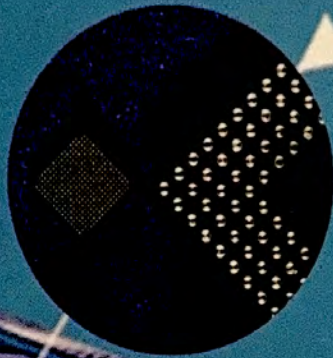


Fundamentals of Microsystems Packaging



Rao R. Tummala

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Murata Manufacturing Co., Ltd.

FUNDAMENTALS OF MICROSYSTEMS PACKAGING

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Microsystems packaging is a \$125 billion worldwide market, employing more than a million people. If one were to include all the microsystem devices in end products, the market is even bigger, accounting for more than \$300 billion; yet, microsystems packaging is not considered an academic subject. A typical academic subject such as microelectronics or VLSI has extensive courses, educational tracks, fundamental books, software tools, and hands-on facilities. None of these exist in microsystems packaging. The number of universities offering research programs and one or more courses, however, is increasing rapidly. It is estimated that this number in the United States, Europe and the Far East is about 50, having grown from less than ten universities about 10 years ago.

The *Fundamentals of Microsystems Packaging* is the first fundamental textbook written to meet the academic needs, at undergraduate and graduate levels, for this burgeoning technology. While there have been many books since my first modern book entitled *Microelectronics Packaging Handbook*, most, if not all, are considered reference books. They typically deal with one or more topics in a review fashion. However, microsystems packaging is not a narrow subject. The topic spans integrated circuit packaging to system board packaging, package assembly, and all the variations in between. It also deals with electrical design, thermomechanical design, cooling, materials and their processes, reliability, and so on. This was the case 10–20 years ago when I wrote the first book. Today's systems are more than microelectronics.

This book defines "microsystems" to include microelectronics, photonics, RF, and MEMS. All these devices need to be packaged, however, until they are systems at that level. Systems need to provide such functions as digital, optical, RF, analog and MEMS. This is exactly what this book is all about. It deals with all these technologies at the fundamental level—defining each, illustrating the key concepts in each, and introducing the critical nomenclature in a systematic fashion. Each topical chapter includes fundamental equations, homework problems, and future trends.

I am grateful to all the 50 global authors from industry and academia. This is perhaps the first book ever written by so many authors; although, I hope it reads as if written by one. I am thankful to the PRC staff, particularly to Nancy Trent who headed the book project from start to finish, to Angie Hughes (PRC), and to Mahesh Varadarajan from the Indian Institute of Science. They have put in endless hours coordinating with all of the 50 authors from around the world.

I am also grateful to Steve Chapman, the Executive Editor of McGraw-Hill, who met every one of my demands, including the two colors and the very affordable low cost for such a book that goes from wafers to systems and all the adjoining complementary technologies. I thank my wife, Anne, for her patience and full support during the course of the book.

My final thanks are to NSF for granting their national ERC to us at Georgia Tech and for challenging us with a need for this book.

Prof. Rao R. Tummala
Georgia Institute of Technology
Atlanta

I would like to dedicate this book:

To my Parents:

For your lifelong dedication to me as your only child, for your love and support, and for teaching me the meaning of family

To my Family (Anne, Dinesh, Vijay and Suneel):

For being my love, pride and joy to go to work for every day

To my Teachers:

For teaching me how to learn for the sake of learning and for the value of education

To my Students:

For teaching me how to teach for the sake of teaching

To IBM:

For giving me endless opportunities to grow and become an IBM Fellow

To Georgia Tech:

For allowing me to pursue my dream of being the new-generation of academician

To PRC Team:

For realizing my dream of the SOP and educating the world about it

To NSF:

For allowing me to pursue my dream of the SOP vision

To my Academic Colleagues:

For accepting me into your world, for using this book, and for working to make Packaging an academic subject

