1.0 Objectives

- To demonstrate the operations of a half-wave rectifier and a full-wave bridge rectifier
- To show the effects of shunt capacitance and load resistance on the outputs of various rectifier circuits
- To demonstrate the operations of several diode clipping circuits
- To demonstrate the operation of a diode clamping circuit

2.0 Apparatus

“Diode and Transistor Circuits” experiment board
DC Power Supply
Dual-trace Oscilloscope
Function Generator
Digital Multimeter
Connecting wires

3.0 Theoretical Background

A p-n junction diode is the most common two-terminal solid-state device. One side of the p-n junction is a p-type semiconductor and another side is an n-type semiconductor. The p-type end is the anode while the n-type end is the cathode. The conceptual structure, the typical appearance, and the schematic symbol of a diode are shown in Figure 1. When the potential applied to the cathode is more positive than that at the anode, the diode is said to be in the reversed bias condition. Ideally, no current can flow through the device. When the voltage at the anode is more positive than that at the cathode, this condition is called forward bias. Figure 2 shows the typical I-V characteristic of a diode. If the forward bias voltage is less than a threshold value, known as the cut-in voltage $V_I$, the current flowing through the diode is very small. As soon as the applied voltage gets above this cut-in voltage, the current will rise rapidly. This cut-in voltage is approximately 0.2 V for a germanium diode and 0.6 V for a silicon diode.
Consider a silicon diode that is connected in series with a 1 kΩ resistor, as shown in Figure 3. When a battery voltage of 3 V is applied, the diode is forward-biased and an electric current will start to flow in both the diode and the resistor. The voltage across the resistor will rise to a value \( V_R = I \times R \) which is slightly lower than 2.4 V. The current is limited to 2.4 mA (= 2.4 V/1 kΩ). This voltage will not rise above 2.4 V because otherwise the voltage across the diode will become lower than 0.6 V, which will then put the diode into a “high resistance” state that will allow only a very small current to flow in the circuit. Therefore, in the analysis of a diode circuit, we can usually assume the voltage across a silicon diode to be 0.6 V, provided that the voltage source in the circuit is higher than 0.6 V and the polarity is to bias the diode in the forward direction (forward biased). The diode acts like a switch that is turned on. If the polarity is reversed, the diode will be reverse-biased and no current can flow in the circuit. In this condition, the diode acts like a switch that is turned off. As a result, the voltage across the resistor will become zero (since \( I = 0 \)).

Due to the unidirectional characteristic of current in the device, a diode can be configured as a rectifier that allows current flow for only half a cycle of an AC waveform. A half-wave rectifier circuit is shown in Figure 4. When the potential at point A is more positive than that at point B, i.e. the supply voltage \( V_S \) is positive, the diode is forward-biased. The voltage across the resistor will have the same waveform as the supply voltage \( V_S \) (minus away 0.6V, to be exact). In the second half cycle, the voltage at A becomes negative, so the diode is reverse-biased. The voltage across the resistor will be zero throughout this half cycle. As a result, a half-wave waveform is obtained at the resistor and a direct current is obtained from the AC source because the current flows only in the X-to-Y direction.

Since the above diode circuit operates only for half a cycle, the efficiency is low. A bridge-rectifier circuit constructed using 4 diodes, as shown in Figure 5, can be used to double the efficiency. In the first half cycle of an AC waveform, diodes D1 and D2 are turned on while D3 and D4 are off. Current flows from X to Y. In the second half cycle, when the potential at point B is more positive than point A, diode D3 and D4 are on while D1 and D3 are turned off. Current flows from X to Y again. Since there is always a current flow during both the positive cycle and the negative cycle, a rectified full-wave waveform is obtained, as shown in Figure 5. Note that there is 1.2 V (=2x0.6 V) lost in \( V_o \) because 2 diodes conduct in series.
A rectifier circuit is usually used to convert an AC voltage into a DC voltage. A transformer can be connected to the 240 V AC mains supply at the wall outlet to step down the voltage to a desired level. The large ripples in the half-wave and full-wave rectified waveforms can be suppressed using a capacitor filter connected in parallel with the load resistor (see Figure 6). This provides a more stable DC voltage, comparable to a battery, for operating an electronic system. However, the ripple cannot be totally eliminated. The amplitude of the residual ripple depends on the size of the capacitor and the load resistance. If the load resistance is small, a large capacitance is required to obtain a DC source with acceptably small ripples.

