Transistors Used as a Switch

Transistors

The transistors we use in lab have parameters given in the following table:

<table>
<thead>
<tr>
<th></th>
<th>Transistors designed for digital circuits ( ECE 320 )</th>
<th>Transistors designed for analog circuits ( ECE 321 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>3904 NPN</td>
<td>TIP 112 NPN</td>
</tr>
<tr>
<td></td>
<td>3906 PNP</td>
<td>TIP 117 PNP</td>
</tr>
<tr>
<td>Current Gain</td>
<td>100 max(Ic) 200mA</td>
<td>1,000 max(Ic) 2A</td>
</tr>
<tr>
<td></td>
<td>100 max(Vce) 40V</td>
<td>1,000 max(Vce) 40V</td>
</tr>
<tr>
<td>Vce(sat)</td>
<td>300mV 3904</td>
<td>2.5V TIP 112</td>
</tr>
<tr>
<td></td>
<td>400mV 3906</td>
<td>2.5V</td>
</tr>
<tr>
<td>price</td>
<td>$0.037 3904</td>
<td>$0.37 TIP 112</td>
</tr>
<tr>
<td></td>
<td>$0.037 3906</td>
<td></td>
</tr>
</tbody>
</table>

• The current gain tells you what $\beta$ is.
• max(Ic): When used as an "on" switch, this is the maximum current this transistor can conduct.
• max(Vce): When used as an "off" switch, this is the maximum voltage the transistor can block.
• Vce(sat): When used as an "on" switch, the voltage drop across the transistor.
• Price: The reason we use the 3904 and 3906 transistors in lab. We go through a lot of them.

Note that Vce depends upon the base current and the collector current. Normally, we assume this is 0.2V for all transistors as a ballpark estimate.

Also note that you can tell the difference between a transistor designed for digital circuits and those designed for analog circuits just from the size of the transistor:
• If the transistor is small, it's designed to act as a switch where either I = 0 (off) or V = 0.2V (on). In either case, the power it dissipates is approximately zero.
• If the transistor has a heat sink, it's designed to operated in the active state where I > 0 and Vce > 0.

Using a Transistor as a Switch

To use an NPN transistor as a switch
• First, design a circuit which turns on your device including an extra 0.2V drop to model the losses in the transistor.

3904 Transistor (left) and TIP112 Transistor (right).
The TIP transistor has a heat-sink, telling you that it's designed to operate in the active region (analog circuits).
- Next, break the path from power to ground, placing the NPN transistor in series with the emitter tied to ground.
- Finally, add a resistor to the base chosen so that 
  \[ \beta I_b > I_c \]

Example: Design a circuit so that your cell phone can turn on and off a 1W LED at 100mA. Assume

Input (Cell Phone)
- 0V / 3V, capable of driving 10mA
- 5V power supply capable of driving 1A (anything more than 100mA)

Output: White 1W LED:
- Vf = 3.5V @ 350mA
- 100 Lumens @ 350mA

Relationship:
- When Vin = 0V,  Id = 0mA
- When Vin = 3V,  Id = 100mA

Solution: First, design a circuit that drives the LED at 100mA along with a 0.2V drop. Assuming a 5V power supply,

\[
R_c = \left( \frac{5V - 3.5V - 0.2V}{100mA} \right) = 13 \Omega
\]

Next, add an NPN transistor (3904) in series with the emitter tied to ground.

Finally, add Rb so that \( \beta I_b > I_c \). When on,

\[ I_c = 100mA \]

meaning

\[ I_b > \frac{I_c}{\beta} = 1mA \]

Let I_b = 2mA. Rb is then

\[
R_b = \left( \frac{3V - 0.7V}{2mA} \right) = 1150 \Omega
\]

The exact value of Rb isn't critical - so long as \( \beta I_b > I_c \). Round Rb to 1k
One way to look at what’s going on with this circuit is to look at the load-line relative to the transistor:

- When $I_c = 0$, $V_{ce} = 10V$
- When $V_{ce} = 0V$, $I_c = 103mA$

The base current, $I_b$, controls the collector current, $I_c$ as

$$I_c = \beta I_b$$

When $I_b = 0$, $I_c = 0$ and the transistor is off. This is easily done by outputting 0V from your cell phone.