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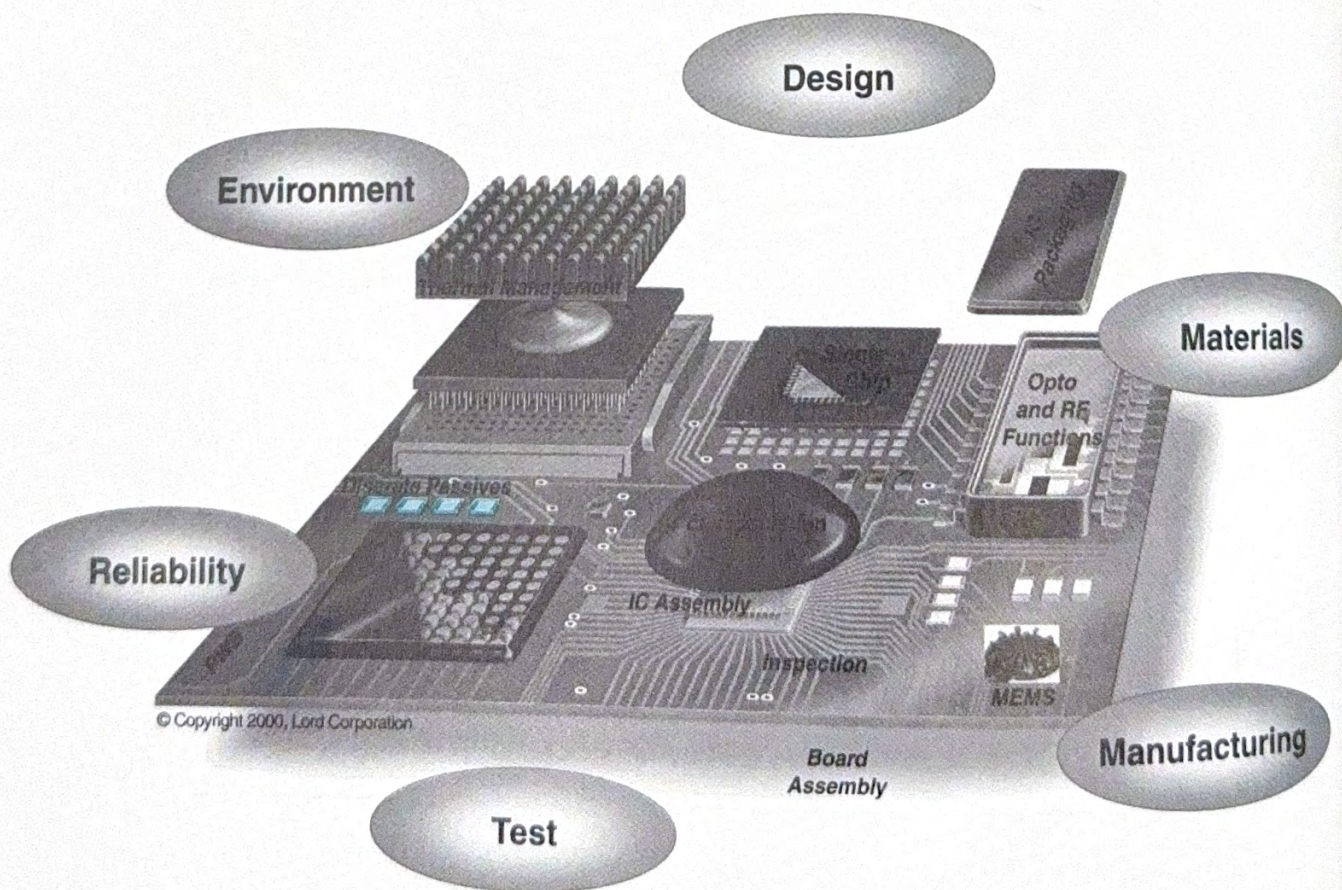
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FUNDAMENTALS OF PASSIVES: DISCRETE, INTEGRATED, AND EMBEDDED

