CHAPTER 3

The Basics – Output

A great deal of your work with PICs will involve turning things on and off. The action may be as simple as illuminating an LED to show program status, or as complex as sequencing multiple motors. You may accomplish these actions with the PIC's input/output pins, unaided, or with external electronic or electromechanical devices. The action may require "sourcing" or "sinking" current or voltage. A high state pin *sources* current into an external load, while a low state output pin receives or *sinks* current from an external load. In this chapter, we will review a few elementary electronics principles and learn how to use them to allow PICs to control external devices.

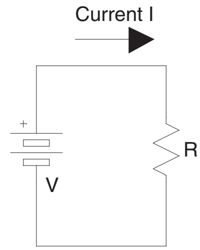


Figure 3-1: Conventional Current Flow

This chapter deals with the electronic characteristics of PIC pins as *output* devices.

Diagrams and discussions in this book assume positive or classical current flow, in which current flow from positive to negative, as shown in Figure 3-1. Traditional circuit equations, as well as the arrow symbol for diodes and transistors follow this convention as well.

Before building any of the sample circuits please download and read the relevant data sheets from the device manufacturer's Internet website. (The CD-ROM supplied with this book also contains some datasheets.) To keep this chapter at a manageable length, I've had to gloss over many subtleties in the specifications and application of these devices, hitting only the highlights. Careful advance study of data sheets and any associated application notes will reduce the time spent designing and debugging your designs.

Pin Architectures

At first glance, Microchip's simplified schematic of the I/O pins may seem confusing. Chapter 3 of the 16F87x Reference, for example, requires ten figures to illustrate the internals of I/O pin construction. At the beginning and intermediate stages of programming with MBasic and concentrating only on the output mode, though, we can simplify things further, reducing the essentials to those of Figure 3-2. In the 16F87x series, and in other mid-range PICs, when in output mode, pins are connected to a classical complementary metal oxide semiconductor (CMOS) configuration. In some cases, such as for RA0…RA3, Microchip's documents show the CMOS transistors directly; in others, such as RB0…RB3, they are not shown but are imbedded in a logic gate symbol.

For many purposes, we can regard the PMOS and NMOS transistors of Figure 3-2 as simply switched resistors; they are either very high resistances, amounting to almost open circuits, or a low value resistor, as illustrated in Figure 3-3. When the output is low, the pin appears to be a low value resistor, approximately 25 ohms. When the output is high, the pin appears to be the V_{DD} source connected through resistor of about 85 ohms, as long as the sourced current doesn't exceed 15 mA or so.

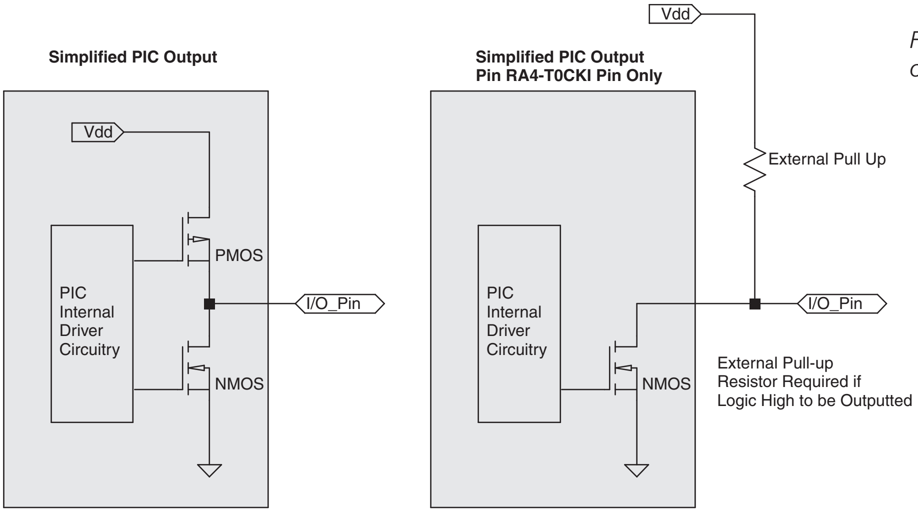


Figure 3-2: Simplified output pin.

When using Basic Micro's development or prototype boards, the 74HC4053 multiplexer needed to permit in-circuit programming adds approximately 50–100 ohms series resistance to pins RB4, RB6 and RB7. In many cases this additional resistance can be ignored.

One pin, RA4, is different; it is configured as an open drain MOSFET. When set to low, it performs identically with the other pin architectures. However, when set to high, there is no internal connection with V_{DD} and hence it will not directly source voltage. If it's necessary to use RA4 as a sourcing output pin, you can add an external "pull-up" resistor, typically in the range of 470 ohms–4.7K ohms. The sourced current then comes from the pull-up resistor. Unlike all other pins that cannot exceed V_{DD}, RA4's open drain is rated to 12 volts.