If $\beta I_b$ is more than 100mA, the current $I_c$ clips at 100mA. This is called the "on" state or the transistor is saturated (it can't draw any more current).

Load Line for the NPN Transistor: Ideally you want to operate in the off or on (saturated) state where the power dissipated by the transistor is zero ($P = V I$)
Both of these states are what you want for an on/off switch:
- Off: $I_c = 0$
- On: $V_{ce} = 0$ (ideally) or 0.2V (in practice)

It also has the advantage that the power the transistor has to dissipate is zero at both of these states:
- The current is zero when off, meaning $P = VI = 0$
- The voltage is zero when off, meaning $P = VI = 0$ (approximately)

What you want to avoid is operating in-between these two points - where the power dissipated by the transistor is a maximum. This is why you design for $\beta I_b > I_c$: you want to make sure the transistor is saturated. Choosing $\beta I_b > I_c$ gives you a safety margin.

Example 2: Design a circuit so that your cell phone can drive an 8 Ohm speaker at more than 100mA

Input (Cell Phone)
- 0V / 3V, capable of driving 10mA
- 5V power supply capable of driving 1A

Output: 8 Ohm 20W speaker

Relationship:
- When $V_{in} = 0V$, $I_s = 0mA$
- When $V_{in} = 3V$, $I_s = 100mA$

Solution: 8 Ohms at 5V means you're trying to drive 625mA through the speaker

$$I_c = \frac{5V - 0.2V}{8\Omega} = 600mA.$$ This exceeds the 200mA the 3904 transistors can take. Instead, use a TIP112 transistor. Note that for this transistor:
- $\beta = 1000$
- $V_{be} = 1.4V$
- $V_{cesat} = 2.5V$

These are kind of large because the transistor is actually a Darlington pair. Anyway, first design a circuit to drive the speaker at more than 100mA (with a 2.5V drop in series to model the transistor). The current is then
\[ I_c = \left( \frac{5V - 2.5V}{8\Omega} \right) = 312mA \]

To saturate this, you need
\[ \beta I_b > I_c \]
\[ I_b > \frac{312mA}{1000} = 312\mu A \]

Let \( I_b = 1mA \). Then
\[ R_b = \frac{5V - 1.4V}{1mA} = 3.6k\Omega \]

The exact value of \( R_b \) isn't critical - so long as \( \beta I_b > I_c \). Let \( R_b = 3k \).

Circuit to allow a cell phone to drive an 8 Ohm speaker at 312mA (0.78W)

**Darlington Pairs:**

The TIP112 and TIP117 transistors are actually Darlington pairs. This is two transistors packaged together to give you a higher gain (1000 in this case). The disadvantage is

- \( V_{be} \) is now 1.4V (since you see two diodes from base to emitter), and
- \( V_{ce} \) can't be driven to 0.2V (transistor T2 is always active).

The latter is OK for analog circuits where you operated in the active region anyway. It sort of works as a switch - but it's not really designed for that.

Darlington Pair (TIP112 Transistor). This gives you a higher gain (1000) but \( V_{ce:sat} = 2.5V \)
Note when driving motors (inductive loads)

If you have an inductive load, you need to add a flyback diode to the circuit. The problem is that when the transistor is turned on, energy is store in the magnetic field of the inductor as

\[ E = \frac{1}{2}LI^2 \]

When the transistor turns off, the current goes to zero - meaning the energy has to go somewhere. What happens is the voltage shoots up as

\[ V = L \frac{di}{dt} \]

until it finds a path to ground. This is how spark-plugs work: the alternator is an inductor which stores energy. When the current is brought to zero, the magnetic field collapses and the voltage shoots up until it finds a path to ground - with the spark plug being that path.

For our transistor circuits, the path to ground is the transistor - meaning you're going to fry the transistor when you turn it off.

To limit the voltage, a flyback diode is used. This can be a diode tied to the power supply (limiting \( V_c \) to +12.7V for the circuit to the left) or a Zener diode can be used (limiting the voltage to +15V for the circuit on the right).

When you have an inductive load, you need to add a flyback diode to prevent frying the transistor when the transistor turns off.