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- 11.1 What Are Passive Components?
- 11.2 Role of Passive Components in Electronic Products
- 11.3 Fundamentals of Passive Components
- 11.4 Physical Representations of Passive Components
- 11.5 Discrete Passives
- 11.6 Integrated Passives
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CHAPTER OBJECTIVES

- Define passives and introduce fundamental parameters
- Describe the role of passives in electronic products
- Introduce and describe the many forms of passives—discrete, integrated, and embedded (integral)
- Describe the materials and process technology for discrete, integrated, and embedded (integral) passives

CHAPTER INTRODUCTION

Passives (primarily R , L , and C) are the key functional elements in all electronic systems. This chapter defines the fundamentals of passive components and describes their role in electronic products, with specific examples of everyday products. The chapter then describes the many forms of passives and shows how they are fabricated. The driving force toward miniaturization of electronic products, with increased functionality and reduced cost is addressed through integration of discrete passive components into arrays, networks and the emerging embedded (integral) passive technology.

11.1 WHAT ARE PASSIVE COMPONENTS?

An electrical system can be envisioned as a collection of components (or devices) that are interconnected in a systematic manner to perform the desired electrical functions. When a circuit is powered, these components perform functions that are classified as active or passive, depending on the electrical characteristics and capabilities. A passive component can sense, monitor, transfer, attenuate, and control voltage. However, passive components cannot differentiate between positive and negative polarity, nor can they render any gain and amplification. These functions are provided by the active components known as semiconductors. Passive components absorb and dissipate electrical energy provided by the active devices. Transformers, filters, mechanical switches, and electro-mechanical relays are also considered as passives.

Passive components are defined by their inability to add gain or perform switching fundamentals in their circuit performance. The switching requirement prevents diodes or discharge devices from being grouped within this category. Major passive components in electronic circuits are capacitors, resistors, and inductors. These components perform various important functions such as bias, decoupling, switching noise suppression, filtering, tuning, feedback, and termination in an electronic circuitry. In a typical circuit, 80% of the electronic components are passives, and they take up to 50% of the printed wiring board area. Passive components substantially influence system cost, size, and reliability.

11.2 ROLE OF PASSIVE COMPONENTS IN ELECTRONIC PRODUCTS

Electronic products such as VCRs, camcorders, television tuners, and other communication devices utilize a large number of passive components. Table 11.1 shows how the

TABLE 11.1 Number and types of passive components in PCs.

Motherboard		486	Pentium 120	Pentium 200 MMX	Pentium II 333 MHz	Pentium III
Capacitors	Leaded multilayer ceramics	58	0	0	0	0
	Surface mount multilayer ceramic	0	151	190	300	600
	Capacitor arrays	0	0	32	140	200
	Leaded tantalum	15	1	0	0	0
	Surface mount tantalum	0	0	0	37	80
	Aluminum	0	7	32	11	15
	Feedthrough	0	0	3	0	0
	Disks	0	0	0	4	0
						895
Total capacitors		73	159	257	492	0
Resistors	Leaded resistors	92	0	0	0	1000
	SMT resistors	0	146	188	635	300
	Resistor arrays	0	64	148	346	1300
Total resistors		92	210	336	981	2195
Total passives		165	369	593	1473	

Source: NEMI 2000 Roadmap.

TABLE 11.2 Active to passive ratio for recent products.

Product	IC	Passive Components	Total Components	Passive/Active
Notebook Computer	53	820	900	6:1
Desktop Computer	182	1066	1285	15:1
PCS Phone	15	322	380	21:1

