LAB VII. TRANSIENT SIGNALS OF PN DIODES

1. OBJECTIVE

In this lab, you will study the transient effects in a $p$-$n$ junction diode due to a sudden change in current. Specifically, you will study the turn-on, turn-off, and reverse-recovery transient behaviors of a $p$-$n$ junction diode. One of the interesting phenomena of the reverse-recovery transient behavior is the "charge storage" delay that allows large reverse-bias currents to flow through a diode for short periods of time, which is an important figure of merit in switching applications.

2. OVERVIEW

For small signals, we assume that the stored charge density in the $n$-side and $p$-side regions of our diode do not change significantly, i.e. we assume that the diode is very close to steady-state. However, this is not the case when larger voltages are applied. In this lab, we will vary the magnitudes of the applied voltages from small to large and observe the resulting transient behavior of the diodes. Next we will use charge control analysis to make a first order approximation of the current and voltage values of the diode as a function of time. From these analyses we can begin to understand the transient behavior, and thus the switching processes, of a $p$-$n$ junction diode.

Information essential to your understanding of this lab:
1. Carrier injection and storage (Streetman section 5.3.2)
2. Transient and AC conditions (Streetman sections 5.5.1-5.5.3)

Materials necessary for this Experiment:
1. You must bring your own "USB" FLASH MEMORY.
2. Standard testing station
3. One rectifier diode (Part: 1N4002)
4. 10 Ω, 2W resistor
3. BACKGROUND INFORMATION

3.1 CHART OF SYMBOLS

Here is a chart of symbols used in this lab manual. This list is not all inclusive; however, it does contain the most common symbols and their units used in this Lab.

Table 1. Chart of the symbols used in this lab.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Symbol Name</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>h⁺</td>
<td>hole</td>
<td>Positive charge particle</td>
</tr>
<tr>
<td>e⁻</td>
<td>electron</td>
<td>Negative charge particle</td>
</tr>
<tr>
<td>q</td>
<td>magnitude of electronic charge</td>
<td>1.6 x 10⁻¹⁹ C</td>
</tr>
<tr>
<td>p</td>
<td>Hole concentration</td>
<td>(number h⁺ / cm³)</td>
</tr>
<tr>
<td>n</td>
<td>electron concentration</td>
<td>(number e⁻ / cm³)</td>
</tr>
<tr>
<td>ni</td>
<td>intrinsic carrier concentration</td>
<td>(number / cm³)</td>
</tr>
<tr>
<td>Δp</td>
<td>hole concentration at depletion edge</td>
<td>(number h⁺ / cm³)</td>
</tr>
<tr>
<td>Δn</td>
<td>electron concentration at depletion edge</td>
<td>(number e⁻ / cm³)</td>
</tr>
<tr>
<td>kb</td>
<td>Boltzmann’s constant</td>
<td>1.38 x 10⁻²³ joules / K</td>
</tr>
<tr>
<td>T</td>
<td>Temperature</td>
<td>K</td>
</tr>
<tr>
<td>Eg</td>
<td>energy gap of semiconductor</td>
<td>eV</td>
</tr>
<tr>
<td>A</td>
<td>junction area</td>
<td>cm²</td>
</tr>
<tr>
<td>τg</td>
<td>general carrier lifetime</td>
<td>sec</td>
</tr>
<tr>
<td>τp</td>
<td>hole lifetime</td>
<td>sec</td>
</tr>
<tr>
<td>τn</td>
<td>electron lifetime</td>
<td>sec</td>
</tr>
<tr>
<td>Lp</td>
<td>diffusion length of holes</td>
<td>cm</td>
</tr>
<tr>
<td>Ln</td>
<td>diffusion length of electrons</td>
<td>cm</td>
</tr>
<tr>
<td>xp</td>
<td>x-axis for p-type material</td>
<td>cm</td>
</tr>
<tr>
<td>xn</td>
<td>x-axis for n-type material</td>
<td>cm</td>
</tr>
<tr>
<td>Io</td>
<td>reverse saturation current</td>
<td>A</td>
</tr>
<tr>
<td>ΔI</td>
<td>change in DC current</td>
<td>A</td>
</tr>
<tr>
<td>VD</td>
<td>DC diode voltage</td>
<td>V</td>
</tr>
<tr>
<td>vi</td>
<td>AC diode voltage</td>
<td>V</td>
</tr>
<tr>
<td>vD</td>
<td>total diode voltage</td>
<td>V</td>
</tr>
<tr>
<td>tf</td>
<td>forward recovery time</td>
<td>sec</td>
</tr>
<tr>
<td>trd</td>
<td>relaxation delay time</td>
<td>sec</td>
</tr>
<tr>
<td>tsd</td>
<td>storage delay time</td>
<td>sec</td>
</tr>
<tr>
<td>trr</td>
<td>reverse recovery time</td>
<td>sec</td>
</tr>
</tbody>
</table>
### 3.2 CHART OF EQUATIONS

