rr} is directly proportional to the reverse current I_R and initial stored charge in i-region.



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Conclusions

A. *If less charge is stored for a given forward current, the diode will recover quicker from the transient and switch faster.*
B. *To store less charge, the carrier lifetime should be shortened in the i-region.*
C. *However, doing so will result in less conductivity modulation of the i-region and higher voltage drop across it.*
D. *Therefore the forward drop of a fast diode is typically greater than that of a slower diode.*

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Thank you

For your attention

Questions?

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