Excerpt Edition

This PDF is an excerpt from Chapter 7
of the Parametric Measurement Handbook.

The
Parametric Measurement Handbook

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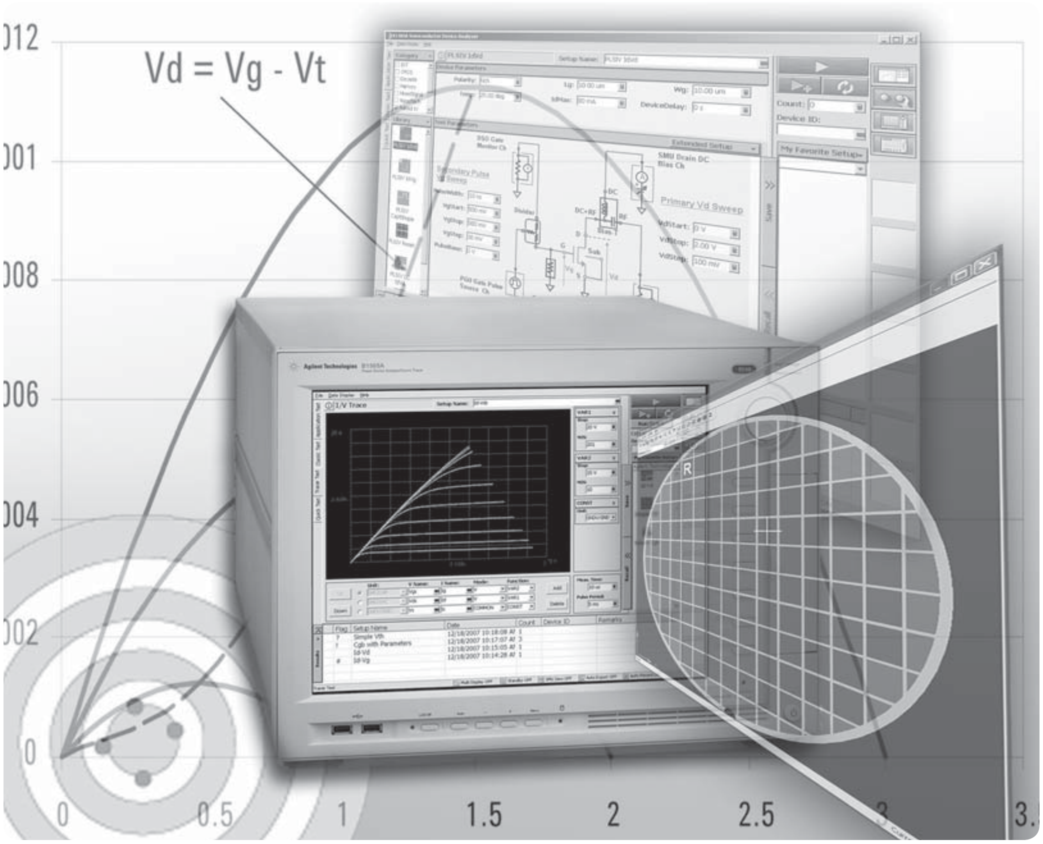

Agilent Technologies

Chapter 7: Diode and Transistor Measurement

"Choose a job you love, and you will never have to work a day in your life"
— Confucius

Introduction

It is not the intent of this handbook to teach a course on semiconductor device physics as there are already an abundance of excellent textbooks available on this subject. However, it is difficult to discuss making parametric diode and transistor measurements without first spending a little time understanding their operation. Therefore, we will give a brief review of pn junctions, diodes, and MOS and bipolar transistor operation with an emphasis on how we characterize them in parametric test as opposed to detailed theoretical derivations.

PN junctions and diodes

Review of PN diode operation

Intrinsic semiconductor materials (such as silicon) do not have an abundance of either electrons or electron holes. However, silicon can be doped with other materials such that it becomes either n-type (possessing excess electrons) or p-type (possessing excess electron holes). When considered individually these materials are not particularly interesting. However, consider the case shown below when these two materials are brought into close contact.

