PN Junction & Schottky Diode
Reverse-Bias PN Junction

Built-In Potential (0 Bias)

\[ \phi_{bi} = V_T \ln \frac{N_A N_D}{n_i^2} \]

\[ V_T = \frac{kT}{q} \approx 26 \text{ mV at } 300^\circ\text{K} \]

\( n_i \) is the intrinsic carrier concentration approximates 1.5e-10 cm\(^{-3} \) at 300\(^{\circ}\)K

K is Boltzmann Constant

Reverse-bias is similar as 0 bias condition

\[ V_T = \frac{kT}{q} \approx 26\text{mV} \]
* Built-In Potential oppose the diffusion of mobile holes and electrons across the junction.

* \[ qN_A x_p = qN_D x_n \] Demand overall charge neutrality.

* Apply Poisson’s equation \[ \frac{\partial^2 V}{\partial x^2} = -\frac{\rho}{\varepsilon} \] to solve for \( V \)

\[
\mathcal{E}(x) \simeq -\frac{qN_A}{\varepsilon}(x + x_p) \quad -x_p \leq x \leq 0
\]

\[
\mathcal{E}(x) \simeq \frac{qN_D}{\varepsilon}(x - x_n) \quad 0 \leq x \leq x_n
\]
* Maximum field increase as the doping density increase.
* Increase reverse bias voltage will increase maximum field.
* Junction breakdowns when bias exceeds $V_{\text{BREAKDOWN}}$ voltage.

$V_{\text{BREAKDOWN}}$

$I$

$V$

$\$ Higher doing will cause higher or lower $V_{\text{BREAKDOWN}}$?
* Apply

$$C_j(V) = \frac{\partial Q}{\partial V} = \frac{C(V = 0)}{\left(1 - \frac{V}{\Phi_{bi}}\right)^{\frac{1}{2}}}$$

for uniform doping in both p,n region

*  

$$C_j(V) = \frac{\partial Q}{\partial V} = \frac{C(V = 0)}{\left(1 - \frac{V}{\Phi_{bi}}\right)^{\frac{1}{3}}}$$

for graded doping in both p,n region

Junction Capacitance

V is the reverse bias voltage

Graded doping

C-V curve for uniform doping

$\$ Higher doping will cause higher or lower capacitance?

** C-V for forward bias?
I-V Characteristics

Impedance of diode vary with bias point and RF swing level.
**Forward Bias**  (used to approximate reverse bias too)

\[ I = I_S \left( e^{\frac{qV}{nkT}} - 1 \right) \]

- **n**: ideality factor
- **\( I_S \)**: reverse saturation current
- **k**: Boltzmann constant
- **T**: absolute temperature
- **V**: bias voltage

PN junction is everywhere
Review:

• Junction capacitance resulted from reverse bias and vary with voltage
• Breakdown voltage inversely proportional with doping
• Diffusion capacitance resulted from forward bias (hard to measure C-V curve, more later)
• One thing not mentioned is the leakage current through the surrounding edge of diode structure for both forward and reverse bias. It’s a OMIC phenomena.
• Breakdown phenomena is not modeled in:

\[ I = I_S (e^{\frac{qV}{nkT}} - 1) \]
Classic rectifying behavior

linear scale

semilogarithmic scale

\[ 0.43 \frac{a}{kT} \]
Ideality factor:

\[ I = I_S \left( \exp \frac{qV}{NkT} - 1 \right) \]

Then, for sufficient forward bias \((V \gg kT/q)\):

\[ N \approx \frac{q}{KT} \frac{I}{\partial I/\partial V} \]
\[ \frac{I}{I_S} = \exp \left( \frac{qV}{kT} \right) - 1 \]

\[ V = \frac{kT}{q} \log \left( \frac{I}{I_S} \right) \]

For large V

Straight line in logarithm scale for large V
Series Resistance (parasitic component)

- Accounts for Ohmic drop, neglected so far

Current (I) appears in both side of equations

\[ V = I R_s + \frac{kT}{q} \log \left( \frac{I}{I_s} \right) \]

For large V

\[ I = I_s \left[ \exp \left( \frac{q(V - IR_s)}{kT} \right) - 1 \right] \]

- Reduces internal diode voltage \( \rightarrow I \downarrow \)

- Higher \( V_F \) required to deliver desired \( I_F \) \( \rightarrow \) more power dissipation, potential process control problems

- \( RC \) time constant degraded.
If \( \log \left( \frac{I}{I_S} \right) = 6 \), \( I_S = 1.6e-6 \) A, and \( V = 0.71V \)

then what is the value of \( R_s \) at 300\(^\circ\)K?