Diodes can also be used to change the shape of an AC waveform. The circuits in Figure 7 are known as the clipping circuits. The diodes are turned on for only the period of time when the AC voltage is at least 0.6 V higher than the reference voltage, \( V_{\text{ref}} \). During this period, a current flows through the diode and the voltage across the diode is about 0.6 V. As a result, part of the output AC waveform, \( V_{o} \), is clipped off.

Another wave shaping circuit, as shown in Figure 8, is the clamping circuit. The capacitor is fully charged to the peak voltage of the AC source when the diode is forward-biased. (For simplicity, we have assumed the forward voltage drop of the diode is negligible.)
As the diode acts like a switch that is turned on, the output voltage taken across the diode is zero when the AC waveform is at its peak. As soon as the AC voltage falls below the peak value, the diode becomes reverse-biased by the voltage sum of the transformer and the capacitor which is a negative value. The resulting waveform is an AC waveform that is “clamped” down below zero volt. If the 0.6 V forward voltage drop of the diode is considered, the capacitor is charge to \((V_m - 0.6)\) V and the average value of \(V_o\) is \(-(V_m - 0.6)\) V. The \(V_o\) peak voltage is 0.6 V above zero volt.

\[
\begin{align*}
V_s & \quad \sim \quad C \quad \Downarrow \quad V_o \\
\end{align*}
\]

\[V_s = V_m - 0.6 \quad \text{and} \quad V_o = -(V_m - 0.6)\]

![Figure 8](image)

**4.0 Laboratory Instructions**

The lab is divided into two parts: **Part A-Theoretical Prediction** and **Part B-Experiment**.

**Read and understand all instructions in Part A and B carefully and prepared for all the questions. Every student must complete Part A theoretical prediction before attending this lab session.** Students should refer to the above notes to work out the answers for Part A theoretical prediction and understand the purposes of the all experiments in Part B. Students are required to submit the **Part B Report Form immediately after the lab session**.

You must sketch waveforms displayed on oscilloscope as instructed in the Part B experiment on the corresponding graph provided in Part B Report Form. Refer to Appendix D for efficient waveform sketching.

**Cautions**

**Oscilloscope**: DO NOT turn the INTENSITY of the displayed waveforms to maximum. High intensity may burn the screen material of the oscilloscope.

**Function generator**: NEVER short-circuit the output (the clip with red sleeve), which may burn the output stage of the function generator.

**Factors affecting your experiment progress**

- Your preparation before coming to the lab (your understanding on the theories, the procedures and the information in the appendices; your planning to carry out the experiments and to take data), attempt all questions before the lab.
- Your understanding on the functions and the operations of the equipment (Your learning on using the equipment during the Induction Program Lab Session; your understanding on checking and presetting the equipment)
- The technique you use to sketch waveforms on graph papers
**Part A: Theoretical Predictions**

Use the provided Part A Report Form to record the answers of your theoretical predictions.

For the cases where $V_S$ is a sinusoidal voltage source, apply $V_S = 10 \sin (2\pi \times 10000t)$ V.

**A4.1 Half-wave Rectifier**

1. Use diode forward voltage drop of 0.6 V, predict the maximum currents flow through the diode D1 ($I_{D,\text{max}}$) in the circuit of Part B Experiment B4.1, if $R3 = 18 \, \text{k}\Omega$ and 10 kΩ. Record the values in Table A4.1 of the Report Form.
2. From Appendix E, find the more exact values of the diode forward voltage drops ($V_F$) at the corresponding maximum currents.
3. Predict the maximum $V_o$ voltages ($V_{o,\text{max}}$) for both cases.
4. Predict the minimum $V_o$ voltage ($V_{o,\text{min}}$).