All of the equations from the background portion of the manual are shown in the table below.

<table>
<thead>
<tr>
<th>Equation</th>
<th>Name</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ideal Diode Equation</td>
<td>[ I_D(t) = I_0 e^{\left(\frac{qV_D(t)}{nkT} - 1\right)} ]</td>
</tr>
<tr>
<td>2</td>
<td>Hole current in a p(^+)n junction as a function of the stored charge (Q_p)</td>
<td>[ i_p(t) = \frac{Q_p(t)}{\tau_p} + \frac{dQ_p(t)}{dt} ]</td>
</tr>
<tr>
<td>3</td>
<td>Stored charge in the (n)-side as a function of time</td>
<td>[ Q_p(t) = I_F \tau_p e^{-t/\tau} = qAL_p \Delta p_n(t) ]</td>
</tr>
<tr>
<td>4</td>
<td>Excess charge carrier concentration at the edge of the depletion region on the (n)-side</td>
<td>[ \Delta p_n(t) = \frac{Q_p(t)}{qAL_p} = p_{n0} \left( e^{\frac{qV(t)}{kT}} - 1 \right) ]</td>
</tr>
<tr>
<td>5</td>
<td>Voltage across the p(^+)n junction assuming quasi-steady state conditions</td>
<td>[ v(t) = \frac{kT}{q} \ln \left( \frac{I_F \tau_p}{qAL_p p_{n0}} e^{-\left(\frac{t}{\tau_p}\right)} + 1 \right) ]</td>
</tr>
</tbody>
</table>
3.3 TIME DEPENDANCE OF THE IDEAL DIODE EQUATION

When time-varying voltages are applied across a p-n junction diode, the diode currents are also time-varying. When the time-variation is slower than the diffusion of minority carriers, the carriers have time to equilibrate in response to the fields. Thus, the diode remains in a quasi-steady state condition and the standard \( I-V \) relation of the p-n junction diode under equilibrium can be assumed:

\[
i_D(t) = I_0 \left( e^{\frac{qV(t)}{nkT}} - 1 \right).
\]  

If the time-variation of the current and voltage signals become much faster than the time it takes for the minority carrier to equilibrate, the \( I-V \) characteristic can no longer be represented by (1).

Figure 1 shows how the minority carrier distribution changes over time (and as a function of the position in the n-side) when the current flow through a p\(^+\)-n junction diode suddenly stops (a “turn-off transient”). As soon as the current stop flowing, there will be no more hole diffusion from the p-side to the n-side and the stored charge distribution decays exponentially over time. However, its decay in space becomes non-exponential, which is due to the charge density at the depletion edge being proportional to the current flow. Thus, when the current flow is zero, the slope of the charge density at the depletion edge must also be zero (Figure 1).

![Diagram showing turn-off transient](image)

Notice how the slope is zero at the depletion edge.

Figure 1. A turn-off transient: current as a function of time (left) and minority carrier re-distribution over time as a function of position in the n-side (right).
This non-exponential spatial decay makes it difficult to directly calculate the stored charge as a function of time. Therefore, a “quasi-steady state” approximation is used to simplify calculations – which in this case is simply assuming that the decay of a stored charge highly resembles an exponential profile in space as the steady state condition (see Figure 2). Using this approximation, we can calculate rather simply the stored charge in time and find the voltage across the junction.