0.346 OHM
Fabricate PN junction diode in CMOS

*Isolation:*

- Parasitic substrate p-n junction → needs to be reverse biased to avoid turning it on.
- Even reverse biased, substrate contributes parasitic capacitance.
- Additional danger: “bipolar effect” between diode and substrate → minority carriers can be extracted by substrate → current diverted away from main body of diode.
• Hard to make integrated pn diodes in CMOS process (unless they hang directly from the power rail that is connected to the substrate).

• Easier in bipolar since n+ buried layer and collector plug can prevent minority carrier injection.
• pn junctions present in most semiconductor devices (BJTs and MOSFETs).

• pn junction diodes used in rectifying circuits, detectors in communications applications, bias shifters, input protection devices against electrostatic discharge.

• For integrated p-n diodes, no special process steps available.

* pn junction is one kind of diode
"Real" p-n diodes have doping profiles that are highly non-uniform:

In Practical!
Fundamental difference between p-n and Schottky diodes: minority carrier storage slows down p-n diode.

Consider simple voltage switching:

\[ V_j \text{ can not change abruptly, need to get rid of minority carrier} \]

\[ \text{trr is the time required to neutralize minority carrier} \]

\[ \text{The mass of P is more heavier than N} \]

As in Schottky diode, delays associated with \( R_sC_j \).

Additionally, delays associated with minority carrier storage.
Forward-bias

Reverse-bias

It takes time
Generate current spike

Forward bias

Instant switched to reverse bias

Majority electron

Act like voltage source, so the resultant voltage source is $V_f + V_r - (I_f \times R_s)$
Switch off Transient

\[ I(0^-) = I_f(V_f) \quad I(0^+) = -\frac{1}{R_s}(V_f - I_f R_s + V_r) \approx -\frac{V_r}{R_s} \]

Two phases to discharge:

**Phase I** - From \( V_j = V_f - I_f R_s \) to \( V_j \approx 0 \).

Since \( Q \sim \exp \frac{V_f}{I_f} \), as \( Q \) discharges, \( V_f \) cannot change much.

Discharge proceeds nearly at constant current \( I_r(pk) \approx -\frac{V_r}{R_s} \)

Time to discharge (reverse recovery time):

\[ t_{rr} \approx \frac{Q}{|I_r(pk)|} \approx \tau_t \frac{I_f(V_f)R_s}{V_r} \]

**Phase II** - From \( V_j \approx 0 \) to \( V_j = -V_r \).

Charge depletion capacitance \( \rightarrow R_s C_j \) time constant (as in Schottky diode).
\* Switch-on transient

![Diagram of switch-on transient](image)

\[
I(0^-) = -I_s
\]

\[
I(0^+) = \frac{V_f + V_r}{R_s}
\]

- First, \( R_s C_j \)-type charge up of junction capacitance.
- Then, minority carrier charge injection \( \rightarrow \) takes \( \tau_i \).
• *Diffusion capacitance* arises from minority carrier storage.

• $C_d \propto J \propto \exp \frac{qV}{kT} \Rightarrow C_d$ dominates in forward bias, $C_j$ dominates in reverse bias.

• Difficult to implemented integrated diodes in CMOS process: parasitic bipolar transistor.

• Dynamics of p-n diode dominated by minority carrier storage.

• *Reverse recovery time* is time required to eliminate minority carrier stored charge in switch-off transient.
Schottky Diode

- Metal-Semiconductor junction.
- Lower forward turn-on voltage.
- Steeper I-V curve
- Majority-carrier (Electron) device. Not like p-n diode using minority-carrier charge-storage effects.
- Higher cutoff frequency, reproducibility and ease of fabrication.
- Exitaxial and ion-implantation.
- Rectifying or non-rectifying (ohmic-contact)

No minority carrier storage!
$G_x : G_{x1} \parallel G_{x2}$
I-V characteristics

- Based on $I = I_S (e^{\frac{qV}{nkT}} - 1)$

  - $n$: ideality factor
  - $I_S$: reverse saturation current
  - $k$: Boltzmann constant
  - $T$: absolute temperature
  - $V$: bias voltage
  - $GxV$: edge leakage current
  - $IR_S$: voltage drop due to ohmic contact and bulk resistance of semiconductor channel.
  (ohmic contact is a metal-semiconductor contact that has a linear I-V and non-rectifying characteristics.)
C-V characteristics

\[ C_D(V) = \begin{cases} 
\frac{C_{j0}}{(1 - \frac{V}{V_j})^m} & \text{for } V < F_c V_j \\
\frac{C_{j0}}{(1 - \frac{V}{V_j})^{m+1}} \left(1 - \frac{F_c (m + 1)}{C} + \frac{mV}{V_j}\right) & \text{for } V > F_c V_j 
\end{cases} \]