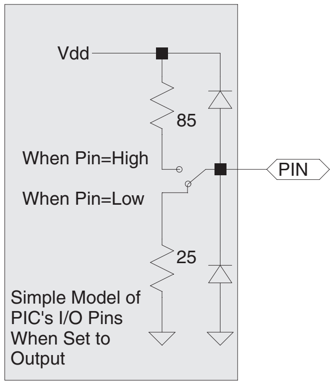


Figure 3-3: For many analyses, the output pins appear to be simple resistors.

When either sourcing or sinking current, the safe operating limits of the PIC must be observed. The following maximum safe parameters apply to the 16F87x series, and the Electrical Characteristics section of Microchip's data sheet for your target PIC should be consulted. Exceeding these limits may cause damage to the device, or reduce its reliability.

Absolute Maximum Ratings for 16F87X PICs				
Symbol	***Characteristic***	***MaximumValue***	***Units***	***Conditions***
V_{OD}	*Open drain high voltage*	*14*	*V*	*Applies to pin RA4 only*
	Voltage on any pin with respect to Vss	*-0.3V to* V_{DD}*+0.3V*	*V*	
	Total chip supply current into V_{DD} *supply pin*	*250*	*mA*	
	Total chip current out of V_{SS} *pin*	*300*	*mA*	
I_{OK}	*Output clamp current (Vf <0 or* $Vf>V_{DD}$*)*	*±20*	*mA*	
	Maximum output current sunk by any I/O pin	*25*	*mA*	

Absolute Maximum Ratings for 16F87X PICs				
Symbol	*Characteristic*	*MaximumValue*	*Units*	*Conditions*
	Maximum output current sourced by any I/O pin	*25*	*mA*	
	Maximum current sunk by PortA, PortB and PortE, combined	*200*	*mA*	*PortD and PortE are not implemented on 16F873/876 devices*
	Maximum current sourced by PortA, PortB and PortE, combined	*200*	*mA*	*PortD and PortE are not implemented on 16F873/876 devices*
	Maximum current sunk by PortC and PortD, combined	*200*	*mA*	*PortD and PortE are not implemented on 16F873/876 devices*
	Maximum current sourced by PortC and PortD, combined	*200*	*mA*	*PortD and PortE are not implemented on 16F873/876 devices*

Before starting our circuit discussion, let's review these maximum ratings.

Open drain high voltage—RA4 is unique and omits the internal PMOS transistor connection to V_{DD}. V_{OD} is maximum safe voltage that may be applied to RA4.

Voltage on any pin with respect to Vss—In the normal circuit, V_{SS} will be at ground potential. Your circuit should be designed so that when in output mode, pins will not be taken more than 0.3 V negative with respect to ground nor more than 0.3 V above the PIC's positive supply voltage, V_{DD}. Should these voltages be significantly exceeded, the protective diodes shown in Figure 3-2 will start to conduct, potentially causing the pin or chip maximum current limit to be exceeded, unless otherwise current limited.

Total chip supply current into V_{DD} supply pin—In addition to sourcing current limits on individual pins, this parameter establishes a global maximum available current for the entire PIC. It is, with negligible error, the sum of all pin sourcing currents.

Total chip current out of V_{SS} pin—In addition to sinking current limits on individual pins, this parameter establishes a global maximum for the entire PIC. It is, with negligible error, the sum of all pin sinking currents.

Output clamp current ($Vf<0$ or $Vf>V_{DD}$)—If a pin is taken above V_{DD} or below ground, it must be current limited, commonly with a series resistor, so that the output clamp current is not exceeded.

Maximum output current sunk by any I/O pin—The maximum safe sinking current when a pin is low. Sinking current is not internally limited and is governed by the external circuit parameters.

Maximum output current sourced by any I/O pin—The maximum current that may be safely sourced by a high pin. Internal circuitry limits sourcing current to approximately 25-30 mA so it is safe, but not good design practice, to operate an output pin into a short circuit.

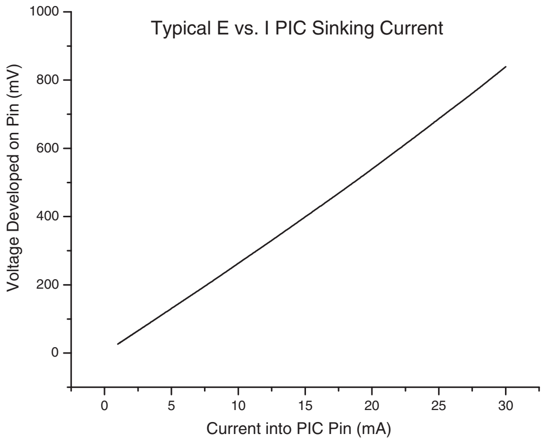
Maximum current sunk by PortA, PortB and PortE, combined—Another composite limit, applying to sinking current by all Ports A, B and E pins combined.

