1.2 THEORETICAL POWER DISSIPATION IN ELECTRONIC COMPONENTS

1.2.1 Theoretical Power Dissipation

Electronic devices produce heat as a by-product of normal operation. When electrical current flows through a semiconductor or a passive device, a portion of the power is dissipated as heat energy. The quantity of power dissipated is found by:

$$P_d = VI$$

where:

P_d = power dissipated (W)
V = direct current voltage drop across the device (V)
I = direct current through the device (A)

If the voltage or the current varies with respect to time, the power dissipated is given in units of mean power P_{dm}:

$$P_{dm} = \frac{1}{t}\int_{t_1}^{t_2} V(t)I(t)\,dt$$

where:

P_{dm} = mean power dissipated (W)
t = waveform period (s)
$I(t)$ = instantaneous current through the device (A)
$V(t)$ = instantaneous voltage through the device (V)
t_1 = lower limit of conduction for current
t_2 = upper limit of conduction for current

1.2.2 Heat Generation in Active Devices

1.2.2.1 CMOS Devices

The power that is dissipated by bipolar components is fairly constant with respect to frequency. The power dissipation for CMOS devices is a first-order function of the frequency and a second-order function of the device geometry. Switching power constitutes about 70 to 90% of the power dissipated by a CMOS. The switching power of a CMOS device can be found by:

$$P_d = \frac{CV^2}{2}f$$

where:

C = input capacitance (F)
V = peak-to-peak voltage (V)
f = switching frequency (Hz)

Short-circuit power, caused by transistor gates being on during a change of state, makes up 10 to 30% of the power dissipated. To find the power dissipated by these dynamic short circuits, the number of on gates must be known. This value is usually given in units of μW/MHz per gate. The power dissipated is found by:

$$P_d = N_{tot} N_{on} q f$$

where:

N_{tot} = total number of gates
N_{on} = percentage of gates on (%)
q = power loss (W/Hz per gate)
f = switching frequency (Hz)

1.2.2.2 Junction FET

The junction FET has three states of operation: on, off, and linear transition. When the junction FET is switched on, the power dissipation is given as:

$$P_{d_{ON}} = I_D^2 R_{DS(ON)}$$

where:

I_D = drain current (A)
$R_{DS(ON)}$ = resistance of drain to source (Ω)

In the linear and off states the dissipated power is again found by VI.

1.2.2.3 Power MOSFET

The power dissipated by a power MOSFET is a combination of five sources of current loss:[2,3]

a. P_c: conduction losses while the device is on,
b. P_{rd}: reverse diode conduction and t_{rr} losses,
c. P_L: power loss due to drain-source leakage current (I_{DSS}) when the device is off,
d. P_G: power dissipated in the gate structure, and
e. P_S: switching function losses.

Conduction losses, P_c, occurring when the device is switched on, can be found by:

$$P_c = I_D^2 R_{DS(ON)}$$

where:

I_D = drain current (A)
$R_{DS(ON)}$ = drain to source resistance (Ω)

Conduction losses when the device is in the linear range are found by VI, as are leakage current losses, P_L, and reverse current losses, P_{rd}. Switching transition losses, P_S, occur during the transition from the on to off states. These losses can be calculated as the product of the drain-to-source voltage and the drain current; therefore:

$$P_S = f_S\left(\int_0^{t_{S1}} V_{DS}(t)I_D(t)\,dt + \int_0^{t_{S2}} V_{DS}(t)I_D(t)\,dt\right)$$

where:

f_S = switching frequency (Hz)
V_{DS} = MOSFET drain-to-source voltage (V)
I_D = MOSFET drain current (A)
t_{S1} = first transition time (s)
t_{S2} = second transition time (s)

The MOSFET gate losses are composed of a capacitive load with a series resistance. The loss within the gate is

$$P_G = V_{GS} Q_G \frac{R_G}{R_S + R_G}$$

where:

V_{GS} = gate-to-source voltage (V)
Q_G = peak charge in the gate capacitance (coulombs)
R_G = gate resistance (Ω)

The total power dissipated by the gate structure, $P_{G(TOT)}$, is found by:

$$P_{G(TOT)} = V_{GS} Q_G f_S$$

1.2.3 Heat Generated in Passive Devices

1.2.3.1 Interconnects

The steady-state power dissipated by a wire interconnect is given by Joule's law:

$$P_D = I^2 R$$

where:

I = steady-state current (A)
R = steady-state resistance (Ω)

The resistance of an interconnect is

$$R = \rho \frac{L}{A_c}$$

where:

ρ = material resistivity per unit length (Ω/m) (see Table 1.1)
L = connector length (m)
A_c = cross-sectional area (m^2)

TABLE 1.1
Resistance of Interconnect Materials

Material	Resistivity, ρ, $\mu\Omega$/cm
Alloy 42	66.5
Alloy 52	43.0
Aluminum	2.83
Copper	1.72
Gold	2.44
Kovar	48.9
Nickel	7.80
Silver	1.63

Source: King, J. A., *Materials Handbook for Hybrid Microelectronics*, Artech House, Boston, 1988, p. 353. With permission.