**A4.2 Full-wave Rectifier**

1. Use diode forward voltage drop of 0.6 V, predict the maximum currents flow through the diodes ($I_{D,\text{max}}$) in the circuit of Experiment B4.2, if $R3 = 18 \, \text{k}\Omega$ and 10 kΩ. Note that two diodes conduct at a time. Record the values in Table A4.2.
2. From Appendix E, find the more exact values of the diode forward voltage drops ($V_F$) at the corresponding maximum currents.
3. Predict the maximum $V_o$ voltages ($V_{o,\text{max}}$) for both cases.
4. Predict the minimum $V_o$ voltage ($V_{o,\text{min}}$).

**A4.3 Clipping Circuits**

1. Use diode forward voltage drop of 0.7 V when $V_S = 5$ to 10 V, 0.65 V when $V_S = 2$ to 4 V and 0.6 V when $V_S = 1$ V, predict the currents flow through the diode ($I_D$) in Part B Procedure 1 of Experiment B4.3 when $V_S = 1, 2, 3, 5, 10$ V. Record the values in Table A4.3(a).
2. From Appendix E, find the more exact values of the diode forward voltage drops ($V_F$) at the corresponding diode currents. (Note for more precise results, iteration is required. Iteration: start with a $V_F$ to calculate $I_D$ and then find new $V_F$. Use this new $V_F$ value to calculate $I_D$ and find another new $V_F$. The process is repeated until subsequent $V_F$ values are about the same.)
3. The set of values predicted in the above step 1 and step 2 can be used to compare with the sketched waveform in the experimental Procedure 2 of Experiment B4.3. Note that in this case $V_F = V_o$.
4. Predict the minimum $V_o$ voltage ($V_{o,\text{min}}$).
5. You have known that the dependence of $V_F$ on $I_D$ from the above steps. For simplicity, use fixed $V_F = 0.7$ V to predict $V_{o,\text{max}}$ and $V_{o,\text{min}}$ for Procedure 4, Procedure 6 and Procedure 8 of Experiment B4.3 for $V_{DC} = 0, 2, 4,$ and 6 V. Note that the largest $I_D$ in Procedure 8 of Experiment B4.3 is $(16 - 0.7)/1k = 15.3$ mA. Record the values in Table A4.3 (b), Table A4.3 (c) and Table A4.3 (d), respectively.

**A4.4 Clamping Circuit**

1. With fixed $V_F = 0.7$ V, predict $V_{o,\text{max}}$ and $V_{o,\text{min}}$ for Procedure 1 of Part B Experiment B4.4 for $V_{DC} = 0, 2, 4,$ and 6 V. Record the values in Table A4.4.
Part B: Experiments

Use the provided Part B Report Form to record the experimental results.

B4.0 Diode Test Procedures

Referring to the circuit board layout in Appendix A, without any connections, test all the diodes on the board by using the go/no-go testing method.

1. Set the multimeter in “diode test” mode (note that some multimeters need to push in two buttons together to set “diode test” mode as indicated on the control panel). The “COM” terminal is negative “–” and the “V, Ω, mA” terminal is positive “+”.
2. Test the diode D1 on the board in forward-biased condition, i.e. connect “+” terminal to anode the and “–” to the cathode. A good diode will give forward voltage drop of about 0.7 V or 700 mV. Record the reading in Table B4.0 of Report Form.
3. Repeat Procedure 2 for other diodes.

