PIN Diodes

Q: *Just how do we **make** switches and voltage controlled attenuators?*

A: Typically, they are constructed with **PIN diodes**.

A PIN diode is simply a *p-n* junction diode that is designed to have a very **small junction capacitance** (0.01 to 0.1 pf).

Sort of the **opposite** of the **varactor** diode!

To see why this is important, recall diode **small signal analysis** from your first electronics course.

In small signal analysis, the **total** diode voltage consists of a D.C. bias voltage (V_0) and a small, time-varying signal (v_d):

$$v_D(t) = V_0 + v_d(t)$$

For radio engineering applications, the small signal is a **microwave** signal !!! I.E.,:

$$v_D(t) = V_0 + v_{RF}(t)$$

Thus, we know that the **diode current** i_D is:

$$i_D = I_s\left(\exp\left[\frac{V_0 + v_{RF}(t)}{nV_T}\right] - 1\right)$$

Since v_{RF} is very **small**, we can **approximate** this diode current $i_D(v_D)$ using a **Taylor Series** expansion around $v_D = V_0$:

$$\begin{aligned} i_D(v_D) &\approx i_D(v_D)\Big|_{v_D=V_0} + \frac{\partial i_D(v_D)}{\partial v_D}\Bigg|_{v_D=V_0} v_{RF}(t) \\ &= I_S\left(e^{V_0/nV_T} - 1\right) + \frac{I_S\, e^{V_0/nV_T}}{nV_T} v_{RF}(t) \end{aligned}$$

We recognize that:

$$I_S\left(e^{V_0/nV_T} - 1\right) = \text{D.C. Bias Current} \doteq \text{I}_0$$

and thus we can write our **small-signal approximation** as:

$$\begin{aligned} i_D &= I_0 + \frac{(I_0 + I_s)}{nV_T} v_{RF}(t) \\ &= I_0 + \frac{v_{RF}(t)}{r_d} \end{aligned}$$

where we have defined the diode **small-signal resistance** r_d as:

$$r_d = \frac{nV_T}{I_0 + I_s}$$

The diode small-signal resistance is also **often** referred to as the **junction** resistance R_j or the **series** resistance R_s.

We can further conclude that the total diode current i_D is the sum of the D.C. bias current I_0, and the **small-signal current** $i_{RF}(t)$, where:

$$i_{RF}(t) = \frac{v_{RF}(t)}{r_d}$$

Just like **Ohm's Law** !

To a small (i.e., low power) microwave signal, a diode "looks" like a **resistor**.

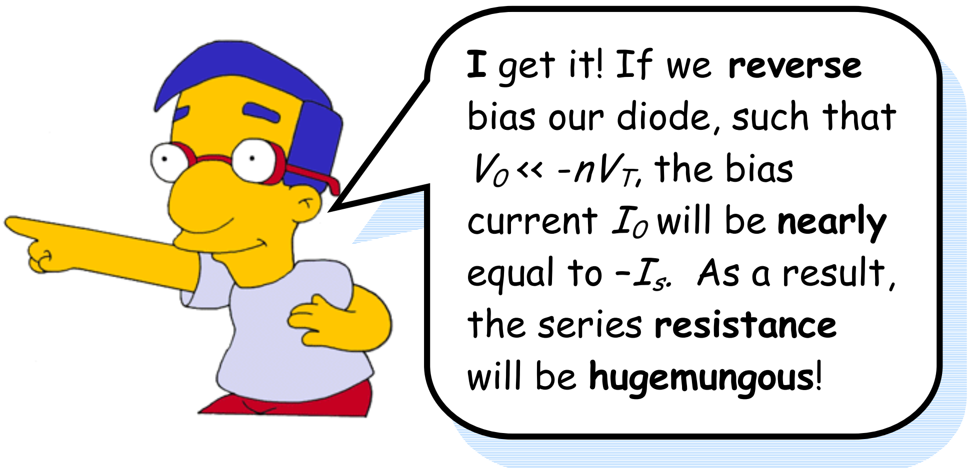
Moreover, we can **control** and **modify** the resistance of the diode by **changing** the D.C. **bias**.

Sort of a **voltage-controlled** resistor!

For example, if we put the diode into **forward** bias ($V_0 >> nV_T$), the bias current I_0 will be positive and **big**, thus the junction resistance will be very **small** (e.g., r_d = a few ohms).

A **forward** biased diode is very nearly a microwave **short circuit**!

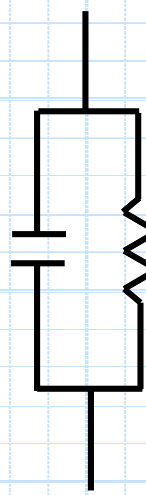
$$r_d = \frac{nV_T}{I_0 + I_s}$$



Not so fast! The small-signal **resistance** of a **reverse** biased diode is in fact **very large**. BUT, we must also consider the junction **capacitance** C_j!

Recall that in **reverse** bias, the junction capacitance of a diode can be **significant**, and in fact generally **increases** as the bias voltage becomes more negative!

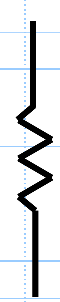
As a result, a good microwave circuit **model** of a diode includes both the series resistance and junction capacitance:



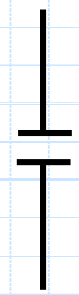
$$Z_D = \frac{r_d}{1 + j\omega\, r_d C_j}$$

For **forward** bias, where r_d is **very small**, we find that diode impedance Z_D is approximately equal to this **small** series **resistance** ($Z_D \approx r_d$)—a **short** circuit (approximately):

$$Z_D^{fb} \approx r_d$$



For reverse bias, where r_d is **very large**, we find that diode impedance Z_D is approximately equal to that of the junction **capacitance** C_j:



$$Z_D^{rb} = \frac{1}{j\omega C_j}$$

For low-frequencies (e.g., kHz), this impedance will be typically be **very** large and thus the diode can be approximate as an **open** circuit.

However, at microwave frequencies (where ω is very large) the reverse bias impedance Z_D^{rb} may **not** be particularly large, and thus the reverse biased diode **cannot** be considered an open circuit.

In order for the impedance $Z_D^{rb} = 1/j\omega C_j$ to be very **large** at **microwave** frequencies, the junction capacitance C_j must be **very**, **very** small.

That's **exactly** why! A PIN diode is approximately a (bias) **voltage controlled resistor** at microwave frequencies. We can select any value of r_d from a **short** to an **open**.

As a result, we can make **many** interesting devices!