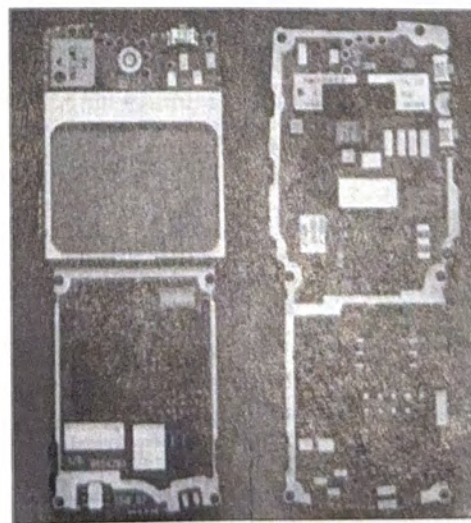
Source: NEMI 2000 Roadmap.

number of passive components is steadily growing as the electronics industry is progressing toward higher functionality, as in the case of personal computers. The ratio of the passive to active components is also increasing as is illustrated in Table 11.2 with popular consumer products. Figure 11.1 shows a photograph of a cellular phone. In the cellular phone like the one depicted in this figure, there are approximately 308 capacitors, 140 resistors, and 13 inductors identified by visual inspection. Comparing this number to the 21 ICs, it is evident that the passive components are dominant in number. Consider the number of cellular phones, PDAs, computers, and audio and video equipment being manufactured with these requirements, and one can see the enormous market being filled with passive devices.

The passive components come in distinct values that are usually basic decade multipliers of the Electronic Industries Association (EIA) classified base numbers. An example of this would be for the looser tolerance of 10% or higher (E-12 Standard EIA Decade Values) base value decade multipliers 1.0, 1.2, 1.5, 1.8, 2.2, 2.7, 3.3, 3.9, 4.7, 5.6, 6.8, and 8.2. The tighter tolerance of 2% and 5% would include those base number decade multipliers from E-12, with these additional values included: 1.1, 1.3, 1.6, 2.4, 3.0, 3.6, 4.3, 5.1, 6.2, 7.5, and 9.1. Using these multipliers, the typical values for capacitors might be seen as 1.2 pF, 12 pF, 120 pF, 1200 pF, 12000 pF, 1.2 μ F, 12 μ F, and 120 μ F. The



(a)



(b)

FIGURE 11.1 (a) Photograph of cellular phone (Courtesy of Nokia) (b) photograph of cellular phone board with passives. (Courtesy of Prismark)

same general values can be found with resistors and inductors. The tight tolerance components are relegated to precise circuit functions such as oscillator and timing circuits. Only stable components with inherent consistency of value over time and temperature can be found as tight tolerance, as the less stable components would drift out of a tight tolerance range in a matter of short time.

The components used in the various circuits are usually value related to the immediate circuit functions. High frequency applications will usually see capacitance values in the pF range and inductors in the nH (nanohenry or 10^{-9} henries) range. Impedance matching involved with coaxial cable will see values trying to match the impedance of these cables such as 50 ohms and 75 ohms impedance. Power supply applications not only deal with lower frequencies, but their bulk or energy requirements will require large capacitors and large inductors. A divider network created by resistors will usually involve high value resistors, as it is common sense that points out that the current loss in this pair creates an energy loss that degrades the efficiency of the circuit.

11.2.1 Digital Packages

Digital applications include decoupling capacitors (0.01–0.1 μF), terminating resistors (1–30 $\text{K}\Omega$), filter resistors (1–10 $\text{M}\Omega$), pull up/down resistors (1–30 $\text{K}\Omega$) and timing capacitors (10–100 pF). Among these, the *decoupling capacitors* are the most critical requirement, and in most cases each chip is accompanied with several decoupling capacitors. These capacitors supply charge to offset peak current demands during switching. Embedded capacitors offer less parasitics and improved electrical performance for faster clock speeds (>350 MHz) as decoupling capacitors. The need for power-ground decoupling capacitance is nearly universal in electronic circuits. For instance, in high frequency packaging, decoupling capacitors need to supply large current surges during very short time intervals, as much as 500 A/nS. The decoupling capacitor should be placed as close to the IC as possible in order to minimize the degree of intervening parasitics.