Equipment Setups for Experiments B4.1 to B4.4

1. Set the vertical sensitivities of CH1 and CH2 of the oscilloscope to 5 V/div and align the ground levels of CH1 and CH2. Set the horizontal (time base) sensitivity to 20 μs/div. Make sure the Var sweep knob is at the full clockwise position. Set the input couplings (AC/GND/DC switches) of CH1 and CH2 to DC. Set the vertical mode to dual waveform display. Set the trigger source to CH1 and the triggering mode/coupling to AUTO. Switch ON the oscilloscope.
2. Switch ON the function generator and set it for a 10 kHz sine wave signal. Connect CH1 of the oscilloscope to the function generator and check the waveform and adjust the amplitude knob of the function generator to set V_{peak-to-peak} = 20V. Refer to Appendix B for equipment check procedure if necessary.
3. Connect the function generator with the sine wave signal to terminals P1 - P2 (grounded at P2) of the diode circuit board. The diode circuit board layout is given in Appendix A. Refer to Appendix B for guidelines to check the value of resistors and capacitors in the board.
4. Connect a probe from CH1 of the oscilloscope to P1 – P2 (grounded at P2).
5. Connect the second probe from CH2 to T9 - P5 (grounded at P5).
6. Keep the oscilloscope ON throughout the experiments.
7. Carry out the following experiments with these setups.
B4.1 Half-wave Rectifier

Procedures
1. Using the circuit board provided, construct the circuit as shown below by connecting T1 to TA5, T2 to TA6, T7 to TA17, T8 to TA18, and T3 to T4.

2. Use the Fine knob of function generator to adjust the signal frequency so that CH1 waveform ($V_I$) has a period of 5 divisions. [5 div x 20 $\mu$s/div = 100 $\mu$s which is approximately equal to $1/f_{gen}$, where $f_{gen}$ is the frequency reading displayed on the function generator, if not refer to Appendix C for other presetting of the oscilloscope]. Adjust the oscilloscope trigger level and the CH1 horizontal position so that CH1 waveform has peaks at the positions as shown in Graph B4.1 (a) of Part B Report Form. This step is important for $V_o$ waveform to be drawn with respect to $V_I$ waveform.

3. Sketch the CH2 waveform ($V_o$) displayed on the oscilloscope on Graph B4.1 (a). **Do not move the waveform positions during the sketching.** Read the maximum and the minimum voltages of CH2 waveform ($V_{o,\max}$ and $V_{o,\min}$) and record them in Table B4.1 (under column header: Procedure 3). Calculate the ripple voltage, $V_{o,r} = V_{o,\max} - V_{o,\min}$.

4. Connect the following components at the rectifier output and record all the respective $V_{o,\max}$, $V_{o,\min}$ and $V_{o,r}$ in their corresponding columns in Table B4.1. Sketch the required $V_o$ waveforms on their corresponding graphs in the Report Form.

   (i) C3 (10 nF) and R3 (18 k$\Omega$) in parallel
   (ii) C3 and R2 (10 k$\Omega$) in parallel
   (iii) C2 (470 pF) and R3 in parallel

Ask the instructor to check your results. Show all the sketched waveforms, Table B4.1 readings and the waveforms of Procedure 4 (iii) displayed on the oscilloscope.
B4.2 Full-wave Rectifier

Procedures
1. Construct the circuit as shown below.

![Circuit Diagram]

2. Check the CH1 horizontal position so that CH1 waveform has peaks at the positions as shown in Graph B4.2 (a) of Part B Report Form. This step is important for $V_o$ waveform to be drawn with respect to $V_I$ waveform.

3. Sketch $V_o$ waveform displayed on the oscilloscope on Graph B4.2 (a). Read $V_{o,\text{max}}$ and $V_{o,\text{min}}$ and record them in Table B4.2. Calculate $V_{o,r} = V_{o,\text{max}} - V_{o,\text{min}}$.

4. Connect the following components at the rectifier output and record all the respective $V_{o,\text{max}}$, $V_{o,\text{min}}$ and $V_{o,r}$ in their corresponding columns in Table B4.2. Sketch the required $V_o$ waveforms on their corresponding graphs in the Part B Report Form.