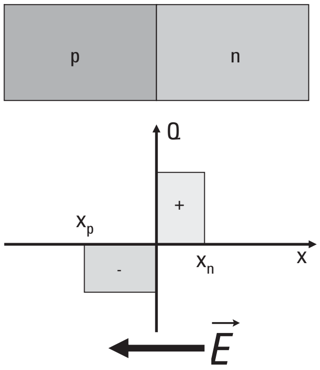

Figure 7.1. The cross section of a pn junction assuming an abrupt change from p-doped to n-doped material. The graph shows the fixed charge remaining after the mobile carrier diffusion has stabilized.

Assuming the extremely idealized case of an abrupt junction (i.e. one that instantaneously transitions from p to n material) as shown in Figure 7.1, we can see that something very interesting happens. The force of diffusion causes holes from the p-type material to flow into the n-type material (leaving behind fixed negative charge), and similarly the force of diffusion causes electrons from the n-type material to flow into the p-type material (leaving behind fixed positive charge). This diffusion process will continue until the electric field created by the fixed charge in what is normally called the space-charge region becomes strong enough to exactly balance the diffusion tendencies of the mobile carriers.

The one-dimensional (x-axis) equations defining current flow in semiconductor are shown below.

$$J_n = q\mu_n \mathrm{E}_x + qD_n \frac{dn}{dx} \qquad \textit{(Equation 7.1)}$$

$$J_p = q\,\mu_p \mathrm{E}_x - qD_p \frac{dp}{dx} \qquad \textit{(Equation 7.2)}$$

Where J is the current density of electrons (n) and holes (p)
q is the electron charge
E_x is the electric field in the x-dimension
μ is the mobility of electrons (n) and holes (p)
D is the diffusion constant for electrons (n) and holes (p)
n is the electron density
p is the hole density

These equations basically state what was alluded to in the previous discussion of an abrupt pn junction. Namely, current flow in a semiconductor consists of two parts: a drift current proportional to the applied electric field and a diffusion current proportional to the spatial first derivative of the mobile carrier density. In addition to the above current flow equations we also have the Einstein relationship which relates the ratios of the mobility and diffusions constants as shown below.

$$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = \frac{kT}{q} \qquad \textit{(Equation 7.3)}$$

Where q is the magnitude of the electron charge (1.602×10^{-19} Coulomb)
k is Boltzmann's constant (1.38×10^{-23} J/K)
T is the absolute temperature [deg K]

The general form of Poisson's equation relates the second derivative of the electric potential to the total space charge density (ρ). Since we know that in a semiconductor this has to be related to the densities of mobile and fixed charge, we can write this as follows.

$$\frac{d^2\varphi}{dx^2} = -\frac{q}{\varepsilon_{Si}}(p - n + N_d - N_a) \qquad \textit{(Equation 7.4)}$$

Where Nd is the donor density concentration
Na is the acceptor density concentration
ε_{Si} is the permittivity of silicon

In the case of the abrupt junction shown in Figure 7.1 we make what is known as the depletion approximation, which assumes that the semiconductor is divided into distinct regions which are either completely neutral or completely depleted of mobile carriers. Therefore, in the depletion region we can write the above equation as follows.

$$\frac{d^2\varphi}{dx^2} = -\frac{q}{\varepsilon_{Si}}(N_d - N_a) \qquad \textit{(Equation 7.5)}$$

Using the depletion approximation we can integrate the above equation to get the electric field in both the p and n regions as shown below.

$$E_x(x) = -\frac{qN_a}{\varepsilon_{Si}}(x + x_p) \qquad -x_p \le x \le 0 \qquad \text{(Equation 7.6)}$$

$$E_x(x) = -\frac{qN_d}{\varepsilon_{Si}}(x_n - x) \qquad 0 \le x \le x_n \qquad \text{(Equation 7.7)}$$

Where x_p is the width of the space charge in the p region (see Figure 7.1)
x_n is the width of the space charge in the n region (see Figure 7.1)

Graphically, these equations have the appearance shown below.

