If there is one single characteristic that justifies the existence of CMOS, it is low power dissipation. In the quiescent state, high-speed CMOS draws five to seven orders of magnitude less power than the equivalent LSTTL function. When switching, the amount of power dissipated by both metal gate and high-speed silicon gate CMOS is directly proportional to the operating frequency of the device. This is because the higher the operating frequency, the more often the device is being switched. Since each transition requires power, power consumption increases with frequency.

First, one will find a description of the causes of power consumption in HC-CMOS and LSTTL applications. Next will follow a comparison of MM54HC/MM74HC to LSTTL power dissipation. Finally, the maximum ratings for power dissipation imposed by the device package will be discussed.

Quiescent Power Consumption

Ideally, when a CMOS integrated circuit is not switching, there should be no DC current paths from VCC to ground, and the device should not draw any supply current at all. However, due to the inherent nature of semiconductors, a small amount of leakage current flows across all reverse-biased diode junctions on the integrated circuit. These leakages are caused by thermally-generated charge carriers in the diode area. As the temperature of the diode increases, so do the number of these unwanted charge carriers, hence leakage current increases.

Leakage current is specified for all CMOS devices as ICC. This is the DC current that flows from VCC to ground when all inputs are held at either VCC or ground, and all outputs are open. This is known as the quiescent state.

For the MM54HC/MM74HC family, ICC is specified at ambient temperatures (TA) of 25°C, 85°C, and 125°C. There are three different specifications at each temperature, depending on the complexity of the device. The number of diode junctions grows with circuit complexity, thereby increasing the leakage current. The worst case ICC specifications for the MM54HC/MM74HC family are summarized in Table 1.

Table 1. Supply Current (ICC) for MM54HC/MM74HC Specified at VCC=6V

<table>
<thead>
<tr>
<th>TA</th>
<th>Gate</th>
<th>Buffer</th>
<th>MSI</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>25°C</td>
<td>2.0</td>
<td>4.0</td>
<td>8.0</td>
<td>μA</td>
</tr>
<tr>
<td>85°C</td>
<td>20</td>
<td>40</td>
<td>80</td>
<td>μA</td>
</tr>
<tr>
<td>125°C</td>
<td>40</td>
<td>80</td>
<td>160</td>
<td>μA</td>
</tr>
</tbody>
</table>

To obtain the quiescent power consumption for any CMOS device, simply multiply ICC by the supply voltage: PDC = ICC * VCC

Sample calculations show that at room temperature the maximum power dissipation of gate, buffer, and MSI circuits at VCC=6V are 10 μW, 20 μW, and 40 μW, respectively.

Dynamic Power Consumption

Dynamic power consumption is basically the result of charging and discharging of external load capacitances. It can be broken down into three fundamental components, which are:

1. Load capacitance transient dissipation
2. Internal capacitance transient dissipation
3. Current spiking during switching

Load Capacitance Transient Dissipation

The first contributor to power consumption is the charging and discharging of external load capacitances. Figure 1 is a schematic diagram of a simple CMOS inverter driving a capacitive load. A simple expression for power dissipation as a function of load capacitance can be derived starting with:

\[ Q_L = C_L V_{CC} \]

where \( Q_L \) is the load capacitance, and \( C_L \) is the charge on the capacitor. If both sides of the equation are divided by the time required to charge and discharge the capacitor (one period, T, of the input signal), we obtain:

\[ \frac{Q_L}{T} = C_L V_{CC} \left( \frac{1}{T} \right) \]

One note of caution is in order. If all the outputs of a device are not switching at the same frequency, then the power consumption must be calculated at the proper frequency for each output:

\[ P_L = V_{CC}^2 (C_1 f_1 + C_2 f_2 + \ldots + C_n f_n) \]

Examples of devices for which this may apply are: counters, dual flip-flops with independent clocks, and other integrated circuits containing dual, triple, etc., independent circuits.
Internal Capacitance Transient Dissipation

Internal capacitance transient dissipation is similar to load capacitance dissipation, except that the internal parasitic “on-chip” capacitance is being charged and discharged. Figure 2 is a diagram of the parasitic nodal capacitances associated with two CMOS inverters.

