EEE1016 Electronics I

Experiment BE2: Transistor Circuits

1.0 Objectives

- To analyze the output characteristic of an npn transistor in the common-emitter circuit
- To evaluate values of DC current gain ($h_{FE}$) and small-signal current gain ($h_{fe}$) from the output characteristic curves
- To plot the load line of a common-emitter circuit
- To analyze the effects of base bias on the AC operation of a common-emitter amplifier
- To measure the magnitude of the small-signal voltage gain of an amplifier circuit

2.0 Apparatus

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

3.0 Introduction

A pnp bipolar junction transistor (BJT) consists of a layer of n-type semiconductor sandwiched between two layers of p-type semiconductor. Alternatively, an npn transistor may be constructed with a layer of p-type semiconductor sandwiched between two layers of n-type semiconductor. The conceptual structure and the schematic symbols of the two types of transistors are shown in Figure 1. The interface between a p-type semiconductor and an n-type semiconductor is similar to a p-n junction diode.

![Figure 1: Conceptual structure and schematic symbols of BJTs](image)

A transistor can be used in three different basic configurations, namely common-emitter (CE), common-base (CB) and common-collector (CC). The common emitter
configuration refers to a circuit with the emitter terminal being common for both the input port and the output port, as shown in Figure 2.

Among the three configurations, the common-emitter configuration is the most versatile and useful. It functions as both voltage amplifier and current amplifier simultaneously. A small change in the input voltage $V_{BE}$ can cause a big change in the output voltage $V_{CE}$. Similarly, a small change in the input current $I_B$ can cause a big change in the output current $I_C$.

The collector current $I_C$, which is the output current, is a function of $V_{CE}$ and base current $I_B$. The typical output characteristic curves consist of plots of $I_C$ versus $V_{CE}$ at different base current $I_B$, as shown in Figure 3. For a fixed base current, say $I_B = 20 \, \mu A$, the collector current $I_C$ will increase initially when $V_{CE}$ is increased. However, $I_C$ will saturate at a nearly constant value when $V_{CE}$ becomes larger than a certain level.

The output characteristics describe the behaviors of the output current $I_C$ and the output voltage $V_{CE}$. The graph can be divided into three operating zones, known as the cut-off region, the active region, and the saturation region. The cut-off region is where $I_C$ is very small due to a small input current $I_B$. This small $I_C$ is associated to the fact that both the collector junction and the emitter junction are reverse biased by the applied voltage. Conversely, the saturation region is where both the collector junction and the emitter junction are forward biased. The bulk of the transistor behaves like a resistor with a very low
resistance. A small increase in $V_{CE}$ can cause a large increase in $I_C$. In short, the transistor works as an open-circuited switch in the cut-off region, but as a short-circuited switch in the saturation region.

For a transistor to function as a linear amplifier, it must be operated in the center of the active region (so that the output current can vary linearly with the input current and reproduce the same waveform as the input but with a larger amplitude). As the base current varies with time, the relationship between $I_C$ and $V_{CE}$ can be represented by a load line (see Figure 3). Since the transistor operates between “open-circuit” and “short-circuit”, the largest value of $V_{CE}$ is equal to the DC supply voltage $V_{CC}$, and the largest value of $I_C$ must be less than $V_{CC}/R_C$.

In the active region, the collector junction is reverse biased while the emitter junction is forward biased. The collector current $I_C$ is related to the base current $I_B$ and a reverse-saturation current $I_{CO}$ as follows:

$$I_C = (1 + \beta) I_{CO} + \beta I_B$$

Since $I_B$ is usually much larger than $I_{CO}$, hence $I_C \approx \beta I_B$. The proportionality constant $\beta$ is known as the large-signal current gain (or dc current gain), and is usually designated by $h_{FE}$ in commercial device data sheet.

$$\beta \approx h_{FE} = I_C / I_B$$

An AC signal usually swings between positive voltage and negative voltage about a 0V reference. During the negative cycle of the AC waveform, the emitter junction will be reverse biased, forcing the transistor to operate into the cut-off region. To overcome this problem so that the transistor amplifier can function throughout the full cycle of the waveform, a DC current must be added to the input AC current. This action is called biasing of the transistor. When there is no AC input, i.e. the quiescent state, a DC current continues to flow into the base terminal, giving rise to a DC current $I_{C,Q}$ that flows into the collector terminal. The coordinate ($V_{CE,Q}$, $I_{C,Q}$) on the output characteristics curve is called the operating point or quiescent point, Q.