Maximum current sourced by PortA, PortB and PortE, combined— Another composite limit, applying to sourcing current by all Ports A,B and E pins combined.

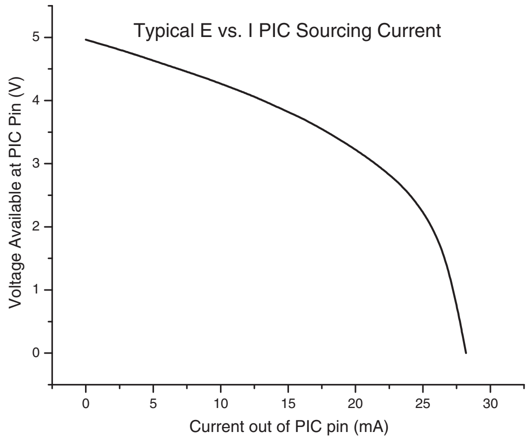
Maximum current sunk by PortC and PortD, combined— Another composite limit, applying to sinking current by all Ports C and D pins combined.

Maximum current sourced by PortC and PortD, combined— Another composite limit, applying to sourcing current by all Ports C and D pins combined.

A high output will source between 25 and 30 mA into a short circuit indefinitely, but when sinking current, the maximum safe current rating must be observed. Figures 3-4 and 3-5 illustrate the typical voltage



Figures 3-4: Typical E vs. I for sinking current.



Figures 3-5: Typical E vs. I for sourcing current.

versus current relationship for both sourcing and sinking current. Also remember that when using Basic Micro's 2840 Development Board, pins RB4, RB6 and RB7 are switched through the 74HC4053 multiplexer which has a 25 mA maximum current limit.

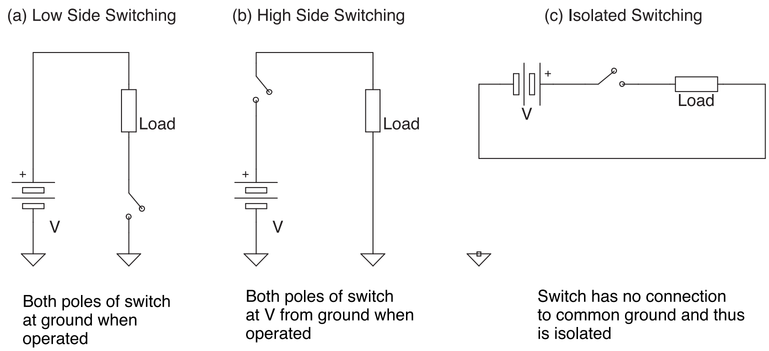


Figure 3-6: Possible switching configurations.

One final bit of terminology and we'll be onto circuitry. Figure 3-6 shows three possible switching configurations. For clarity, the drawing shows a mechanical switch. We, of course, will use a variety of electronic substitutes.

Low side switching—The switch is between the load and ground. When closed, both sides of the switch are at ground potential.

High side switching—The switch is between the voltage being switched and the load. When closed, both sides of the switch are at the switching voltage.

Isolated switching—There is no common connection between the circuit being switched and the controlling PIC. Many devices suitable for isolated switching also work for low side or high side switching.

LED Indicators

In learning how to programming a PC in a high level language, the traditional first program writes "Hello World" to the screen. Since PICs don't have a screen, the first MBasic program traditionally blinks an LED. We'll do that idea one better, building up to four states with one LED and one PIC pin. But, first we'll start with two LEDs and two pins as shown in Figure 3-7.

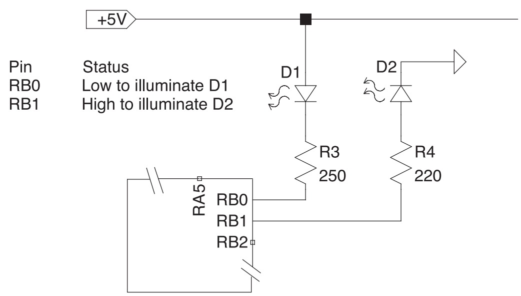


Figure 3-7: LED connections.

Program 3-1

```
i       var     byte

For i = B0 to B1       ;LEDs are on B0…B1
    Output I   ;so we make them outputs
Next

Main
        For i = B0 to B1       ;some will illuminate with a low
            Low i
        Next
        Pause 1000
        For i = B0 to B1       ;some will illuminate with a high
                High i
        Next
        Pause 1000
GoTo Main

End
```

The code is straightforward; After declaring our index variable **`i`**, we set pins RB0…RB1 to be outputs with the **`Output`** procedure inside a **`For…Next`** loop. The **`Output(i)`** procedure takes the pin address as its argument, with **`i`** ranging from **`B0`** to **`B1`**, pre-defined in MBasic as the numerical addresses of pins RB0…RB1. We then set these pins to alternate between low and high, with 1 second (1,000 milliseconds) in each state using MBasic's **`High`** and **`Low`** procedures inside two **`For…Next`** loops, each followed by a **`Pause(1000)`** procedure. An endless loop (**`Main…GoTo Main`**) causes the alternating high/low steps to be repeated.

