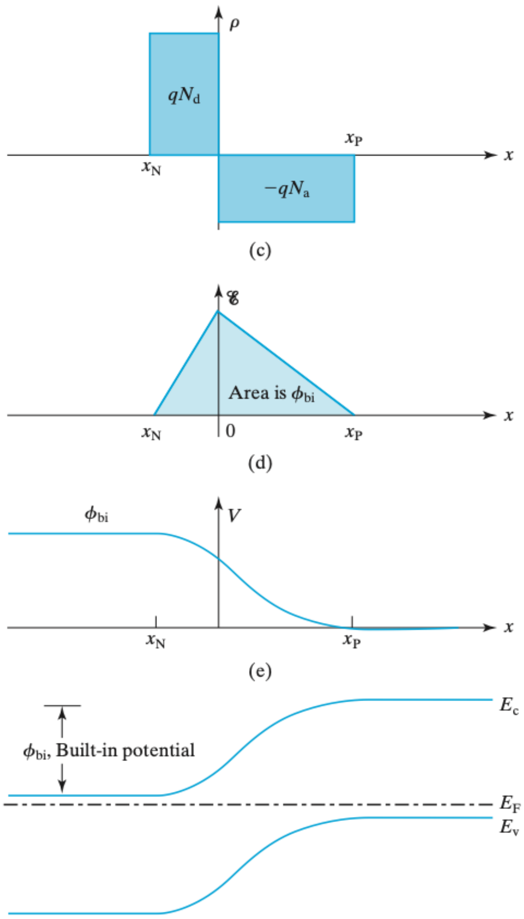
MODULE II: AC-MEASUREMENT: Non-Linear Component: Small Signal Model: CV Measurement

Again, at this point, I am hoping that you are all familiar with using the oscilloscope function of AD2 and using the dynamic response to measure capacitance and inductance. This write-up is a nice segue to the next module, MODULE III: Nonlinear Components. So far, we have been using passive linear components such as resistors, capacitors, and inductors. As linear components, we can easily calculate these components in series and in parallel. With these, we can do some simple signal processing such as frequency filtering, etc…. But, with nonlinear components, we can do more interesting things. With a diode, we can control the direction and with certain diodes (such as tunneling diodes), we can amplify signals. Before, we get started in how we apply these nonlinear components, let's look at the physics of a semiconductor diode and what information we can garner from a CV measurement.

First, we will look at the *pn* junction Diode. A *pn* junction diode refers to a diode made from an *n*-type and *p*-type semiconductor. If the semiconductor is the same, we refer it as homojunction and if they are different (i.e., AlGaAs/GaAs), as heterojunction. Let's keep it simple by assuming a homojunction and that the doping levels in the *n*-type and *p*-type are constant. For such conditions, we call the junction as abrupt, and the following is an abrupt junction model of a *pn* diode. We also assume that far from the junction, an equilibrium conditions hold. Some definitions. In a *n*-type semiconductor, electrons are the majority carrier and the holes are minority carriers, and vice-versa for a *p*-type semiconductor, holes as majority and electrons as minority. Charge carriers by definition are free to move depending on the potential. Dopant atoms are fixed in space. When a dopant atom is activated, a donor atom contributes an electron carrier and an acceptor atom a hole carrier, and the dopant atoms are ionized (i.e., N_d^+ and N_A^-). Now, when the *n*-type and *p*-type are physically contacted, the chemical potential (Fermi energy) are aligned across the junction.



As a consequence, in a *pn* junction, we now have three areas. Far from junction, which equilibrium conditions hold as well as a depletion layer at the junction where free carriers are absent. The free carriers are swept away from the junction as a built-in potential ϕ_{bi} is formed across the junction between any dissimilar materials, here *n*-type and *p*-type semiconductors. Then at the junction, we are left with ionized dopant atoms, N_d^+ in the *n*-type side, and N_A^- in the *p*-type side. Again, the ionized dopant atoms are fixed in space in the crystalline lattice of the semiconductor. Then, we can apply the Gauss's Law to ascertain the electric field near the junction, $\mathcal{E}(x)$. Furthermore, application of Poisson's equation allows us to calculate the built-in potential ϕ_{bi}, and with some math, we can approximate the depletion zone widths in the *n*-type and *p*-type side to get the total widths. Now, reverse biasing the junction (V_r), we will drive more carriers away near the junction and the depletion width across the junction with vary as $\sqrt{V_r}$.

Looking at the depletion zone, it should look very much like a parallel-plate capacitor, so that $C = A\frac{\epsilon_s}{W}$, where A is the area of the junction, ϵ_s is the dielectric constant of the semiconductor, and W is the width of the semiconductor. Now, with the width of the depletion zone dependent on the reverse bias V_r, we are left with the following,

$$\frac{1}{C^2} = \frac{2(\phi_{bi} + V_r)}{qN\epsilon_s A^2}$$

where $\frac{1}{N} = \frac{1}{N_d} + \frac{1}{N_a}$. So, if we plot the measured capacitance inverse squared as function of the reverse bias, we can ascertain some very useful information about the underlying semiconductor.

Now, we need to analyze the situation and measure the capacitance of the *pn* junction diode. Here, the situation is a lot complicated than a capacitor. We have a nonlinear device as well as a DC bias that is applied across the diode. In electrical engineering, nonlinear components are modeled as linear components for particular conditions, small signal model. Then, for our purposes, we need a small signal model for a *pn* junction in reverse bias.

Because of the relative large DC reverse bias, we want to take some care. In the Waveform program, you might have noticed an option to AC-couple the probes. You might want to take some time to understand what this function does. In the same vein, you will want to bias the diode through a high resistance or large inductance to prevent your ac signal from flowing into the DC source (as AD2 input impedances are not great) as well as using a coupling capacitor to prevent DC current into the function generator. A small resistance in series with the diode can be used to sense the ac signal through the diode. Similar to measuring resistance, use two channels to measure the voltage across the diode as well as the resistor. Then, the phase of current and voltage across the diode can be measured by plotting the Lissajous ellipse.