$$\begin{align*}
\beta &\approx h_{FE} = I_C / I_B \\
I_C &= (1 + \beta) I_{CO} + \beta I_B
\end{align*}$$

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$$\begin{align*}
\beta &\approx h_{FE} = I_C / I_B \\
I_C &= (1 + \beta) I_{CO} + \beta I_B
\end{align*}$$

Figure 4: h-parameter model representation of a common-emitter circuit
For an AC input signal with small amplitude, a transistor circuit is usually analyzed using the h-parameter model (see Figure 4). The relationship between the input voltage $v_{be}$ and output current $i_c$ can be expressed as functions of input current $i_b$ and output voltage $v_{ce}$ as follows:

\[
v_{be} = h_{ie} i_b + h_{re} v_{ce} \\
i_c = h_{fe} i_b + h_{oe} v_{ce}
\]

where

- $h_{ie} = \frac{v_{be}}{i_b} \mid_{v_{ce} \text{ constant}}$ = input resistance with output short-circuited
- $h_{re} = \frac{v_{be}}{v_{ce}} \mid_{I_b \text{ constant}}$ = reverse open-circuit voltage amplification
- $h_{fe} = \frac{i_c}{i_b} \mid_{v_{ce} \text{ constant}}$ = short-circuit current gain
- $h_{oe} = \frac{i_c}{v_{ce}} \mid_{I_b \text{ constant}}$ = output conductance with input open-circuited

$v_{be}$, $i_c$, $i_b$ and $v_{ce}$ are incremental values which are not affected by the DC bias of the transistor. $h_{fe}$ is also known as the small-signal current gain. It is usually the most important parameter for a small-signal transistor amplifier circuit design. It is not the same as the $h_{FE}$. From the definition of $h_{fe}$ and the output characteristics curve in Figure 3, the value for $h_{fe}$ can be approximated as:

\[
h_{fe} = \frac{i_c}{i_b} \approx \frac{\Delta I_c}{\Delta I_B} = \frac{I_{C2} - I_{C1}}{I_{B2} - I_{B1}}
\]

at a particular operating condition specified by $V_{CE,Q}$ and $I_{C,Q}$. The method to determine the approximate value of $h_{fe}$ is illustrated in Figure 5.

Figure 5: Determining $h_{fe}$ from the output characteristics
Instructions

Theoretical predictions
Students must complete the theoretical predictions before attending the corresponding lab session. All students must immediately submit the Short Report Form to the instructor just after coming into the lab. The instructor will check your predictions and then return it back to you. During the processes of theoretical predictions, students should attempt to understand the purposes of the experiments. Use the predicted results to verify your measured data.

Cautions
Oscilloscope: Make sure the INTENSITY of the displayed waveforms is not too high, which can 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.

Sketching oscilloscope waveforms on graph papers
Refer to Appendix D for efficient waveform sketching.

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)
- 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

Theoretical Predictions

4.1 Static Characteristics
No prediction is carried out in this part. The DC current gain $h_{FE}$ covers large range (see Table AE1, Appendix E). The $h_{FE}$ obtained in Experiment 4.1 should fall in this range at the same conditions. The shapes of the characteristic curves obtained in Experiment 4.1 can be compared with the characteristic curves in Figure AE2 and Figure AE4. The non-linearity of the static characteristic curves is sorely caused by the dependency of $h_{FE}$ on $I_C$ and $V_{CE}$ (note $h_{FE}$ also changes with temperature). Figure AE4 shows the $h_{FE}$ dependence of $I_C$ at $V_{CE} = 1V$.