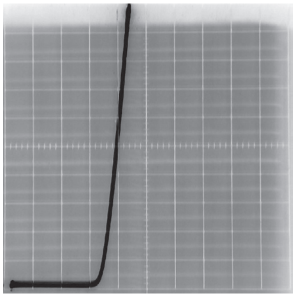


Figure 3-8: E/I curve trace of red LED. Horiz: 0.5V/div Vert: 5mA/div.

D1 illuminated when RB0 low—When RB0 goes low, current from the +5 V supply goes through series combination of LED D1, resistor R3 and the internal resistance of RB0. LEDs may be regarded as a device that have approximately a constant voltage drop for typical operating currents in the range from 1 mA to tens of mA. Figure 3-8 illustrates, for current levels between 1 and 50 mA, the LED's voltage drop is between 1.7 and 2.2 V. With only a small error, we may regard the LED as a constant voltage device, with about a 2 V drop. (There's a slight difference in voltage drop for different output colors, but for almost all red, green and yellow LEDs, we may calculate the current limiting resistors assuming a 2 volts drop.)

We may now solve the current loop equation for the circuit involving D1, remembering that a low pin is functionally equivalent to a 25 ohm resistor:

$$5V = 2V + 250I + 25I$$

rearranging

$$5V - 2V + 250I + 25I \quad \text{so} \quad 3V = 275I$$

or

$$I = \frac{3}{275} = 10.9\ mA$$

Where I is the current through the LED and series resistor.

More often, we wish to calculate the series current limiting resistor needed for a particular LED current I (in mA) where the LED is on when the PIC driving pin is low:

$$R_3 = \frac{3000}{I_{mA}} - 25$$

We fudged a bit by assuming the voltage drop across D1 is constant regardless of current, but these simple equations will be within 10% of a more detailed calculation, more than accurate enough for determining the current through an LED indicator.

D2 Illuminated when RB1 high—When RB1 goes high, current from the V_{DD} (the +5 V supply in Basic Micro's development boards) goes through series combination of LED D2, resistor R4 and the internal resistance of RB1. This is only a slight rearrangement of our earlier analysis of D1, with the internal equivalent resistance of the high pin being 85 ohms. Hence,

$$5V = 2V + 220I + 85I$$

rearranging

$$5V - 2V + 220I + 85I \quad \text{so} \quad 3V = 305I$$

or

$$I = \frac{3}{305} = 9.8\ mA$$

Where *I* is the current through the LED and series resistor.

Or, to calculate the series current limiting resistor where the LED is on when the PIC driving pin is high (in mA):

$$R_4 = \frac{3000}{I_{mA}} - 85$$

In addition to the constant voltage drop fudge, this analysis assumes a high pin is modeled accurately by as an 85 ohm resistor in series with V_{DD}. As Figure 3-5 shows, this assumption starts to fail as the sourced current exceeds 15 mA and the plot of *I* versus E diverges from a straight line.

Two LED's on one pin—We can connect two LEDs to one pin using the circuits we just developed as shown in Figure 3-9. The current for each LED is calculated using the same equations for individual pin connections.

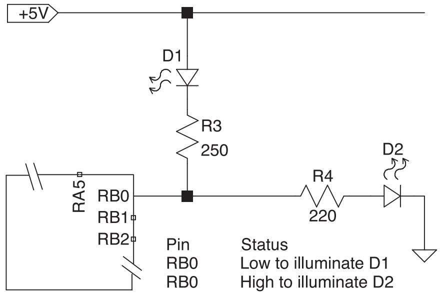


Figure 3-9: Two LEDs on one pin.

Four states from one pin—Using the connection of Figure 3-10, it's possible for one pin to produce four states in a 2-pin dual LED. (Most dual LEDs have two pins, but some dual LEDs have three pins permitting the circuit of Figure 3-9 to be used.) Fairchild's MV5491A two-pin dual LED is configured as a red and green LED in anti-parallel whereby current flow in one direction provides red light while the opposite direction provides green light.

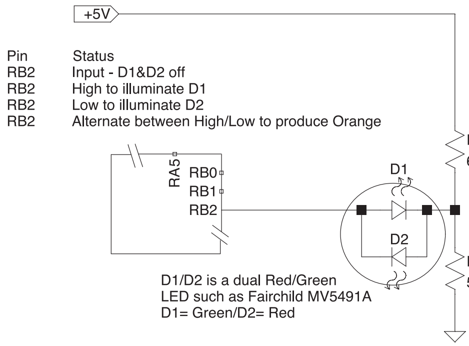


Figure 3-10: One pin, four states.