C₁ and C₂ are capacitances associated with the overlap of the gate area and the source and channel regions of the P- and N-channel transistors, respectively. C₃ is due to the overlap of the gate and source (output), and is known as the Miller capacitance. C₄ and C₅ are capacitances of the parasitic diodes from the output to V₉ and ground, respectively. Thus the total internal capacitance seen by inverter 1 driving inverter 2 is:

C₉ = C₁ + C₂ + 2C₃ + C₄ + C₅

Since an internal capacitance may be treated identically to an external load capacitor for power consumption calculations, the same equation may be used:

P₉ = C₉V₉²f

At this point, it may be assumed that different parts of the internal circuitry are operating at different frequencies. Although this is true, each part of the circuit has a fixed frequency relationship between it and the rest of the device.

Current Spiking During Switching

The final contributor to power consumption is current spiking during switching. While the input to a gate is making a transition between logic levels, both the P- and N-channel transistors are turned partially on. This creates a low impedance path for supply current to flow from V₉ to ground, as illustrated in Figure 3.

For fast input rise and fall times (shorter than 50 ns for the MM54HC/MM74HC family), the resulting power consumption is frequency dependent. This is due to the fact that the more often a device is switched, the more often the input is situated between logic levels, causing both transistors to be partially turned on. Since this power consumption is proportional to input frequency and specific to a given device in any application, as is C₉, it can be combined with C₉. The resulting term is called “CpD,” the no-load power dissipation capacitance. It is specified for every MM54HC/MM74HC device in the AC Electrical Characteristic section of each data sheet.

It should be noted that as input rise and fall times become longer, the switching current power dissipation becomes more dependent on the amount of time that both the P- and N-channel transistors are turned on, and less related to CₚD as specified in the data sheets. Figure 4 is a representation of the effective value of CₚD as input rise and fall times increase for the MM54HC/MM74HC08, MM54HC/MM74HC139, and MM54HC/MM74HC140. To get a fair comparison between the three curves, each is divided by the value of CpD for the particular device with fast input rise and fall times. This is represented by “CpD,” the value of CpD specified in the data sheet for each part. This comparison appears in Figure 5. CpD remains constant for input rise and fall times up to about 20 ns, after which it rises, approaching a linear slope of 1. The graphs do not all reach a slope of 1 at the same time because of necessary differences in circuit design for each part. The MM54HC/MM74HC08 exhibits the greatest change in CpD, while the MM54HC/MM74HC139 shows less of an increase in CpD at any given frequency. Thus, the power dissipation for most of the parts in the MM54HC/MM74HC family will fall within these two curves.

One notable exception is the MM54HC/MM74HC04.
Inputs that do not pull all the way to $V_{CC}$ or ground can also cause an increase in power consumption, for the same reason given for slow rise and fall times. If the input voltage is between the minimum input high voltage and $V_{CC}$, then the input N-channel transistor will have a low impedance (i.e., be “turned on”) as expected, but the P-channel transistor will not be completely turned off. Similarly, if the input is between ground and the maximum input low voltage, the P-channel transistor will be fully on and the N-channel transistor will be partially on. In either case, a resistive path from $V_{CC}$ to ground will occur, resulting in an increase in power consumption.

Combining all the derived equations, we arrive at the following:

$$P_{TOTAL} = (C_{PD} + C_{CC})V_{CC} + l_{CC}V_{CC}$$

This equation can be used to compute the total power consumption of any MM54HC/MM74HC device, as well as any other CMOS device, at any operating frequency. It includes both DC and AC contributions to power usage. $C_{PD}$ and $l_{CC}$ are supplied in each data sheet for the particular device, and $V_{CC}$ and $f$ are determined by the particular application.

Comparing HC-CMOS to LSTTL

Although power consumption is somewhat dependent on frequency in LSTTL devices, the majority of power dissipated below 1 MHz is due to quiescent supply current. LSTTL contains many resistive paths from $V_{CC}$ to ground, and even when it is not switching, it draws several orders of magnitude greater supply current than HC-CMOS. Figure 6 is a bar graph comparison of quiescent power requirements ($V_{CC}$x$l_{CC}$) between LSTTL and HC-CMOS devices.