Terminating resistors are largely required in high-speed digital systems (>200 MHz) with long low-loss lines. Lines can be left unterminated if the round-trip delay time on a signal line is shorter than approximately one-third of the signal rise time. If series and parallel terminations are required, then two resistors per long signal lines are required. A typical high-speed digital package requires as many termination resistors as the number of chip I/Os (1000–5000 for a typical MCM-D). This number can be calculated using the Rent's Rule. Inductors are rarely required in digital systems. Digital circuits, other than terminating resistors, are least demanding in terms of component tolerance. Further, the decoupling capacitors and termination resistors are required to have low parasitics. According to the Semiconductor Industries Associations (SIA) Roadmap, decoupling capacitors in years 2004–2006 will have values ~ 20 and 72 nF/cm^2 for the hand-held and computer products, respectively.

11.2.2 RF Packages

There are many applications of RF packages, including power amplifier, transmit/receive modules, etc. Some of the key components in RF packages include filters (both lumped and distributed elements), couplers, RF crossings, impedance matching, and antennas.

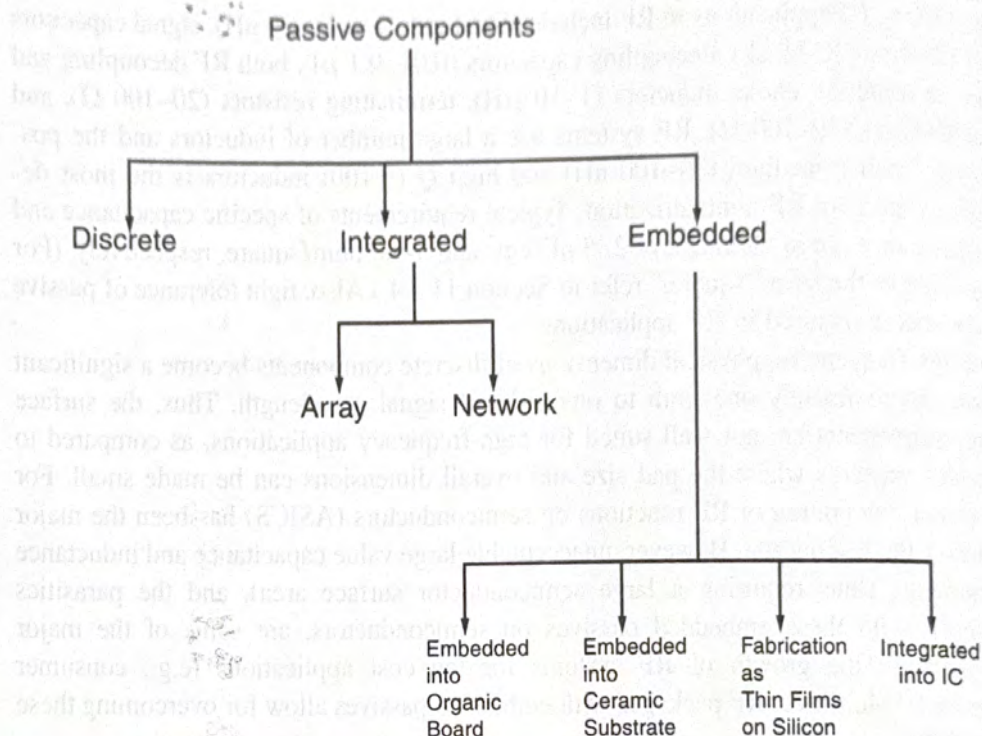


FIGURE 11.2 Representations of passive components.

cations, cellular phones and pagers, for example, is widespread and this includes decoupling, EMI filter capacitors (typically a RC combination), choke inductor, terminating resistors, etc.

This chapter defines the fundamentals of passive components and describes their role in electronic products with specific examples of everyday products. The chapter then describes the many forms of passives and shows how they are applied in electronic products. The driving force toward miniaturization of electronic products with increased functionality and reduced cost is addressed through integration of discrete passive components into arrays, networks and the emerging embedded (integral) passive technology (Figure 11.2).