In the circuit of Figure 3-10 when RB2 is high, current flows from RB2 through D1 and R2. When RB2 is low, current flows from the +5 V supply through R1, D2 and is sunk at RB2. The suggested resistors yield 6.9 mA current for the green LED (D1) and 8.6 mA for the red LED (D2).

It's possible to get a third color out of this design as well. By rapidly switching between the red and green LEDs, the eye perceives orange. The following code fragment will accomplish this, switching at approximately 100 Hz.

```
Main
        High B2
        Pause 5
        Low B2
        Pause 5
GoTo Main
```

Finally if a fourth condition, LED off, is desired, switch RB2 to input. As an input, RB2 is essentially an open circuit, and neither D1 nor D2 will be illuminated. This trick will not work with the configuration of Figure 3-9, as both diodes will illuminate in that state.

Program 3-2 exercises all four states of Figure 3-10's dual LED.

Program 3-2

```
;Four states from one dual color LED and one PIC Pin
;Assumes bi-color LED on RB2
;With voltage divider circuit

i       Var             Byte


Main
        High B2                 ;Green
        Pause 1000
        Low B2                          ;Red
        Pause 1000

        For i = 0 to 255                ;Orange
                High B2
                Pause 5
                Low B2
                Pause 5
        Next

        Input B2                        ;no illumination
        Pause 1000

GoTo Main

End
```

Program 3-2 first illuminates the green LED for 1 second followed by red for 1 second, followed by 2.5 seconds of orange when both the red and green diodes are sequentially active for 5 ms. Finally, the diode is dark for 1 second.

Switching Inductive Loads

Stepper motors and relays are common inductive loads switched by PICs. Consider the circuit shown in Figure 3-11 that controls a small Omron G2RL-24 relay.

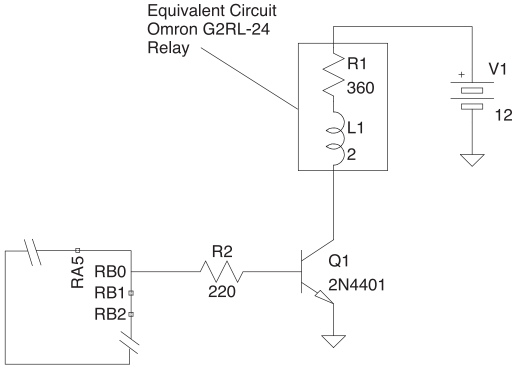


Figure 3-11: Switching an inductive load.

From introductory circuit theory, we know that when current flows through an inductor, energy is stored in its magnetic field. When the circuit is switched off, the stored energy must go "somewhere." What happens, of course, is the collapsing magnetic field causes a voltage spike—hundreds of volts even in a the small G2RL-24 relay—at the collector of Q1. In the absence of protective circuitry, Q1 will temporarily break down when the spike exceeds its V_{CEO} rating (40 V for a 2N4401) and the stored energy is dissipated in Q1. Even if Q1 isn't damaged by the repeated over-voltage breakdown, good design practice says that we should limit the over voltage to safe limits. Fortunately, as shown in Figure 3-12 it's easy to add a protective diode. D1 is called a "clamping diode" because it clamps the voltage spike. You may also see it referred to as a "snubbing diode" or "snubber."

When the magnetic field collapses as Q1 is switched off, the induced voltage causes diode D1 to conduct, and the stored energy is dissipated in the internal resistance of the inductor, R1 in Figure 3-12, and an optional external resistor, R3.

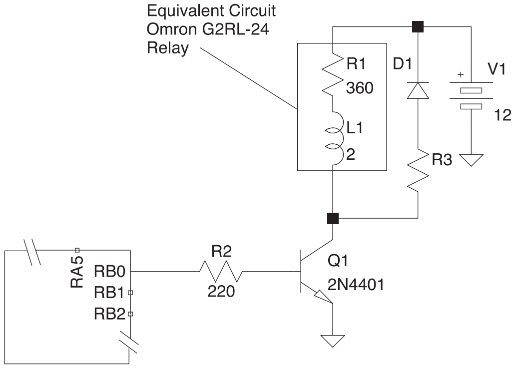


Figure 3-12: D1 and R3 are added protective components.

As with many things in electronics, there is a trade off here. The current resulting from the magnetic field decay doesn't drop to zero instantaneously, but rather as a function of the total resistance in the D1-R3-R1 circuit. The faster we make the current drop to zero (smaller the series resistance) the higher the voltage spike. Conversely, if we limit the voltage spike to its minimum level by setting R3 at zero ohms, we find the longest time for the induced current to decay. Figure 3-13 illustrates how the peak voltage spike and current decay times interact for the circuit of Figure 3-12. If you are familiar with elementary calculus, this relationship is obvious since the voltage *E* across an inductor of value *L* Henries is proportional to the time rate of change of the instantaneous current *i* through the inductor:

$$E = L\frac{di}{dt}$$

A faster decay (greater di/dt) means more induced voltage and vice versa.

