Modified supporting material for “Minority carrier lifetime in a semiconductor photodiode”

Siddharth Tallur, Sept 17th 2017
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Aim of the experiment: Basic experiment to characterize AC response of a photodiode

Motivation: So far we have looked at DC characteristics (i.e. how the device behaves when subjected to DC excitation in form of light or voltage) of some basic semiconductor diodes (we looked at LEDS, solar cells in detail). In any practical application, the AC response of a semiconductor device is also important, as most phenomena of interest that you would want to measure will be time-varying in nature. By now you have learnt enough calculus to know that when differential equations in time are involved, the systems behave differently at DC and AC frequencies. The measurement techniques you learnt in previous labs will not directly be applicable for an AC analysis. This lab will focus on doing a basic experiment to understand how to do AC analysis. (This is also sometimes referred to as “transient analysis”).

Intuitive understanding (Theory): Consider the simple circuit shown in Fig. 1. You have analyzed such a circuit for DC source V_s in both forward biased and reverse biased conditions. If V_s is an AC signal on the other hand, the diode will switch from forward bias to reverse bias and so on with every successive half-cycle of the AC signal. The purpose of this handout is to understand what happens when the switching from one bias condition to the other occurs. For e.g. if V_s is a square wave, how will the diode behave at falling and rising edges of the square wave? Once you have understood this, you are qualified to analyze the steady state (DC) and transient (AC) response.

(Note: In AC response, one also discusses the concept of ‘bandwidth’, which this experiment will not cover. You will learn more about bandwidth in AC analysis in analog circuits lab in following semester)

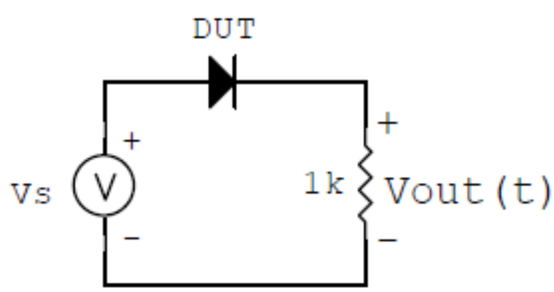

Figure 1. Simple diode-resistor circuit. Voltage drop across the resistor gives a measure of the diode current ($I = V_{out}/R$; $R=1k\Omega$)

By now you have figured out that when a diode is forward biased, the barrier height in the energy band diagram is reduced and minority carriers are injected which increases their concentration (electrons in P region and holes in N region). Thus in forward bias, the diode conducts a large current. In reverse bias condition, the current in the diode is very small, and due to diffusion of minority carriers from neutral region into depletion region (the direction and hence sign of the current is opposite to forward bias condition). This is pretty much independent of the negative bias voltage value (except when the diode breaks down if a very large reverse bias voltage is applied).

Suppose in Fig. 1 we apply a square wave to the diode of a voltage level large enough (compared to knee voltage) to push the diode into conduction. In forward bias (i.e. positive half cycle of the square wave), the current across the diode is large, and we will measure a large voltage drop across the resistor (same current flows through diode and resistor – the resistor is just used as a 'probe'). Let us analyze what happens when we switch from positive half cycle to negative half cycle, using Fig. 2.

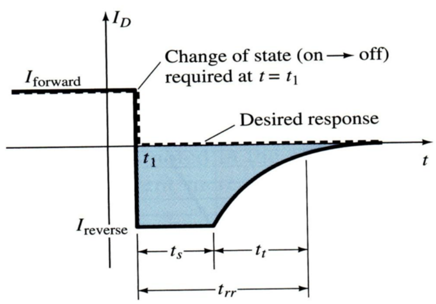

Figure 2. Illustration of diode transient response

When the square wave switches from positive half cycle to negative half cycle, you would expect that the current should instantaneously drop down to the reverse saturation current value as shown in dotted line in Fig. 2. However, realize that the current is carried by electrons, and electrons cannot instantaneously disappear or appear when you change the voltage (you would violate all known conservation laws in physics if that happened!)

In reverse bias, the current is on account of minority carrier diffusion. In all the experiments you have performed so far, the concentration of minority carriers in p (N_{p0}) and n regions was dependent on intrinsic carrier concentration (n_i) and the doping density (N_d) $\left(N_{p0} = {n_i^2}/{N_d}\right)$. However, in case of Fig 2, there is an "extra" concentration of minority carriers at the edge of the depletion region due to injection of minority carriers during positive half cycle $\left(N_p = N_{p0}e^{qV/kT}\right)$. These extra minority carriers start diffusing into the depletion region giving a much larger (in magnitude) reverse bias current as compared to the reverse saturation current as shown in Fig. 2. The entire time taken for the current to reach reverse saturation current level is called reverse recovery time (t_{rr}).

This reverse recovery time is comprised of 2 components. The first component, stored delay time (t_s) is the time during which current flowing through the diode corresponds to removal of injected carriers from the bulk, and the second component, recombination time (t_r, wrongly labeled as t_t in Fig. 2) is the time during which the minority carriers at depletion region edge diffuse into the depletion region and recombine. For more details, refer to slides 1-6 of handout here: http://www-inst.eecs.berkeley.edu/~ee130/sp03/lecture/lecture14. The formula for ts as derived in that handout is $t_s = \tau_n ln\left(1 + \frac{I_{forward}}{I_{reverse}}\right)$, where τ_n is minority carrier lifetime for electrons. Thus by measuring t_s, we can measure the carrier lifetime.

As you can imagine, the t_s is a limitation when designing an AC circuit. This can be reduced by reducing the carrier lifetime by adding impurity atoms of materials such as gold or iron intentionally when manufacturing the device, or by using Schottky diodes, that have poor carrier injection.

Note: When calculating $I_{forward}$ and $I_{reverse}$ for your calculation, be aware of the built-in voltage in the diode, assumed to be 0.6V. Thus, the formulae for these currents will be:

$$I_{forward} = \frac{V - 0.6}{R}$$

$$I_{reverse} = -\frac{V + 0.6}{R}$$

Question: t_s can be reduced by adding impurity atoms. Do you think this is required for square waves of all frequencies? What happens when the square wave frequency is small i.e. large period? What happens when the frequency is very large? Perform some intuitive analysis as explained in theory section above and arrive at the answer.

Remember: Equations will only teach you how to design circuits; they won't teach you how the device works. For that you need good intuition.