4.2 Effects of Biasing on a BJT amplifier
To understand the operation of a BJT amplifier with AC signals, some output characteristic curves were generated with PSpice. Note that these output characteristic curves may not be the same like those obtained in Experiment 4.1 since the parameters of a BJT are most likely different from those of other BJT. Indeed, the output characteristics are controlled by a set of parameters which result small chance of two BJTs with identical characteristics. Even the BJTs of a super-matched pair used for differential amplifier (Electronics 3) have slightly different characteristics. Amplifier circuit analysis for AC signals is split into DC analysis and AC analysis.
DC analysis:

Apply KVL at the output circuit of the amplifier circuit:

\[ V_{CC} = I_C R_C + V_{CE} \rightarrow I_C = - \frac{1}{R_C} V_{CE} + \frac{V_{CC}}{R_C} \]

It is a linear equation (line) with slope \( m = -1/R_C \) and intersection \( C = V_{CC}/R_C \). This line is called load line which is the locus of any possible operating points (DC or AC) of the amplifier. This load line has been drawn in Figure AE2 in Appendix E.

AC analysis:

The equivalent circuit of the amplifier circuit in Experiment 4.2 for AC signals is shown below (short \( V_{CC} \) to ground, replace capacitor with a wire and apply \( h \)-parameter model for the BJT). All the current and voltage are ac components. For approximation, let the equivalent resistance of the 500k potentiometer (assume it’s setting value is not small), 150k and 18k network is relatively large as compared with 10k + \( h_{ie} \), and \( h_{re} v_{ce} \) is relatively small as compared with \( v_i = 0.1 V_{\text{amplitude}} \). Hence, \( i_b \approx v_i/(1k + 10k + h_{ie}) = v_i/(11k + h_{ie}) \).

The steps to determine the output voltage (\( V_{CE} \)) swing are shown below.

1. Determine \( I_{C,Q} \) for a given \( I_{B,Q} \) which intersects with the DC load line in Figure AE2. Subscript \( Q \) indicates quiescent point.
2. Determine \( h_{ie} \) from Figure AE3 in Appendix E.
3. Calculate \( i_b \) swing amplitude.
4. Determine \( V_{CE,\text{max}} \) and \( V_{CE,\text{min}} \) from Figure AE2 based on \( i_b \) swing.
5. Calculate \( \Delta V_{CE,+} = V_{CE,\text{max}} - V_{CE,Q} \) and \( \Delta V_{CE,-} = V_{CE,Q} - V_{CE,\text{min}} \).

Example:

For \( I_{B,Q} = 5 \mu A \rightarrow I_{C,Q} \approx 0.75 mA \rightarrow h_{ie} \approx 4.5 k\Omega \rightarrow i_b \approx 6.5 \mu A_{\text{amplitude}} \rightarrow V_{CE} \approx 10.1 V, 13V, 15V \) (note \( V_{CE} = 15V \) is the most possible value), \( \Delta V_{CE,+} \approx 2V, \Delta V_{CE,-} \approx 2.9V \)

Another approach is using all the \( h \)-parameters to calculate \( v_{ce} \). However, this will not make you to understand the operation of the BJT amplifier.

Complete Table T4.2 in the Short Report Form for other \( I_{B,Q} \) values.

[10 marks]

Note: “Theoretical Prediction” to be submitted to the lab staff two (2) days before your respective lab session.
Experiments

4.0 Transistor Test
Procedures
Referring to the circuit board layout in Appendix A, without any connections, test the transistor Q1, Q2 (will not be used) and the voltage source transistor on the board by using the go/no-go testing method.

1. Set a multimeter in “diode test” mode (note that some multimeters need to push two buttons in together to set “diode test” mode). The “COM” terminal is negative “−” and the “V, Ω, mA” terminal is positive “+”.

2. Test the base-emitter and the base-collector junctions of the transistor Q1 on the board in forward bias condition, i.e. connect “+” terminal to the base and “−” to the emitter or collector. A good transistor will give forward voltage drops ($V_{BE}$, $V_{BC}$) of about 0.7V or 700mV in both junctions. Record the reading in Table 1. Note that one junction is always relatively higher the forward voltage than another.