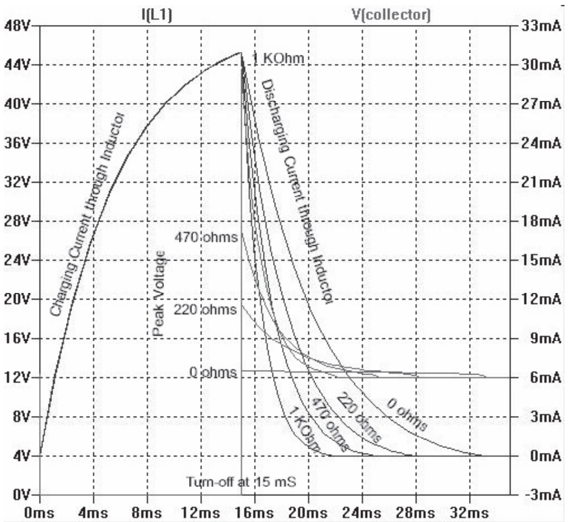


Figure 3-13: "Shutdown at 15 ms, current and voltage vs. clamping circuit resistance.

If we are concerned with the relay release time, we want the current to decay below the release current as quickly as possible. This suggests a higher series resistor, perhaps with a Q1 possessing a higher V_{CEO} to accept the resulting higher voltage spike. Perhaps more of a concern exists with when driving a stepper motor. We wish the magnetic field to collapse as quickly as possible when current is removed from a winding, particularly if we are interested in running the motor near its maximum steps per second rating.

For critical applications, and particularly for stepper motors, the clamping diode should be a fast switching device, such as a Schottky diode. Alternatively, it is possible to use a Zener diode, set to avalanche upon turn off. By delaying the onset of current flow until the Zener diode avalanches, significantly faster decay is possible. (The Zener is in series with D1, polarized so that D1 prevents forward current flow through the Zener.) We'll look at stepper motor driving circuits in detail in a later chapter.

It is possible to calculate the inductive spike level and decay time analytically, but it's much easier to use a SPICE circuit simulation program such as Linear Technology's LTSpice.[Ref 3-4]

The remainder of this chapter won't mention inductive spike protection, unless it is appropriate because of device characteristics.

Low Side Switching

Small NPN Switch

Figure 3-14 depicts a simple low side switch. When RB0 is high, Q1 is forward biased into conduction and current flows through the load. Let's work through a few design concerns with this simple circuit. We will assume the load is a 100 ohm resistor and V is 12 volts. Hence, the current being switched is 120 mA. We'll treat the current through this circuit as a constant and ignore the voltage drop across the switching device to simplify our calculations. Since our switch circuits will operate with a voltage drop of well under 0.5V, our simplifications will not introduce appreciable error.

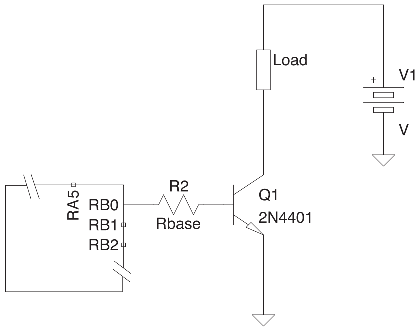


Figure 3-14: 2N4401 NPN low side switch.

Voltage rating—When RB0 is low, Q1 appears as an open circuit and thus has the full load supply voltage V across it. In a transistor data sheet, the maximum voltage that may safely be applied in this mode is V_{CEO} or maximum collector to emitter voltage, base open. Our particular device, a 2N4401 is rated for 40 V V_{CEO}. It should be safe to use it up to about 25 volts, applying a reasonable safety margin to the rated value. Our 12 V switching example will be well within Q1's ratings.

Leakage current—When the 2N4401 is cut off—that is, the base voltage is less than about 0.4 V, some leakage current, I_{CEX}, will still flow through the device's collector. I_{CEX} is rated not to exceed 0.1 µA in the 2N4401, a negligible value in the context of our circuits.

Saturation voltage—When the base drive is sufficient to saturate a bipolar transistor, the voltage drop between the collector and emitter is approximately a constant, referred to in data sheets as $V_{CE(SAT)}$, 0.4 V for a 2N4401 at current levels near 100 mA.

Collector current and device power dissipation—The 2N4401 has a maximum continuous collector current rating of 600 mA, and a maximum power dissipation rating of 625 mW at room temperature (25°C). The saturated collector voltage, $V_{CE(SAT)}$ is 400 mV at 150 mA and 750 mV at 500 mA. The thermal resistance junction to ambient $R_{\theta JA}$ is 200°C/watt and the maximum junction operating temperature is +150°C.

We'll assume adequate base drive to saturate Q1, hence we expect the collector voltage at 120 mA to be 400 mV or less. We'll also assume Q1 is to be on continuously—continuously in this context means long enough for thermal equilibrium to be reached, a matter of a few seconds for a 2N4401 size device. Hence:

The device dissipation will be 120 mA × 400 mV, or 48 mW.