Let’s now use Figure 3 to better understand the quasi-steady state approximation and determine the total diode current. Consider a turn-on transient signal across a p-n junction (Figure 3, left). In this case, the current is suddenly stepped up from zero to $I_F$. For $t > 0^+$, the increased hole injection current will first cause an increase in the excess hole density at the edge ($x_n=0$) of the depletion region. Shortly after, the excess holes will have had time to diffuse into the neutral region of the n-side, thus increasing the charge stored in the n-side as time progresses from 0 to $t_1$ to $t_2$ to steady state, as shown in Figure 3. The diffusion process takes time and the build-up of charge within the n-region will always lag the build-up of the charge near $x_n = 0$. During this transient process, the total diode current is the sum of the “recombination” current and the “charge build-up” current, yielding:

$$i_p(t) = \frac{Q_p(t)}{\tau_p} + \frac{dQ_p(t)}{dt}.$$  

(2)

Figure 2. Excess carrier concentration as a function of position in time: the dotted lines are the actual carrier distributions while the solid lines are quasi-steady state charge approximations.
Figure 3. A turn-on transient: current as a function of time (left) and minority carrier redistribution over time as a function of position in the n-side (right).

3.4 CHARGE CONTROL ANALYSIS

In many cases, we will know the current running through a diode and can use it to find the stored charge in a p-n junction diode. After finding the stored charge, it is possible to find the charge density at the depletion region edge, which in turn can be used to calculate the voltage across the junction as a function of time. To find the stored charge we will use Laplace transforms on the equation (2) to solve for the stored charge $Q(t)$.

For generality, we are going to use $I_F + \Delta I$ as our current at $t=0$. $I_F$ is the initial current which establishes a steady state charge; and $\Delta I$ is the change in current, which can be a positive or negative time varying function. After taking the Laplace transform of equation (2), one can use the initial conditions for the charge density (i.e., $Q(t=0) = I_F \tau_p$) to solve the equation. A bit of algebraic manipulation and a reverse Laplace transform will give us:

$$Q_p(t) = I_F \tau_p e^{-t/\tau_p} = qAL_p \Delta p_n(t)$$ (3)

Solving for the excess charge carrier concentration at the edge of the depletion region and equating it to (1), we get:

$$\Delta p_n(t) = \frac{Q_p(t)}{qAL_p} = p_{n0} \left( e^{\frac{qV(t)}{nkT}} - 1 \right)$$ (4)

Solving for $v(t)$, we get:

$$v(t) = \frac{kT}{q} \ln \left( \frac{I_F \tau_p}{qAL_p p_{n0}} e^{\frac{t}{\tau_p}} + 1 \right)$$ (5)

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3.5 SWITCHING TRANSIENTS

Let’s take a look at the switching transients in the ideal diode’s $I$-$V$ characteristic curves. When a diode is suddenly turned on (turn on transient), the switching trajectory is straight up the current axis and then across the voltage axis in time (Figure 4).

If the current changes less abruptly, then the switching trajectory will more closely follow the ideal diode characteristic as shown in Figure 5.

Notice the current change is instantaneous.

![Diagram showing switching transients](image)

Figure 4. A turn-on transient of a diode: the bottom graph illustrates the switching trajectory derived from our charge control modeling against an ideal diode trajectory.

Figure 5. The switching trajectory for different turn-on transient conditions.
3.6 TIME DELAYS INCURRED BY SWITCHING

Now that you have some idea of what a switching trajectory is and how it works, we are going to look at a slightly more complex circuit with a voltage signal, a series resistance, and a diode configured as shown in Figure 6. The purpose of this analysis is to find out how long it takes for our switching operation to reach steady-state (i.e. “recover”). Since diodes are used more often in AC applications than in DC applications, switching speeds of a diode becomes a very important diode feature.