3. Repeat procedure 2 for other transistors. Note for the voltage source transistor, the potentiometer need to be turned such that $V_{BC}$ is the maximum. [2 marks]

Circuit setups
1. To construct the circuit in Experiments 4.1 and 4.2, compare the resistors and capacitors in the circuit to be constructed against the list of component in Appendix A.
2. Check and mark the locations of the resistors and capacitors on the circuit board layout that corresponds to the components in the circuit to be constructed.
3. Construct the circuit by cross-referencing the given circuit diagram with the board layout.

4.1 Static Characteristics
Procedures
1. Using the circuit board provided, construct the circuit as shown below by referring to the circuit board layout in Appendix A. Caution: Do not short circuit point P15, TB12 or

![Circuit Diagram](image-url)
P16 to ground, the resistor R14 or the voltage source transistor may be overheated and burned.

2. Set the DC power supply to 15V. Set the current scale switch to LO (if any). Set the current adjustment knob to about ¼ turn from the min position. On the DC power supply unit, connect the "−" output terminal to the “GND” terminal.

3. Switch off the DC power supply. Connect the positive terminal from the power supply to the socket labeled V_CC on the circuit board, and the negative terminal to GND.

4. Switch on the DC power supply. Check whether there is 15V across TB9 and TB3 with a multimeter.

(Read all the Procedures 5, 6 and 7 before collecting data in Procedures 8 and 9.)

5. Setting the base current (I_B): Turn the 500kΩ potentiometer and measure the voltage (V_B1) across the 10kΩ resistor (R12, named as R_B1) with a multimeter. The relationship between I_B and V_B1 is given by Ohm’s Law, V_B1 = R_B1*I_B. E.g. for I_B = 5μA, V_B1 = 10k*5μ = 50mV. Calculate the V_B1 values corresponding to the I_B values as listed in Table E4.1 in the Short Report Form. Set the multimeter at suitable range for accurate measurement. Since the exact V_B1 values are difficult to be achieved (and time consuming) via the adjustment of the potentiometer, the measured V_B1 value can be V_B1(exact) ± 2mV.

6. Setting the collector-to-emitter voltage (V_CE): Turn the 10kΩ potentiometer and measure the voltage across P13 (or TB13, TB12, P15) and TB11 (or TB3, P14, TB2, P9) for V_CE voltage. (Do not measure V_CE across the collector-leg and base-leg to avoid accidental connecting the collector to the base by the multimeter probing pin. If this happens, I_B can be as high as 13.3V/100Ω = 133mA). Set the multimeter at suitable range for accurate measurement. The measured V_CE can be V_CE(exact) ± 0.02V (± 0.01V for V_CE(exact) = 0.2V and 0.5V).

7. Getting the collector current (I_C): Measure the voltage (V_C1) across the 100Ω resistor (R_C1). Calculate I_C = V_C1/R_C1. Set the multimeter at suitable range for accuracy.

8. Collecting data to observe the DC current gain h_FE varying with I_C at V_CE = 1.0V: Set I_B = I_B, min (the achievable minimum I_B current) and then set V_CE = 1V. Repeatedly recheck I_B and V_CE until the desired values (because I_B varies with V_CE and V_CE = V_CC - R_C1*I_C varies with I_C which varies with I_B). Measure and record V_C1 in Table E4.1(a). Repeat for I_B = 10, 20 and 30μA. Calculate I_C, h_FE = I_C/I_B.

9. Collecting data for plotting the output characteristics: Set I_B to 5μA [if 5μA cannot be achieved, use I_B, min (which is > 5μA) and correct the I_B value in Table E4.1(b)]. Record V_C1 value of for each V_CE value (Note I_B varies with V_CE for V_CE change in between 0V and ~1V). Calculate the I_C value. Repeat for I_B = 10, 15, 20, 30μA.

10. Using the values recorded in Table E4.1(b), plot the output characteristic curves on Graph E4.1 with 0.5mA/cm for vertical scale (or suitable scale to cover the graph area) and 1V/cm for horizontal scale. Note that the data points (marked with cross ‘x’) must be visible in the plot.

Ask the instructor to check your results. Show all the tables and Graph E4.1. Show the multimeter readings at V_CE = 14V, I_B = 30μA.
4.2 Effects of Biasing on a BJT Amplifier

Procedures
Before starting the experiment, check and verify that the equipment to be used is functioning properly, including voltage probes [see Appendix B].