The junction temperature rise over ambient will thus be 200°C/watt × 0.048 watts, or 9.6°C. Assuming the ambient air temperature is 120°F (49°C), the maximum junction temperature will thus be 48° + 9.6° = 57.6°C.

To determine case temperature, we use the thermal resistance junction to case $R_{\theta JC}$ specification, 83.3°C/watt. The case will thus be at 83.3°C/watt × 0.048 watts, or 4°C above ambient temperature. Our design thus is well within the safe operating parameters of the 2N4401.

If the 2N4401 is being cycled off and on at a rapid rate, the duty cycle will enter into certain of these ratings. For example, suppose the 2N4401 is driving a multiplexed LED display, on for 2 ms and off for 8 ms, for a duty cycle of 0.20. The average power dissipation of Q1 will thus be 20% of the peak power and the permissible peak power dissipation limit may be as much as five times the continuous value. Of course, for this averaging effect to work, the on time must be short compared with the time it takes for the device to reach thermal equilibrium.

Base current drive—As a rough approximation, we may regard Q1 as a current operated switch—that is, for every milliampere of current we wish to be sunk by Q1's collector, we must inject into the base a certain current level. (This is a highly simplified approximation of semiconductor operation, but adequate for our purpose.) The ratio of collector current to base current is known as h_{FE} or "DC current gain." The DC current gain varies from device type to device type, is not well controlled from example to example of the same device type and, finally, varies with current even for a particular transistor. 2N4401 devices, for example, have an h_{FE} that varies from 20 to 300, depending on the collector current.

If we are not concerned with switching time, or power minimization, the simplest design approach is to assume the worst case h_{FE} and design accordingly. To sink 120 mA, for example, since the minimum specified h_{FE} at 100 mA is 100, the target base current should be 1.2 mA. However, we note that at both 500 mA and 10 mA collector currents, the minimum h_{FE} drops to 40. Hence, as a matter of perhaps excessive caution, and to ensure Q1 is driven well into saturation, we will design for h_{FE} of 40, representing 3 mA base current.

The base to emitter junction voltage, V_{BE}, for a 2N4401 is specified at 750 mV for a base current of 15 mA and collector current of 150 mA, so we will use this value in calculating the base resistor, R2. (Since the base to emitter junction is modeled as a forward biased silicon diode, 700 mV is a commonly used rough estimate for the base to emitter voltage over a wide range of base currents for all silicon bipolar junction transistors.) R2's value (neglecting the PIC's approximately 85 ohm series resistance when sourcing current) is thus:

$$R2 = \frac{5V - 0.750V}{0.003A} = 1.4\ kohm$$

Switching Speed—We've alluded to Q1's switching speed concerns several times in our design. If we are switching an LED, or relay or stepper motor, these problems are unlikely to concern us. However, there are times where it is critical to switch a load as fast as possible. Figure 3-15 shows what happens when very short switching intervals are used in the circuit of Figure 3-14. RB0 emits a fast rise and fall 200 ns wide pulse and Q1 turns on with less than 20 ns delay. However, when RB0 goes low, Q1 exhibits nearly 500 ns turn off delay. The turn-off delay results from the "stored charge" effect, where excess minority carrier charge is stored in the base region of the transistor junction structure and must be removed before the transistor turns off and collector current ceases. We assume that anyone desirous of switching speeds in the sub-microsecond range knows about stored charges and the mitigating techniques to deal with the problem.

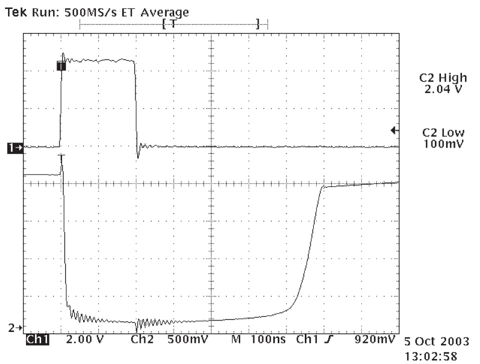


Figure 3-15: 2N4401 switching time Ibase = 6 mA, Ic = 40 mA; Ch1: PIC pin to base drive; Ch2: 2N4401 collector.

One final point should be noted with the bipolar transistor design of Figure 3-14—the voltage V being switched is immaterial. Of course, Q1 must be rated to withstand the voltage, but with a suitable transistor, the circuit of Figure 3-14 could switch 500 volts as easily as it switches 5 volts. The current required to saturate or cut off Q1 is not affected by the voltage it switches.

Small N-Channel MOSFET Switch

At the risk of considerable oversimplification, Q1 in Figure 3-14 may be thought of as a current controlled switch; current injected into the base causes the collector to be pulled close to ground potential. There is a similar voltage controlled switch, the MOSFET, whereby voltage applied to the device's gate causes the drain voltage to be pulled close to the source, or ground potential in a low side switch.

