

EE 462: Laboratory # 5  
Dynamic Effects in P-N Junctions

by  
Dr. A.V. Radun  
Dr. K.D. Donohue (9/27/03)  
Department of Electrical and Computer Engineering  
University of Kentucky  
Lexington, KY 40506

Laboratory # 5      Pre-lab due at lab sessions October 7, 8, and 9  
Lab due at lab sessions October 14, 15, and 16

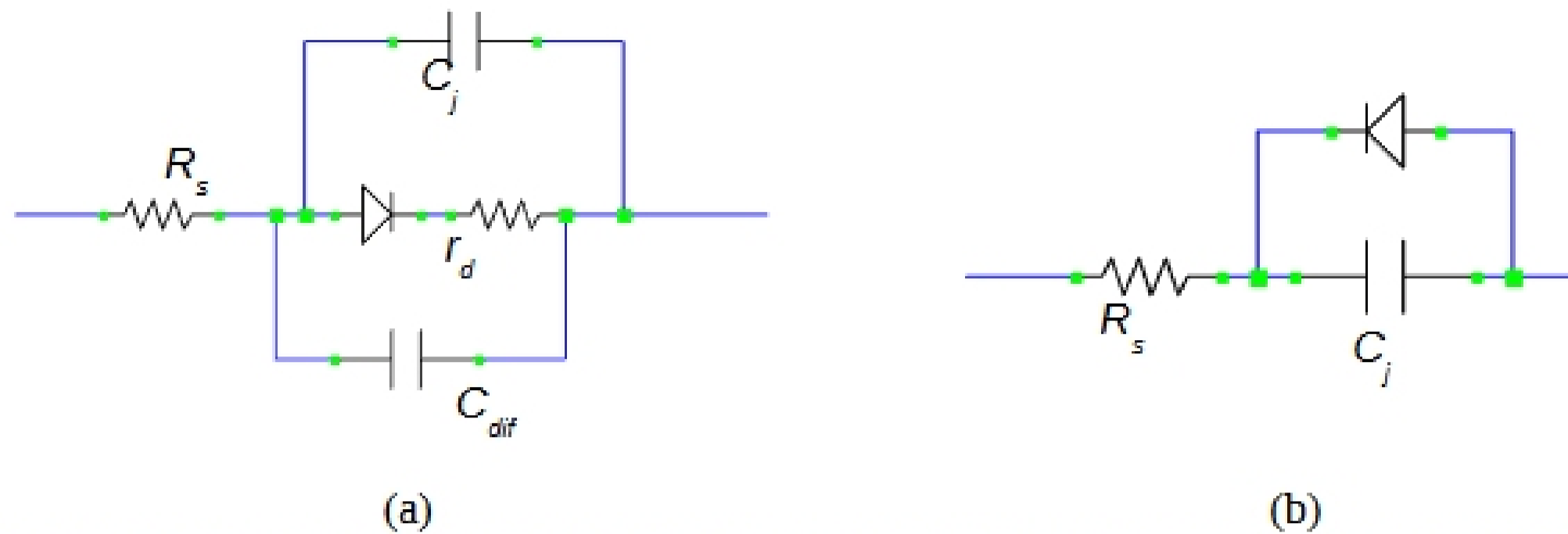
### I. Instructional Objectives

- Perform an AC incremental analysis of a P-N junction over a range of reverse bias voltages.
- Measure the reverse bias junction capacitance.
- Measure the reverse recovery of a diode.

See Horenstein chapter 3.3

### II. Background

The I-V curves completely characterize diode behavior when the dynamic effects of its junction are not considered. Behavior is constant, independent of frequency. However for high frequency or for large scale switching behavior, the two charge storage mechanisms in real diodes can create a significant dynamic behavior. The charge storage mechanisms occur at the depletion region of the P-N junction and in the neutral regions adjacent to the depletion region. These storage phenomena are modeled as capacitors as shown in Fig. 1. The capacitance at the P-N junction depletion region in reverse bias mode is referred to as *depletion capacitance* or *junction capacitance*, which is in parallel with the open circuit ideal diode. The effective circuit in reverse bias mode is shown in Fig. 1b. Recall that capacitance relates an increase in voltage to the charged stored ( $Q = C \Delta V$ ). In the forward bias mode both charge storage mechanisms have an effect and are modeled with capacitances shown in Fig 1a. However, the junction capacitance is not significant when the diode is forward biased. One reason for its minimal effect is that the voltage across the diode's junction capacitance is essentially constant (0.7V) and very little current flows into the junction capacitance. In addition, the current through the junction capacitance is much smaller than the forward current and typically can be neglected. On the other hand, junction capacitance can have a significant effect when the diode is reversed biased for two reasons. First, the reverse diode voltage is generally not constant. Second, the reverse leakage current through a diode is very small and thus the current through the junction capacitance can be much larger than the reverse leakage current.



**Fig. 1.** (a) Forward bias diode model (b) Reverse bias diode model with junction capacitance  $C_j$ , diffusion capacitance  $C_{dif}$ , bulk material resistance  $R_s$ , and dynamic resistance  $r_d$ .