   (i) C3 (10 nF) and R3 (18 kΩ) in parallel
   (ii) C3 and R2 (10 kΩ) in parallel
   (iii) C2 (470 pF) and R3 in parallel

Ask the instructor to check your results. Show all the sketched waveforms, Table B4.2 readings and the waveforms of Procedure 4 (iii) displayed on the oscilloscope.
B4.3 Clipping Circuits

Procedures

1. Construct the circuit as shown below.

![Circuit Diagram]

2. Check the CH1 horizontal position so that CH1 waveform has peaks at the positions as shown in Graph B4.3 (a) of Part B Report Form. Sketch $V_o$ waveform displayed on the oscilloscope on Graph B4.3 (a) and label the waveform with $V_{DC} = 0$ V. Record $V_{o,max}$ and $V_{o,min}$ in Table B4.3 (a) under $V_{DC} = 0$ V column.

3. Set the DC Power Supply to 0 V. Set the current adjustment knob to about ¼ turn from the min position. Make sure that the negative terminal of the DC power supply is not connected to the ground.

4. Switch off the DC power supply and connect it to the circuit as shown below.

![Circuit Diagram 1]

5. Switch on the DC power supply. Set it to $V_{DC} = 2$ V. Sketch $V_o$ waveform on Graph B4.3 (a). Record $V_{o,max}$ and $V_{o,min}$ in Table B4.3 (a). Repeat for $V_{DC} = 4$ V and 6 V. Label the waveforms.

6. Switch off the DC power supply. Construct the circuit as shown below.

![Circuit Diagram 2]

7. Switch on the DC power supply. Set it to $V_{DC} = 0$ V (turn the voltage knob of the power supply to the minimum position and then short the power supply output with a wire). Sketch $V_o$ waveform on Graph B4.3 (b). Record $V_{o,max}$ and $V_{o,min}$ in Table B4.3 (b). Repeat for $V_{DC} = 2, 4$ and 6 V. Label the waveforms.
8. Switch off the power supply and reconnect it to the circuit as shown below.

9. Switch on the DC power supply. Sketch $V_o$ waveforms on Graph B4.3 (c) for $V_{DC} = 0$, 2, 4 and 6 V (accurate to 0.1 V). Label the waveforms. Record $V_{o,max}$ and $V_{o,min}$ in Table B4.3 (c).

Ask the instructor to check your results. Show all the sketched waveforms, table readings and the oscilloscope waveforms of Procedure 9 for $V_{DC} = 6$ V.

### B4.4 Clamping Circuit

**Procedures**

1. Make sure that the DC power supply is off. Construct the circuit as shown below.

2. Check the CH1 horizontal position so that CH1 waveform has peaks at the positions as shown in Graph B4.4 (a). Sketch $V_o$ waveforms on Graph B4.4 for $V_{DC} = 0$ V and 2 V (accurate to 0.1 V). Label the waveforms. Record $V_{o,max}$ and $V_{o,min}$ in Table E4.4.

3. Record also $V_{o,max}$ and $V_{o,min}$ when $V_{DC} = 4$ V and 6 V. Calculate the peak-to-peak voltages of $V_o$ waveforms, $V_{o,pp} = V_{o,max} - V_{o,min}$.

Ask the instructor to check your results. Show all the sketched waveforms, Table B4.4 readings and the oscilloscope waveforms of Procedure 3 for $V_{DC} = 6$ V.

**Report Submission**

*Part B Report Form must be submitted immediately upon completion of the laboratory session.*