![Figure 6. A circuit diagram for the time delay measurement.](image)

When a step-on voltage is applied to a p-n junction with a series resistance, you should have an output similar to Figure 7. Notice that the voltage across the junction spikes and then settles down to a steady-state voltage level. When the voltage across the diode has dropped to within 10% of the steady-state value the junction is said to have “recovered.” The **forward recovery time**, \( t_f \), is the time from the “switching-on” of the voltage source to the time that diode has “recovered.”

When a voltage source is turned off, the stored charge is present until it recombines or is dissipated over the resistor in the circuit. We will give this type of charge storage delay a special name, the **relaxation delay time**, \( t_{rd} \), (see Figure 8). We state that the system is “relaxed” if it’s current value is within 10% of the steady-state value.
Figure 7. A turn on transient: the graph above shows applied voltage waveform (step function) from the function generator and the bottom graph shows corresponding voltage signal across the diode. Note how to determine the $t_{fr}$.

Figure 8. A turn off transient: the graph above shows applied voltage waveform from the function generator and the bottom graph shows corresponding voltage signal across the diode. Note how to determine the $t_{rd}$.
When you switch from forward to reverse bias ("a positive to negative transient" or a "reverse recovery transient") reverse recovery switching will occur as shown in Figure 9. Figure 9-a depicts the case of an ideal current source which is stepped from a forward biasing current $I_F$ to a current of opposite polarity. Due to steady flow of $I_F$, we should expect to see a steady state charge density at $t=0$. Note that when $t=0^+$, the slope of the charge distribution (i.e. time rate of charge distribution) must match the current that is flowing. The reverse current consists of minority carrier being drawn back across junction from the n-side into the p-side. The charge density in n-side is shown in Figure 10 below.

![Diagram](attachment:lab7_transient_signals_of_pn_junction_diodes_page10.png)

**Figure 9. Reverse recovery switching trajectories for a current source (a) and a voltage source (b).**

![Diagram](attachment:lab7_transient_signals_of_pn_junction_diodes_page10.png)

**Figure 10. Changes in the excess charge carrier distribution over time. Note the positive slopes near the edge of the depletion region.**

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When the stored charge density on both sides of the junction reaches zero, the storage delay portion of the transient is over. The current source will then rapidly drive the diode towards reverse breakdown. In the case of a voltage source, depicted in Figure 9-b, the current supplied to the circuit can be approximated as the voltage supplied by the source over the series resistance. This means that the current sourced is dependent on the voltage dropped across the resistor. After the storage delay time \( t_{sd} \), the diode turns off changing the diodes role in the circuit from that of a simple voltage drop to impedance many orders of magnitude larger than that of the series resistance; this causes nearly all of the voltage to fall across the \( p-n \) junction. Note that the voltage dropped across the resistor decays exponentially in time (Figure 9-b, 11). Since the current for the circuit is the same as that flowing through the resistor, the exponential decay in voltage causes the reverse current to saturate to the reverse saturation current (Figure 9-b).

The total reverse recovery time \( t_{rr} \) is the time it takes the voltage signal across the diode to reach 10% of the steady-state value from the reverse voltage experienced by the diode during the storage delay period. Figure 11 demonstrates both the storage delay time \( t_{sd} \), and the reverse recovery time, \( t_{rr} \).
Figure 11. A reverse recovery transient of a diode. Note the time period of each delay on the time axis.
4. PREPARATION

1. Make sure you understand how to properly operate the oscilloscope by reading the section 3.3 of the Lab 1 manual. Outline section 3.3 of the Lab 1 manual.

2. Outline sections 3.3 to 3.6 of this Lab 7 manual. Take note of key assumptions and main concepts contained in each section.

5. PROCEDURE

The following measurements will be made using a rectifier diode (1N4002). Since there will be substantial currents flowing at various times in the experiment, be sure to use a 10 Ω, 2W resistor for this experiment. If you use ordinary ¼ W resistor, excessive current flowing over the diode may burn the diode.

In this lab, you will not use any LabView program. You will manually control the function generator and the oscilloscope to get the data.

5.1 TURN-ON TRANSIENT

In this section, you will measure the forward recovery transient of the diode voltage as the pulsed current is switched on from $I = 0$ to $I = I_F$.