Table 1.2 shows the maximum current-carrying capacity of copper and aluminum wires in amperes:[5]

TABLE 1.2
Maximum Current-Carrying Capacity of Copper and Aluminum Wires (in Amperes)

	Copper MIL-W-5088		Aluminum MIL-W-5088			Underwriters Laboratory			
Size, AWG	Single Wire	Bundled Wire[a]	Single Wire	Bundled Wire[a]	National Electrical Code	+60°C	+80°C	American Insurance Association	500 cmil/A
30	–	–	–	–	–	0.2	0.4	–	0.20
28	–	–	–	–	–	0.4	0.6	–	0.32
26	–	–	–	–	–	0.6	1.0	–	0.51
24	–	–	–	–	–	1.0	1.6	–	0.81
22	9	5	–	–	–	1.6	2.5	–	1.28
20	11	7.5	–	–	–	2.5	4.0	3	2.04
18	16	10	–	–	6	4.0	6.0	5	3.24
16	22	13	–	–	10	6.0	10.0	7	5.16
14	32	17	–	–	20	10.0	16.0	15	8.22
12	41	23	–	–	30	16.0	26.0	20	13.05
10	55	33	–	–	35	–	–	25	20.8
8	73	46	58	36	50	–	–	35	33.0
6	101	60	86	51	70	–	–	50	52.6
4	135	80	108	64	90	–	–	70	83.4
2	181	100	149	82	125	–	–	90	132.8
1	211	125	177	105	150	–	–	100	167.5
0	245	150	204	125	200	–	–	125	212.0
00	283	175	237	146	225	–	–	150	266.0

Rated ambient temperatures:

57.2°C for 105°C-rated insulated wire

92.0°C for 135°C-rated insulated wire

107°C for 150°C-rated insulated wire

157°C for 200°C-rated insulated wire

[a] Bundled Wire indicates 15 or more wires in a group.

Source: Croop, E. J., in *Electronic Packaging and Interconnection Handbook,* Harper, C.A., Ed., McGraw-Hill, New York, 1991. With permission.

These values can be rerated at any anticipated ambient temperature by the equation:

$$I = I_r \sqrt{\frac{T_c - T}{T_c - T_r}}$$

where:

I = current rating at ambient temperature (T)
I_r = current rating in rated ambient temperature (Table 1.2)
T = ambient temperature (°C)
T_r = rated ambient temperature (°C)
T_c = temperature rating of insulated wire or cable (°C)

1.2.3.2 Resistors

The steady-state power dissipated by a resistor in given by Joule's law:

$$P_D = I^2R$$

where:

I = steady-state current (A)
R = steady-state resistance (Ω)

The instantaneous power, $P_D(t)$, dissipated by a resistor with a time-varying current, $I(t)$, is

$$P_D(t) = I^2(t)R$$

where $I(t) = I_M \sin(\omega t)$ and I_M = peak value of the sinusoidal current (A).

The average power dissipation when a sinusoidal steady-state current is applied is

$$P_D = 0.5I_M^2R$$

1.2.3.3 Capacitors

Although capacitors are generally thought of as non-power-dissipating, some power is dissipated due to the resistance within the capacitor. The power dissipated by a capacitor under sinusoidal excitation is found by:

$$P_D(t) = 0.5\omega CV_M^2 \sin 2\omega t$$

where:

C = capacitance (F)
V_M = peak sinusoidal voltage (V)
ω = radian frequency, $2\pi f$
f = frequency (Hz)

TABLE 1.3
Typical Resistances of Capacitors[6–9]

Dielectric Material	Capacitance (μF)	R_{ES} @ 1 kHz, mΩ
BX	0.1	19.0 k
X7R	0.1	16.0 k
X7R	0.18	10.0 k
BX	1.0	2.0 k
Z5U	3.3	0.60 k
Tantalum	2.2	1.0 k
Tantalum	22	0.20 k
Tantalum	33	0.20 k
Tantalum	33	0.26 k
Tantalum	68	0.168 k

The equivalent series resistance of a capacitor in an AC circuit can lead to significant power dissipation. The average power in such a circuit is given as:

$$P_D = \frac{1}{T}\int_{t_1}^{t_2} I^2(t) R_{ES}\, dt$$

where R_{ES} = equivalent series resistance (Ω).

Table 1.3 shows the typical resistance of commercial capacitors.

1.2.3.4 Inductors and Transformers

Inductors and transformers generally follow the power dissipation of resistors,

$$P_D = I^2 R_L$$

where R_L = direct current resistance of the inductor or winding (Ω).

If the high-frequency component of the excitation current is significant, the winding resistance will increase due to the skin depth effect. The power dissipated by the sinusoidal resistance of an inductor is found by:

$$P_D(t) = 0.5 L I_M^2 \omega \sin 2\omega t$$

where:

L = inductance (Henry)
I_M = peak sinusoidal current (A)
ω = radian frequency ($2\pi f$)

When a ferromagnetic core is used, the loss consists of two sublosses: hysteresis and eddy current. The rate of combined core power dissipation can be found by:

$$\dot{P}_{D(CORE)} = 6.51 f^n B_{MAX}^m$$

where:

$P_{D(CORE)}$ = power dissipation (W/kg)
n, m = constants of the core material
f = switching frequency (Hz)
B_{MAX} = maximum flux density (Tesla)

The power dissipation is then found by:

$$P_D = \dot{P}_{D(CORE)} M$$

where M = mass of the ferromagnetic core (kg).