- Semi-empirical equation
- \( m \): grating coefficient
- \( V_j \): built-in potential of the barrier height of junction
- \( C_{j0} \): zero-bias junction capacitance.
- \( F_c \): depletion capacitance coefficient.
- approximated by \( C_D(V) = \frac{C_{j0}}{V} \frac{V}{V_j}^m \)
- \( G_D = \frac{\partial I_D}{\partial V} \)
Diode modeling

- DC I-V measurement

When $I_D R_s << \text{Bias voltage}$ and ignore $I_s$ and $G_x V$ as compared with $I_S e^{qV/nkT}$

Total diode current $I_D$ approximated by $I_D = I_S e^{qV/nkT}$

$$\log(I_D) = \log(I_S) + \log(e^{qV/nkT}) = \frac{qV}{nkT} \log(e) + \log(I_S)$$

By taking the derivation with respect to $V \Rightarrow n = \frac{q \log(e)/kT}{\Delta \log(I)/\Delta V}$
• Is can be calculated from the curve.
• knowing n and Is, Gx can be found by curve fitting at low current region
• At high current region, ignore GxV and Is as compared with $I_s e^{\left[\frac{q(V - I_D R_S)}{nkT}\right]}$

$$I_D = I_S e^{\left[\frac{q(V - I_D R_S)}{nkT}\right]}$$

$$\log(I_D) = \log(I_S) + \frac{q(V - I_D R_S)}{nkT} \log(e)$$

$$= \log(I_S) + \frac{q(V - \Delta V)}{nkT} \log(e)$$

$$\Delta V = I_D R_S$$

For Rs is a weak function of bias voltage V and increase with it
Small signal model

or simplified as

- measure S-parameter at particular bias voltage and curve fitting.
- measure S-parameter at various bias V and curve fitting to find C-V relation data. One can use the C-V data and curve fitting to find C-V semi-empirical equation.
• \( f_T \) : cutoff frequency

\[
f_T = \frac{1}{2\pi R_s C_D}
\]
(bias and RF power dependent)

• Noise: shot noise and thermal noise are two major sources

Shot noise \( <i_s>^2 \) (mean square value)

\[
<i_s>^2 = \frac{2q}{n} (I_D + 2I_s) \Delta f
\]

Thermal noise \( <i_T>^2 \) (mean square value)

\[
<i_T>^2 = \frac{4kT}{R_s} \Delta f
\]

\( \Delta f \) : bandwidth
\( q \) : charge of electron
\( n \) : ideality factor
\( T \) : absolute temperature
\( K \) : Boltzmann constant

• these two noise sources are statistically uncorrelated.
In addition Flicker noise \( <i_f>^2 \)

\[
<i_f>^2 = k_f \frac{I_D^a}{f^b} \Delta f
\]

- A random fashion of generation-recombination effect in the depletion layer.
- Energy concentrated at low frequency.
- \( I_D \): the diode current.
  \( f \): center frequency
  \( \Delta f \): bandwidth
  \( k_f, a, b \): constant

  (device dependent, \( a \) in the range of 0.5-2, and \( b \) is close to 1)

- Flicker noise is in the shunt with shot noise, and is uncorrelated to thermal noise.
• model parameters can be estimated from the measurement of the diode noise.
Schottky diode as level shift

\[ I_D \approx I_S \left( \exp \left( \frac{q V_f}{K T} \right) - 1 \right) \]

\[ V_f = \frac{K T}{q} \ln \left( \frac{I_D}{I_S} \right) \]

\[ V_{D, Drop} = V_f + I_f R_S \]

- Both \( V_f \) and \( R_s \) are function of temperature but temperature coefficient of \( V_f \) dominates.
- Temperature coefficient of \( V_D \) drop typically ranges from -1 to -2 mV/°C
- Low diode forward current have temperature coefficient close to -2 mV/°C
- High diode forward current have temperature coefficient close to -1 mV/°C
Diode

- multiplier
- Detector
- Mixer
- Varactor
- Switch
- Limiter
- Level-Shifting Device

Small signal model