11.3 FUNDAMENTALS OF PASSIVE COMPONENTS

11.3.1 Resistor

A resistor is a two-terminal electric circuit component that offers opposition to an electric current. The name, resistor, comes from its main property: it resists the flow of charge through itself, hence allowing us to control the current. Resistors can be made of various kinds of materials, but whatever the choice, it must conduct some electricity, otherwise it would not be of any use. In general, resistors absorb power from a circuit and convert it into mostly heat; therefore, they are normally rated for the maximum amount of power that they can safely handle, their power handling capability. In the case of thin-film resistors, the resistor will be damaged when power exceeds the limit.

11.3.2 Resistance Fundamentals

In many materials, there is a simple relationship between the applied electrical potential (V) across two points, and the resulting current (I) between those, independent of magnitude and direction of the current. Such materials are called Ohmic materials, obeying Ohm's Law:

$$V = IR \quad (11.1)$$

R is a constant called the resistance of the material, which has units of ohms (Ω). Figure 11.3a shows the circuit symbol of a resistor. When the resistors are connected in series as shown in Figure 11.3b, the same current exists in each circuit element (Kirchhoff's Current Law), thus the total resistance in a series connection is:

$$R = \sum R_i = R_1 + R_2 + R_3 \quad (11.2)$$

Similarly, in parallel connection as shown in Figure 11.3c, there are three current paths, but there is only one voltage connected across each of the three resistors, thus the total current I_t is given by:

$$I_t = I_1 + I_2 + I_3 = V_1/R_1 + V_2/R_2 + V_3/R_3 = V_t/R_t \quad (11.3)$$

Since all voltages are the same, Equation (11.3) reduces to:

$$1/R_t = 1/R_1 + 1/R_2 + 1/R_3 \quad (11.4)$$

Resistance is the property of an electric conductor by which it resists or opposes a flow of electricity, and dissipates electrical energy away from the circuit, usually as thermal energy and also light energy, as an electrical charge passes through them. Although Ohm's Law predicts the linear dependence of the V - I curve, the heating of the conductor changes the resistance resulting in a nonlinear V - I curve, an apparent violation of the Ohm's Law. Therefore, Ohm's Law applies only at a constant temperature. Materials with low resistance are called good conductors (10^{-3} – 10^{-6} Ω -cm), while those with high resistance are insulators (10^{19} – 10^6 Ω -cm). Materials in between the conductor and insulator range are classified as semiconductors. An example of a semiconductor would be MnO_2 , found in solid tantalum capacitors. With a resistivity of ~ 6 Ω -cm, it is neither a

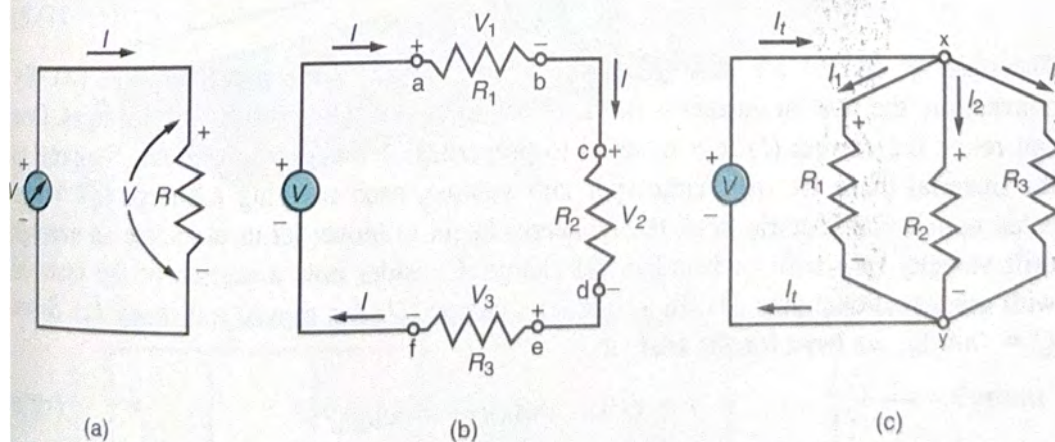


FIGURE 11.3 (a) Schematic of resistor circuit; (b) schematic of resistors in series; (c) schematic of resistors in parallel.

good conductor nor a good insulator. Although simple rectifiers and transistors are many times classified as semiconductors, possession of this property in a singular element has no junction created and has no rectification property. In addition, there are some non-Ohmic materials, such as combined semiconductors, varistors, rectifiers, and so on.