The reduction in CMOS power consumption as compared to LSTTL devices is illustrated in Figure 7 and Figure 8. These graphs are comparisons of the typical supply current ($l_{CC}$) required for equivalent functions in MM54HC/MM74HC, MM54HC/MM74HC, CD4000, and 54LS/74LS logic families. The currents were measured at room temperature ($25^\circ$C) with a supply voltage of 5V.

Figure 7 represents the supply current required for a quad NAND gate with one gate in the package switching. The MM54HC/MM74HC family draws slightly more supply current than the 54C/74C and CD4000 series. This is mainly due to the large size of the output buffers necessary to source and sink currents characteristic of the LSTTL family. Other reasons include processing differences and the larger internal circuitry required to drive the output buffers at high frequencies. The frequency at which the CMOS device draws as much power as the LSTTL device, known as the power cross-over-frequency, is about 20 MHz.

In Figure 8, which is a comparison of equivalent flip-flops (174) and shift registers (164) from the different logic families, the power cross-over frequency again occurs at about 20 MHz.
crease, it is of such a small magnitude (nanoAmps per device) that there will be very little increase in total power consumption.

Secondly, as system complexity increases, the percentage of the total system operating at the maximum frequency tends to decrease. Figure 9 shows block diagrams of a CMOS and an equivalent LSTTL system. In this abstract system, there is a block of parts operating at the maximum frequency (Fmax), a block operating at half Fmax, a block operating at one quarter Fmax, and so on. Let us call the power consumed in the first section P1. In a CMOS system, since power consumption is directly proportional to the operating frequency, the amount of power consumed by the second block will be (P1)/2, and the amount used in the third section will be (P1)/4. If the power consumed over a large number of blocks is summed up, we obtain:

\[ P_{TOTAL} = P1 + (P1)/2 + (P1)/4 + \ldots + (P1)/(2^{n-1}) \]

and for \( n > 2 \), \( P_{TOTAL} > 2P1 \)

Thus, an LSTTL system will draw more power than an equivalent HC-CMOS system.

Maximum Power Dissipation Limits

It is important to take into consideration the maximum power dissipation limits imposed on a device by the package when designing with high-speed CMOS. The plastic small-outline (SO) can dissipate up to 500 mW, and the ceramic DIP and plastic DIP can dissipate up to 700 mW. Although this limit will rarely be reached in typical high-speed applications, the MM54HC/MM74HC family has such large output current source and sink capabilities that driving a resistive load could possibly take a device to the 500 or 700 mW limit. This maximum power dissipation rating should be derated, starting at 65°C for the plastic packages and 100°C for the ceramic packages. The derating factor is different for each package. The factor for the plastic small-outline is −8.83 mW/˚C; the plastic DIP, −12 mW/˚C; and the ceramic DIP, −14 mW/˚C. This is illustrated in Figures 11, 12. Thus, if a device in a plastic DIP package is operating at 70°C, then the maximum power dissipation rating would be 500 mW − (70°C − 65°C) (12 mW/˚C) = 384 mW. Note that the maximum ambient temperature is 85°C for plastic packages and 125°C for ceramic packages.
FIGURE 11. Plastic Package (MM74HC)
High Temperature Power Derating
for MM54HC/MM74HC Family

FIGURE 12. Ceramic Package (MM54HC)
High Temperature Power Derating
for MM54HC/MM74HC Family
Summary
The MM54HC/MM74HC high-speed silicon gate CMOS family has quiescent (standby) power consumption five to seven orders of magnitude lower than the equivalent LSTTL function. At high frequencies (30 MHz and above), both families consume a similar amount of power for very simple systems. However, as system complexity increases, HC-CMOS uses much less power than LSTTL. To keep power consumption low, input rise and fall times should be fast (less than 50 to 100 ns) and inputs should swing all the way to $V_{CC}$ and ground.

There is an easy-to-use equation to compute the power consumption of any HC-CMOS device in any application:

$$P_{TOTAL} = (C_L + C_{PD})V_{CC}^2f + l_{CC}V_{CC}$$

The maximum power dissipation rating is 500 mW per package at room temperature, and must be derated as temperature increases.

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