Figure 3-16 is the MOSFET counterpart of Figure 3-14. A 2N7000 MOSFET compares favorably with the 2N4401 in the maximum permissible voltage, with a 60 V rating. However, the 2N7000 is rated at 200 mA maximum continuous current and 500 mA maximum pulsed current with a total device maximum dissipation of 400 mW. Let's look at the areas of difference between the MOSFET and NPN bipolar transistor.

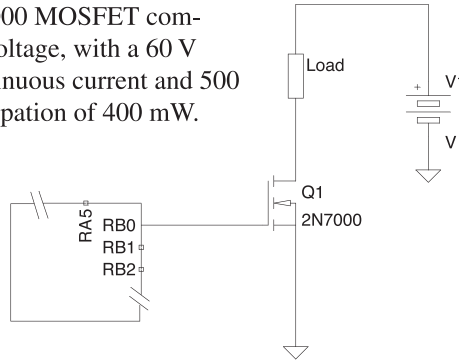


Figure 3-16: 2N7000 NPN Low Side Switch.

When saturated, a MOSFET acts like a low value resistor between the drain and source, referred to $R_{DS(ON)}$, with the corresponding voltage between the drain and source determined by the product of the drain current I_D and $R_{DS(ON)}$. Recall that in the 2N4401, the corresponding voltage $V_{CE(SAT)}$ is approximately a constant value over a wide current range.

The relationship between $R_{DS(ON)}$ and the gate voltage is, as illustrated in Figure 3-17, complex. The point to be taken away from Figure 3-17 is that since we can drive Q1's gate only to +5 volts with a high on an output pin, we exit the saturation region with only modest drain current.

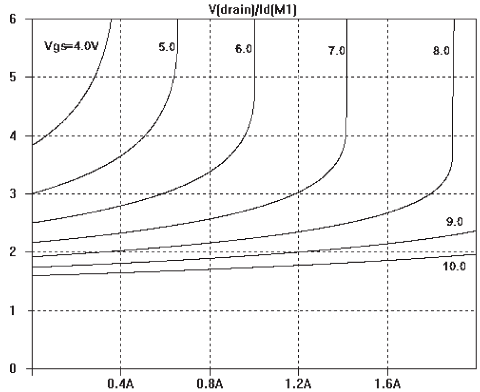


Figure 3-17: 2N7000 predicted on-resistance variation with gate voltage and drain current.

Let's run through the same 120 mA sink design we did for the 2N4401. We've already determined that the 2N7000 meets our open circuit voltage requirements and that 120 mA is less than the maximum permissible continuous drain current. With a gate drive of +5V and 120 mA drain current, Figure 3-17 shows $R_{DS(ON)}$ will be about 3.2 ohms. Since V_{DS} is the IR drop across $R_{DS(ON)}$, we may calculate it as 0.120 A × 3.2 ohms, or 0.38 volts, very similar to our 2N4401 NPN bipolar transistor design.

The power dissipated in Q1 equals $I_D \times V_{DS}$, or 0.38 volts × 0.120 mA or 46 mW, almost identical in value with the 48 mW we found for the 2N4401 bipolar switch and well within the device ratings. The 2N7000's thermal resistance junction to ambient $R_{\theta JA}$ is 312.5°C/watt and the maximum junction operating temperature is +150°C. The temperature rise at the case will thus be 312.5°C/watt × 0.046 watt, or 14.4°C. Assuming the ambient air temperature is 120°F (49°C), the maximum junction temperature will thus be 48°C + 14.4°C = 62.4°C, all quite acceptable values.

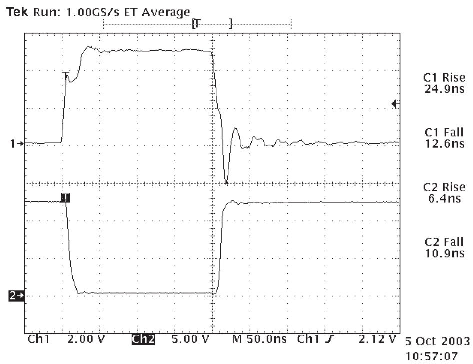


Figure 3-18: 2N7000 driven by PIC turn-on/turn-off speed Ch1: PIC output; Ch2: 2N7000 drain.

If we were to repeat this series of calculations for, say a 400 mA load, we will find $R_{DS(ON)}$ is 3.6 ohms, V_{DS} is 1.44 V and Q1's dissipation is 576 mW, well over the maximum permissible value for a 2N7000. The problem is that 5 V is inadequate gate voltage to fully turn the MOSFET at 400 mA.

When looking at nanosecond switching with a 2N4401, we found significant turn-off problems due to stored charge. As Figure 3-18 shows, both the turn on and turn off times for a 2N7000 are quite respectable. But, a close examination of the leading edge of the PIC output