1. Measure the exact value of your ~10 Ω resistor using the Keitheley SMU and record it in the Table 3. You will need “exact” resistance value to accurately analyze the data later.

2. Construct the circuit as shown in Figure 12.

![Figure 12. Circuit used to make the turn on and turn off transient measurements.](image)
3. **Function Generator settings:**

*In this lab, we’ll use the “High-Level” and “Low-Level” settings on the function generator rather than the “Amplitude” and “Offset” settings.*

- Set the function generator to output a **square wave**.
- Next, set the function generator to have a **high-level** voltage of 1 V and a **low-level** voltage of 0 V. We choose the low-level to be 0 V because we need a step function rather than a square wave in this part of the experiment. This generates a 1V step function output from the function generator. (Later, you will increase this voltage; see Table 3.)
- Set the **frequency** of the function generator at 20 kHz.
- Do not change the duty cycle (default value is 50 %).

4. **Oscilloscope Settings:**

*If you are not sure how to operate the oscilloscope, go back to the Lab 1 manual and read more on the oscilloscope operation.*

Adjust the waveform settings of the oscilloscope to **optimally display** the turn-on transient signals. Your displayed waveforms should be similar to those in Figure 7.

5. Save the waveform to your USB to collect CH1 (diode) and CH2 (whole circuit) data separately as .CSV files.

6. Using cursors (or import .CSV files into EXCEL spreadsheet), calculate the forward current \( I_F \) as follows (be sure to record your values in Table 3):

\[
I_F = \frac{V_{Ch2,ss} - V_{Ch1,ss}}{R_{measured}},
\]

Here the subscript “ss” means “steady-state”. If using cursors, be sure the probe signals are at same “ground” on the screen.

7. Next, leave only the Channel across the diode (CH1) on. Use the cursors for both voltage and time to measure the **Vpk - Vss** and the **forward recovery time** \( t_{fr} \) as shown in Figure 7. Record the “forward recovery time” in the Table 3.

8. Again, save your waveform to USB to collect data. You can use this data to recheck step 7 if needed.

9. Repeat Steps 5-7 for the other voltages given in Table 3 (2.5V and 5V) and be sure to record the corresponding \( I_F \) and \( t_{fr} \). Remember to also save your waveforms to your USB.
Table 3. Measured data for the turn on and turn off transient.

<table>
<thead>
<tr>
<th>$V_{\text{High-Level}}$</th>
<th>$V_{\text{Low-Level}}$</th>
<th>$R$</th>
<th>$I_F$</th>
<th>$V_{pk-Vss}$</th>
<th>$t_{fr}$</th>
<th>$V_{ss-Voff}$</th>
<th>$t_{rd}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1,V$</td>
<td>$+,0.0,V$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$2.5,V$</td>
<td>$+,0.0,V$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$5,V$</td>
<td>$+,0.0,V$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5.2 TURN-OFF TRANSIENT

Next, you will measure the turn-off characteristics of the $p$-$n$ junction diode.

1. Use the same circuit and the same input as used in the previous section (5.1), but this time adjust the oscilloscope to see the close up view of the waveforms similar to the Figure 8. In other words, you’ve investigated the first half, the step up portion of the signals, now scroll over (in time) to investigate the step down portion of the signals.

2. Use the Channel across the diode (CH1) to measure the $V_{ss} - V_{off}$ and relaxation delay time ($t_{rd}$) and record it in Table 3 above; use Figure 8 as a guide to making the measurements for all step voltages shown in the Table 3. Do not forget to save waveforms to USB to collect data for graphs for each $t_{rd}$ measurement. You may not see a significant voltage drop as noted in Figure 8.

5.3 REVERSE RECOVERY TRANSIENT

Next, you will measure the “reverse recovery transient” of the diode as the pulsed current is switched from $I_F$ to $I_R$.

1. Construct the circuit as shown in Figure 13. You will need only one oscilloscope probe, set across the resistor, and attached to CH1.