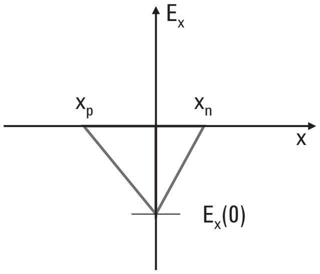

Figure 7.2. The electric field in an abrupt pn junction under the depletion approximation assumption.

We know that the electric field has to be continuous at x = 0.

$$E_x(0) = -\frac{qN_d x_n}{\varepsilon_{Si}} = -\frac{qN_a x_p}{\varepsilon_{Si}} \qquad \text{(Equation 7.8)}$$

This gives us the result shown below.

$$N_d x_n = N_a x_p \qquad \text{(Equation 7.9)}$$

Equation 7.9 shows an important characteristic of pn junctions: the width of the depletion region varies inversely with the magnitude of the dopant concentration. In other words, higher dopant concentrations result in narrower space charge regions.

When no voltage is applied to the pn junction a barrier exists to current flow and the diode acts as an open circuit. The derivation of the current flow equations are involved and beyond the scope of this text. However, it should be somewhat intuitive that as we apply a positive voltage (i.e. electric field) to the p-region we are acting to reduce the built-in electric field of the pn junction. At some point the electric field is reduced enough to allow current to flow through the pn junction.

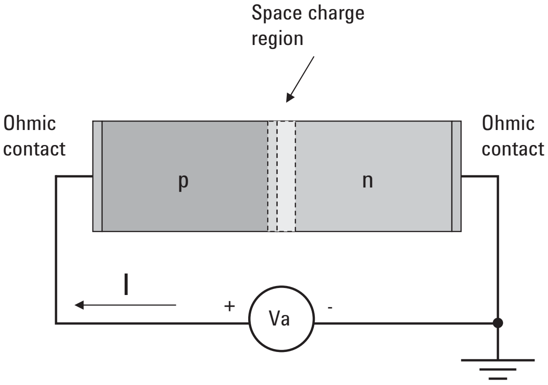

Figure 7.3. The behavior of a pn junction under positive applied bias.

Therefore, without any detailed derivations we will ask the reader to take it on faith that the current flow through a pn diode exhibits exponential dependence upon applied voltage (Va) and is given by the equation shown below.

$$I = I_o\left(e^{\left(qV_a/kT\right)} - 1\right) \qquad \textit{(Equation 7.10)}$$

This is sometimes called the ideal diode equation. It predicts a saturation current of $-I_o$ for negative values of Va and an exponentially rising current for positive values of Va. To emphasize that a diode only conducts current in one direction, it has the circuit symbol shown below.

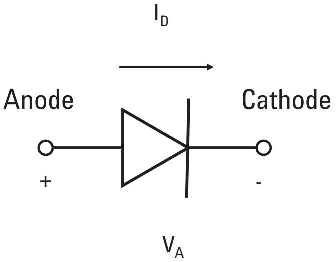

Figure 7.4. The circuit symbol for a diode.

The p-doped region is denoted as the anode, and the n-doped region is denoted as the cathode. Note: In actuality diodes can conduct current in both directions. However, typically much larger voltages need to be applied to the cathode (relative to the anode) in order for current flow to occur in the reverse direction. In this condition the diode is said to "breakdown", which is a logical term for this phenomenon since it is an aberration from normal diode behavior. The physics of semiconductor junction breakdown will not be discussed in this handbook, but later some practical measurement examples will be explored.