Resistance depends on the intrinsic material property, ρ , resistivity of the conductor, and the conductor's geometry such as cross-sectional area (A) and length (L). The resistance is defined as:

$$R = \rho(L/A) \quad (11.5)$$

Higher resistance is provided by a conductor that is long, small in cross section and of a material with high resistivity. Resistance is basically the same for alternating and direct current circuits. Resistors are normally designed and operated with varying levels of current, so that variations of their resistance values are negligible. However, an alternating current of high frequency tends to travel near the surface of a conductor, the so-called skin effect. Since such a current uses less of the available cross section of the conductor than a direct current, an alternating current causes more resistance than a direct current at higher frequencies.

11.3.3 Current

Ohm's Law can also be explained using conductivity (σ). For a uniform sample, the electric field in the sample is the voltage divided by the length. ($E = V/L$). Moreover, the current density, J , can be defined as the current divided by area ($J = I/A$). Therefore, Ohm's Law, $V = IR$, can become, by using Equation (11.5):

$$E/J = \rho \quad (11.6)$$

By modifying this equation, the conductivity $\sigma (= 1/\rho)$ can be obtained:

$$J = (1/\rho)E = \sigma E \quad (11.7)$$

When acted upon by an electric field, E , a charge experiences a force, and thus moves. One defines the *current* associated with this flow of charge as the amount of charge (Q) flowing past a point in a time interval t :

$$I = Q/t \quad (11.8)$$

The units of current are thus Q/second , which are given the name *amperes* (A). By convention, the flow of current is in the direction of the motion of positive charges. One can relate the current (I) in a material to properties of the atomic charges. Suppose in the material there are (n) charges per unit volume, each carrying a charge (q). When acted upon by an electric field, these charges begin to move; let us associate an average drift velocity (v_d) with each individual charge. Consider now a section of the material with cross-sectional area (A). In a time (t) a charge (Q) has moved a distance (x). Since $Q = (nAx)q$, we have for the current:

$$I = Q/t = (nAx)q/t = nAqv_d \quad (11.9)$$

The drift velocity (v_d) is very small for typical currents. The current density, J , is defined as I/A :

$$J = I/A = nqv_d \quad (11.10)$$

If we define the mobility of free electrons, μ_e , as $v_d = \mu_e E$, then the equation can become:

$$J/E = \sigma = nq\mu_e \quad (11.11)$$

The conductivity depends on the product of the charge carrier density and the mobility. Therefore, the resistivity can be explained as:

$$\rho = 1/nq\mu_e \quad (11.12)$$

Therefore, the conductivity and resistivity of materials can be obtained from the product of the charge carrier density (n) and the mobility of free electrons (μ_e). These properties can be experimentally obtained by the Hall measurement which determines the Hall coefficient, R_H , explained as ($\sigma R_H = \mu_e$).

11.3.4 Sheet Resistance

The resistance of a thin-film resistor is directly proportional to the resistivity (ρ), and inversely proportional to the thickness (d). It is therefore convenient to define a quantity, sheet resistance (R_s), which is equal to ρ/d . From Equation (11.5):

$$R = \rho(L/A) = \rho(L/dw) = (\rho/d)(L/w) = R_s(L/w) \quad (11.13)$$

The quantity, R_s , is called the sheet resistance, and may be thought of as a material property when the thin film is assumed as two-dimensional. The ratio (L/w) is sometimes called "the number of squares" in the resistor as shown in Figure 11.4, because it is equal to the number of squares of side w that can be superimposed on the resistor without overlapping. The term "squares" is a dimensionless number. The dimension of sheet resistance, R_s , is unit of ohms; however, it is convenient to refer to it in ohms per square, since the sheet resistance produces the resistance of the resistor when multiplied by the number of squares.