1. Switch off the DC power supply. Construct a common-emitter amplifier as shown below using the provided circuit board.

![Circuit Diagram]

2. Set CH1 to 50 mV/div and CH2 to 2 V/div. Set time base to 20 µs/div. Make sure the variable knobs of Volt/div and Time/div at the calibrated (CAL’D) positions. Set the input couplings 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. [For other presetting, refer to Appendix C].

3. Set the function generator for a 10kHz sine wave with 0.1V amplitude [use the attenuation button (ATT) for small amplitude adjustment]. Check the waveform using the oscilloscope.

4. Connect the sine wave signal to terminals P8 - P9 (grounded at P9) on the circuit board.

5. Connect a probe from CH1 and a 2nd probe from CH2 of the oscilloscope to the circuit as shown in the figure above. Both probes must be grounded properly.

6. Switch on the DC power supply which is set at 15V. Make sure the voltage across TB9 and TB3 is 15 ± 0.1 V with a multimeter.

7. Set I_B to 5µA. (Refer to Procedure 5 of Experiment 4.1 for accurate I_BQ setting. If 5µA cannot be achieved, use the achievable minimum I_B current.)

8. Align the ground levels of CH1 and CH2 as indicated in Graph E4.2. Finely adjust the function generator frequency so that CH1 waveform (v_i) has period of 5 divisions (5div x 20 µs/div = 100 µs which is approximately equal to 1/f_gen, where f_gen is the frequency reading displayed on the function generation). Adjust the oscilloscope trigger level and the CH1 horizontal position so that CH1 waveform has peaks at the positions as shown in Graph E4.2. This step is important for all V_CE waveforms to be drawn with respect to v_i waveform. Keep the oscilloscope ON all the time because it needs to be warmed up.

9. Sketch the CH2 waveform (V_CE) displayed on the oscilloscope on Graph E4.2. **Do not move the waveform positions during the sketching.** Label this waveform with I_BQ = 5µA (correspondingly if 5µA cannot be achieved). Measure the maximum and the
minimum voltages of CH2 waveform (V_{CE,\ max} and V_{CE,\ min}) and record them in Table E4.2 (b). Calculate \( A_V = \frac{V_{CE,\ max} - V_{CE,\ min}}{v_{i(pp)}} \), where \( A_V \) is the voltage gain of the amplifier circuit and \( v_{i(pp)} \) is the peak-to-peak voltage of the input signal (\( v_i \)).

10. Repeat Procedures 8 and 10 for \( I_B = 10, 15, 20, 30 \mu A \). [7 marks]

Ask the instructor to check your results. Show Table E4.2 (a), Graph E4.1, Graph 4.2, Table E4.2 (b) and the waveforms for condition \( I_B = 30 \mu A \) on the oscilloscope.

**Marking Scheme for BE2:**

<table>
<thead>
<tr>
<th>Item</th>
<th>Marks (BE2)</th>
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<tbody>
<tr>
<td>Theoretical Predictions</td>
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<tr>
<td>Experimental Results</td>
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<td>Discussions</td>
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**Report Submission**

*Students are to submit the report immediately upon completion of the laboratory session*

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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>
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</thead>
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<td>1</td>
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</tr>
<tr>
<td>Brown</td>
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</tr>
<tr>
<td>No Color</td>
<td>-</td>
<td>-</td>
<td>20%</td>
</tr>
</tbody>
</table>

Capacitance
AB x 10^c pF 0.abc μF

Potentiometer

EQUIPMENT CHECKS
The go/no-go method of testing is used. Always do these checks before starting your experiment.

Oscilloscope voltage probe check
Use oscilloscope calibration (CAL) terminal. A good probe will give a waveform of positive square wave with 2V 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 waveforms being sketched. Hence, the important or interested points of a waveform as displayed on the oscilloscope screen will 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 2.5V DC reference
APPENDIX E

Diode and BJT characteristics

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

![Forward voltage characteristics of diode 1N4148](image)

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

Figure AE 2: PSpice simulated output characteristics of 2N3904

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

![Input resistance graph]

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

![DC current gain graph]

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

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

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