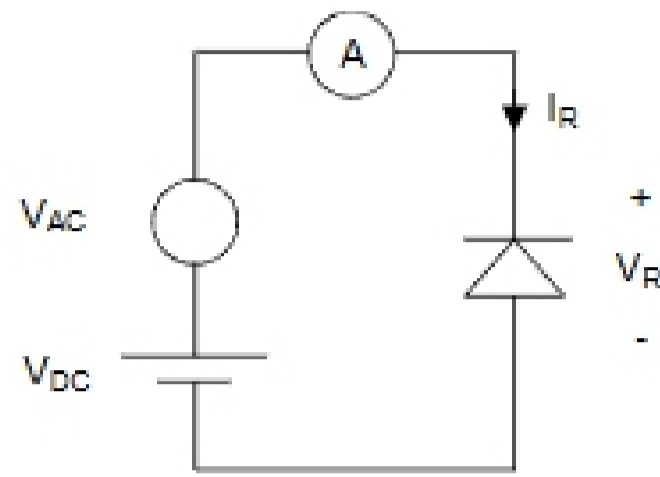
The capacitance of a P-N junction is not a constant, but depends on the reverse bias voltage on the junction, which changes the size of the depletion region. As a result, the growing or shrinking depletion region changes the charge separations distance (unlike a conventional capacitor with a constant distance between charges). Thus, the capacitance of a P-N junction is a function of the P-N junction's reverse voltage. The capacitance decreases as the reverse voltage increases (distance between the charge increases  $C = \epsilon \cdot A / d$ ). The junction capacitance of a reversed biased junction is modeled by:

$$C_j(V_R) = \frac{C_{j0}}{\left[1 + \frac{V_R}{V_J}\right]^m} \quad (1)$$

where  $V_R$  is the reverse bias voltage,  $V_J$  is the junction potential,  $m$  is the grading coefficient, and  $C_{j0}$  is the zero biased junction capacitance. Three constants ( $C_{j0}$ ,  $V_J$ , and  $m$ ) must be specified to determine the relationship between  $V_R$  and  $C_j$ . The constant  $C_{j0}$  has units of Farads, and is referred to as the zero-bias ( $V_R = 0V$ ) junction capacitance. The junction potential  $V_J$  has the units of Volts and is sometimes called the built-in potential. The junction potential's value is about 0.7V for silicon (Si) junctions. For Si diodes  $V_J$  changes slightly from 0.7V depending on the doping levels on both sides of the junction, while  $V_J$  changes significantly from one semiconductor material to another. The grading coefficient  $m$  is unitless and its value depends on the nature of the P-N junction. If the P region changes abruptly (a step change) to the N region at the junction, then  $m = \sqrt{0.5}$  and the junction is called an abrupt P-N junction. If the P region changes linearly into the N region (graded junction), then  $m = \sqrt[3]{.333}$ . High voltage power diodes often go from P to intrinsic semiconductor to N semiconductor (PIN diode). This results in  $m = 0$ , which implies a constant capacitance. The parameter  $m$  is found by plotting the log of the capacitance versus the log of the voltage ( $m$  is the slope of this curve for voltages  $\gg V_J$ ).

The circuit in Fig. 2 can be used to measure the junction capacitance of a diode (P-N junction) as a function of its reverse bias voltage. The diode is reverse biased by the DC source, and the reverse bias voltage is varied by a relatively small sinusoidal AC signal. The DC voltage is called the bias voltage while the AC voltage is called the incremental voltage. With a known AC

voltage amplitude and frequency, the diode's reverse current is measured to determine the junction capacitance at the DC value of reverse voltage.



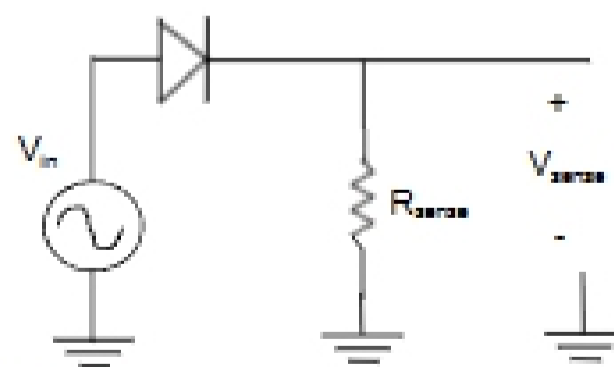
**Fig. 2.** Elements to measure junction capacitance.

The second charge storage mechanism at a P-N junction is charge stored in the neutral regions adjacent to the junction. The amount of charge stored is proportional to the forward current and the proportionality constant is called the transit time and has the units of seconds.

$$Q = \tau_T \cdot I_f = \tau_T \cdot I_s \left[ e^{\frac{qV_f}{nkT}} - 1 \right] \quad (2)$$

where  $\tau_T$  is the transit time, which typically varies from 10 $\mu$ s to about 10ns depending on junction processing, and  $I_f$  is the forward bias current. In the second part of Eq. 2,  $I_f$  is substituted out with the Shockley Equation, where  $I_s$  is the saturation current (on the order of 10<sup>-14</sup> A for small signal diodes at 300K),  $q$  is the charge on an electron (1.6x10<sup>-19</sup>C),  $T$  is the junction temperature in kelvins,  $k$  is Boltzmann's constant (1.38x10<sup>-23</sup> J/K),  $n$  is a the emission coefficient (typically between 1 and 2), and  $V_f$  is the voltage drop over the diode. This charge storage mechanism is very nonlinear leading to a very nonlinear capacitance. The stored charge is significant for forward bias and nearly zero for reverse bias. This charge storage affects the diode's turn-off properties, delaying its turn-off time. The turn-off delay is called reverse recovery and the delay time is called the reverse recovery time.

The reverse recovery time is close in value to the transit time, but not exactly equal to it. The reverse recovery time depends on the transit time and the circuitry connecting the diode. The basic diode rectifier circuit shown in Fig. 3 can be used to study diode reverse recovery. The resistor  $R_{sense}$  performs 2 functions; it is the load for the circuit in forward bias mode and is a resistor used to sense the current in the diode.



**Fig. 3.** Test circuit to measure reverse recovery time.