2. Program the function generator to:
   - Output a square wave.
• Set the function generator to have a **high-level** voltage of 0.9 V and a **low-level** voltage of 0 V (this is the first entry of Table 9; you will be adjusting these voltages as noted in the Table).
• Set the frequency of the function generator to 20 kHz.
• Do not change the duty cycle (default value is 50%).

3. Measure the **forward current** \((I_F)\) and the **reverse current** \((I_R)\) as follows and record them in the Table 4; Use the equation given below. You would set up the oscilloscope to show the close-up view of the waveforms similar to the Figure 11.

\[
I = \frac{V_{ch1}}{R_{measured}}.
\]

Note: the transient signals may not be perfectly flat. Estimate a middle region.

4. Now use the cursors for both voltage and time to find the **storage delay time** \((t_{sd})\) and the **total reverse recovery time** \((t_{rr})\) as shown in Figure 11 and record them in the Table 4.

5. Save waveforms to USB to collect data; you may use this data to verify Step 4 later in case there were any errors in your measurement in the lab.

6. Repeat steps 3-5 for the voltage settings listed in the Table 4 and record the corresponding \(t_{sd}\) and \(t_{rr}\).

![Figure 13. Circuit used to make the reverse recovery transient measurements.](image-url)
Table 4. Measured data for the reverse recovery transient.

<table>
<thead>
<tr>
<th>$V_{\text{High-Level}}$</th>
<th>$V_{\text{Low-Level}}$</th>
<th>$V_F$</th>
<th>$I_F$</th>
<th>$V_R$</th>
<th>$I_R$</th>
<th>$t_{sd}$</th>
<th>$t_{rr}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9 V</td>
<td>0.0 V</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.9 V</td>
<td>-0.5 V</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.9 V</td>
<td>-1 V</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.9 V</td>
<td>-2 V</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.9 V</td>
<td>-4 V</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5 V</td>
<td>-1 V</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.1 V</td>
<td>-1 V</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.4 V</td>
<td>-1 V</td>
<td></td>
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<tr>
<td>1.8 V</td>
<td>-1 V</td>
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</tbody>
</table>

6. LAB REPORT

Type a lab report with a cover sheet containing title, your name, your lab partner’s name, class, section number, date the lab was performed and the date the report is due. Use the following outline to draft your lab report:

- **ABSTRACT**: Briefly describe the contents of your report.
- **DATA PRESENTATION**:
  - Create a well formatted table presenting the data from Table 3.
  - Create a well formatted table presenting the data from Table 4.
- **ANALYSIS**:
  - Turn ON Transient
    - Using any one particular data set from Table 3 (e.g., 1V High-Level and 0V Low-Level), and properly plot the voltage waveforms from both channels and show how you calculated the forward current $I_F$. You should import your graph into your report and use labels to show $Vch1,ss$ and $Vch2,ss$, etc.
• Again, using any one particular data set, properly plot the Ch2 voltage waveform and show how you calculated the forward recovery time $t_{fr}$. Be sure to use labels to show $V_{peak}$ and $V_{ss}$.

• In your own words, briefly explain what is happening in the diode during this turn on transient. You may want to read Sec. 3 (background information) to give better explanation.

  o Turn OFF Transient

    • Present all acquired data plots for this section in one graph. Make sure it is titled, both axes are labeled, and the plots are distinguishable and have appropriate legends.

    • Using any one particular data set (e.g., 1V High-Level and 0V Low-Level), properly plot the Ch2 voltage waveform and show how you calculated the relaxation delay time $t_{rd}$. Be sure to use labels to show $V_{ss}$ and $V_{off}$.

    • In your own words, briefly explain what is happening in the diode during this turn-off transient.

  o Reverse Recovery Transient

    • Using any one particular data set (e.g., 0.9V High-Level and -0.5V Low-Level), properly plot the voltage waveform from Ch1 and show how you calculated $t_{sd}$ and $t_{rr}$. Be sure to clearly label $V_F$, $V_R$, $t_{sd}$, and $t_{rr}$. In your own words, briefly explain what is happening in the diode during this reverse recovery transient.

• CONCLUSION: Describe how your analyses correspond with the theory described in BACKGROUND section and the textbook.

• Attach: Signed instructor verification form.