End of Lab Sheet
APPENDICES

APPENDIX A: Circuit Board Layout

Circuit diagram improved by twhaw Apr 2002
**APPENDIX B**

### The Resistor color code chart

<table>
<thead>
<tr>
<th>COLOR</th>
<th>SIGNIFICANT DIGIT</th>
<th>MULTIPLIER</th>
<th>TOLERANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black</td>
<td>0</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Brown</td>
<td>1</td>
<td>10</td>
<td>1%</td>
</tr>
<tr>
<td>Red</td>
<td>2</td>
<td>100</td>
<td>2%</td>
</tr>
<tr>
<td>Orange</td>
<td>3</td>
<td>1,000</td>
<td>3%</td>
</tr>
<tr>
<td>Yellow</td>
<td>4</td>
<td>10,000</td>
<td>4%</td>
</tr>
<tr>
<td>Green</td>
<td>5</td>
<td>100,000</td>
<td>-</td>
</tr>
<tr>
<td>Blue</td>
<td>6</td>
<td>1,000,000</td>
<td>-</td>
</tr>
<tr>
<td>Violet</td>
<td>7</td>
<td>10,000,000</td>
<td>-</td>
</tr>
<tr>
<td>Gray</td>
<td>8</td>
<td>100,000,000</td>
<td>-</td>
</tr>
<tr>
<td>White</td>
<td>9</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Gold</td>
<td>-</td>
<td>0.1</td>
<td>5%</td>
</tr>
<tr>
<td>Silver</td>
<td>-</td>
<td>0.01</td>
<td>10%</td>
</tr>
<tr>
<td>No Color</td>
<td>-</td>
<td>-</td>
<td>20%</td>
</tr>
</tbody>
</table>

### Equipment checks

**Oscilloscope voltage probe check**

Use oscilloscope calibration (CAL) terminal. A good probe will give a waveform of positive square wave with 2 V peak-to-peak and about 1 kHz.

**Oscilloscope channel check**

Use oscilloscope calibration (CAL) terminal and a good voltage probe. A good input channel will give the corresponding waveform of the CAL terminal.

**Function generator check**

Check the output waveform by oscilloscope. A good function generator will give a stable waveform on the oscilloscope screen. **Caution: Never short-circuit the output to ground, this can burn the output stage of the function generator.**
APPENDIX C

OSCILLOSCOPE INFORMATION

Below are the functions of switches/knobs-buttons:

**INTENSITY** knob: control brightness of displayed waveforms. **Make sure the intensity is not too high.**

**FOCUS** knob: adjust for clearest line of displayed waveforms.

**TRIG LEVEL** knob: adjust for voltage level where triggering occur (push down to be positive slope trigger and pull up to be negative slope trigger).

**Trigger COUPLING** switch: Select trigger mode. Use either AUTO or NORM.

**Trigger SOURCE** switch: Select the trigger source. Use either CH1 or CH2.

**HOLDOFF** knob: seldom be used. Stabilize trigger. Pull out the knob is CHOP operation. This operation is used for displaying two low frequency waveforms at the same time.

**X-Y** button: seldom be used. **Make sure this button is not pushed in.**

**POSITION** (Horizontal) knob: control horizontal position of displayed waveforms. Make sure that it is pushed in (pulled up to be ten times sweep magnification).

**POSITION** (vertical) knobs: control vertical positions of displayed waveforms. Pulled out CH1 POSITION knob leads to alternately trigger of CH1 and CH2. Pulled out CH2 POSITION knob leads to inversion of CH2 waveform.

Time base:

**TIME DIV**: provide step selection of sweep rate in 1-2-5 step.

**VARIABLE** (for time div) knob: Provides continuously variable sweep rate by a factor of 5.

Make sure that it is in full clockwise (at the CAL’D position, i.e. calibrated sweep rate as indicated at the time div knob).

Vertical deflection:

**VOLTS DIV**: provide step selection of deflection in 1-2-5 step.

**VARIABLE** (for volts div) knob: A smaller knob located at the center of VOLTS DIV knob. Fine adjustment of sensitivity, with a factor of 1/3 or lower of the panel-indicated value. Make sure that it is in full clockwise (at the CAL’D position). Pulled out knob leads to increase the sensitivity of the panel-indicated value by a factor of 5 (x 5 MAG state). Make sure that it is pushed down.

**AC/GND/DC** switches: select input coupling options for CH1 and CH2. AC: display AC component of input signal on oscilloscope screen. DC: display AC + DC components of input signal on oscilloscope screen. GND: display ground level on screen, incorporate with AUTO trigger COUPLING selection).