The "Ohmic contacts" shown at the ends of the diode in Figure 7.3 simply mean that the semiconductor material is heavily doped enough such that the metal to semiconductor contact does not present any sort of barrier to the flow of current. If the semiconductor material is lightly doped the metal to semiconductor contact can actually behave as another form of diode known as a Schottky barrier diode. Current flow in a Schottky barrier diode has a dependence on applied voltage as shown below.

$$I = I'_o \left(e^{\left(qV_a / nkT \right)} - 1 \right) \quad \textit{(Equation 7.11)}$$

In Equation 7.11 "n" is a constant usually ranging from between 1.02 and 1.15. The prime symbol is present on I_o to emphasize that this constant is different in value from that for the case of a pn junction. Schottky diodes typically have an effective "turn-on" voltage that is several hundred millivolts less than that of a pn junction diode, which makes them essential in the design of bipolar logic circuits since they can keep the base to collector junction from forward biasing and therefore keep the transistor out of saturation.

One important point to note about pn junctions is that they behave as voltage-dependent parallel plate capacitors, since as we apply external voltages we modify the charges in and around the space-charge region. Therefore, junction capacitance is one important parameter that must be characterized for all semiconductor devices, since this impacts the speed at which the devices will switch when used in an integrated circuit. However, since capacitance measurement is much more challenging to perform correctly than simple current and voltage (IV) measurements, we will defer a detailed discussion of semiconductor capacitance measurement to Chapter 8.

Basic diode characterization

Diodes are relatively simple devices to characterize. From Equation 7.10 we can see that a plot of the log of the diode current (Id) should be linear with respect to applied voltage. A plot of diode current and the log of the diode current for a "typical" diode are shown below.

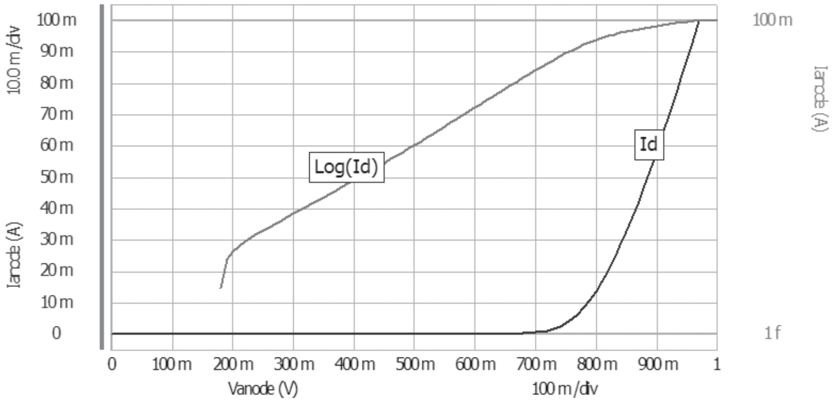

Figure 7.5. A pn diode sweep in the forward direction plotting both Id and Log(Id).

Of course, another important parameter is the reverse breakdown characteristics of the pn diode. A plot of this is shown below.

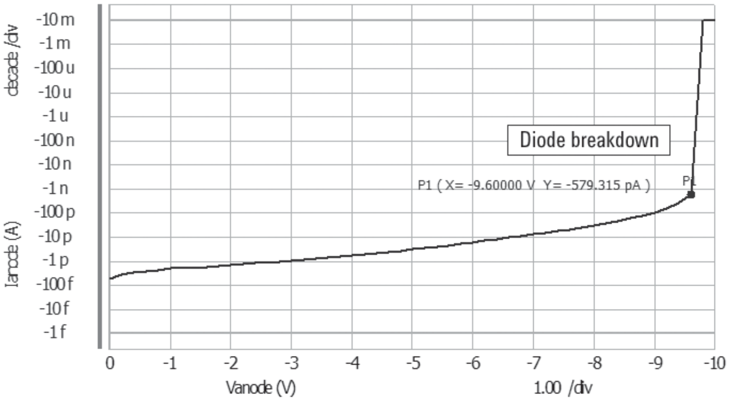

Figure 7.6. The reverse breakdown characteristics of a diode.

Using various processing techniques it is possible to control the reverse breakdown characteristics of certain classes of diodes very precisely. Diodes with these sorts of precisely controlled breakdown characteristics are known as zener diode. This has some obvious beneficial uses in circuit design, since it permits the zener diodes to be used as voltage clamps within the circuit.

To Get Complete Handbook

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