**CH1/CH2/DUAL/ADD** switch: select the operation mode of the vertical deflection. CH1: CH1 operates alone. CH2: CH2 operates alone. DUAL: Dual-channel operates with CH1 and CH2 swept alternately. This operation is used for displaying two high frequency waveforms at the same time.

**Note**: Keep the oscilloscope ON. The oscilloscope needs an amount of warm up time for stabilization.

**CAUTION**: Never allow the INTENSITY of the displayed waveforms too bright. This can burn the screen material of the oscilloscope.
APPENDIX D

Sketching oscilloscope waveforms on graph paper

Sketch is a quick drawing technique without loss of important or interested information of the displayed waveforms. Hence, the important or interested points of a waveform as displayed on the oscilloscope screen should be marked first on a graph paper before the waveform is sketched.

Procedures
1. Set suitable “time/div” and “V/div” to display the interested waveform portions. Often, the required “time/div” and “V/div” are estimated first.
2. Mark & label channel ground level, normally at the vertical major grid position.
3. Mark the important/interested points.
4. Sketch the waveform by connecting the points together accordingly.
5. Label waveform labels (if more than one channel involved).
6. Write down “time/div” and “V/div”

Example 1:
A sinusoidal waveform is amplified through an amplifier with a delay network.
Interested points: maxima, minima, points crossing ground level, etc
Information retained: amplitudes, peak-to-peak values, period, phase shift, approximate shapes of the waveforms

Note: The ground level is important to indicate the values of average, positive peak, negative peak, turning points, etc.

Example 2:
Diode clipping circuit with 2.5 V DC reference
APPENDIX E

Diode and BJT characteristics

Figure AE1: Forward voltage characteristics of diode 1N4148 (from National Semiconductor data sheets)

Table AE 1: DC current gain $h_{FE}$ of 2N3904 at 25°C (from Motorola data sheets)

<table>
<thead>
<tr>
<th>Conditions (DC)</th>
<th>$h_{FE,\text{min}}$</th>
<th>$h_{FE,\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_C = 0.1$ mA, $V_{CE} = 1.0$ V</td>
<td>40</td>
<td>-</td>
</tr>
<tr>
<td>$I_C = 1.0$ mA, $V_{CE} = 1.0$ V</td>
<td>70</td>
<td>-</td>
</tr>
<tr>
<td>$I_C = 10$ mA, $V_{CE} = 1.0$ V</td>
<td>100</td>
<td>300</td>
</tr>
</tbody>
</table>

Figure AE 2: PSpice simulated output characteristics of 2N3904
Figure AE 3: Input resistance $h_{ie}$ of 2N3904 at $V_{CE} = 10$ V, $f = 1$ kHz and $25^\circ$C (from Motorola data sheets)

![Input resistance graph](image)

Figure AE 4: DC current gain $h_{re}$ curves of 2N3904 at $V_{CE} = 1.0$ V and various junction temperature $T_J$ (from Motorola data sheets)

![DC current gain graph](image)

**Reading Log Scale**

Let the distance in a decade of the log scale in the figure below is measured as $x$ mm. Since $\log_{10}1 = 0$, it is taken as the origin ($0$ mm) in the linear scale. Then, the reading $10$ is located $x$ mm and the reading $0.1$ is located at $-x$ mm. For reading $y$, it is located at $[\log_{10}(y)]x$ mm.

Examples:
- Reading $2.5$ is located at $[\log_{10}(2.5)]x$ mm = $0.39x$ mm
- Reading $0.25$ is located at $[\log_{10}(0.25)]x$ mm = $-0.602x$ mm

Reversely, a point at $z$ mm location is read as $10^{z/x}$.

Examples:
- $0.6x$ mm is read as $10^{0.6x/x} = 3.98$
- $-0.3x$ mm is read as $10^{-0.3x/x} = 0.501$

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wosiew Mar 2004, wosiew Sep 2005