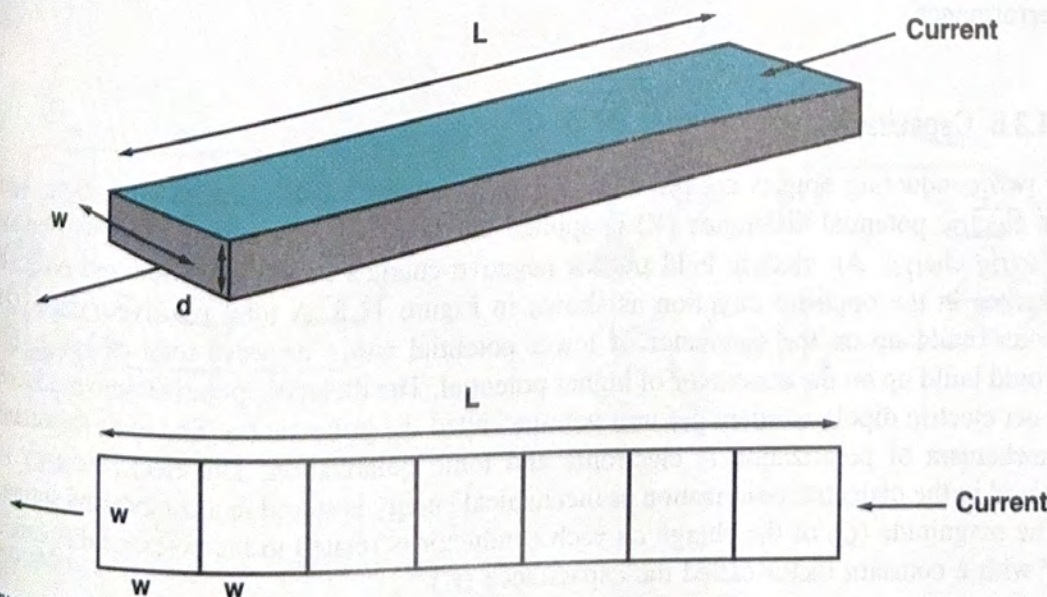


FIGURE 11.4 Resistor geometry.

Since the sheet resistance is a basic thin film material property, it is important to measure it without patterning a resistor. This is commonly done with the "four-point probe" technique. In this method, four contacts, equally spaced in a straight line, are made to the film; current is injected through one contact and out another, using two outer probes, and the resultant voltage drop across the two remaining points is measured with two inner probes. Then the sheet resistance is proportional to the ratio of the voltage (V) to the current (I):

$$R_s = C(V/I) \quad (11.14)$$

C is a constant of proportionality that depends on the configuration, position, and orientation of the probes, and also on the geometry of the thin film resistor. The probe spacing is usually made small, compared to the planar dimensions of the film, so that the film may be assumed to be infinite in extent. If the film were infinite in all directions, the constant (C) would be equal to $\pi/\ln 2$, or $C = 4.5324$ (for infinite film).

When using the four-point probe technique, it is convenient to adjust the current until it is numerically equal to C [for example, 4.53 milliamps (mA)], so that the voltage reading will be numerically equal to the sheet resistance. However, the constant (C) may have to be corrected for the size of the substrate, location of probing, and substrate conditions such as holes.

11.3.5 Capacitor

The capacitor is a device for storing an electrical charge (Q). In its simplest form, a capacitor consists of two metal plates separated by a dielectric layer. Capacitance is measured as the ratio of charge versus the applied voltage. A capacitor of one farad capacitance would have one coulomb of charge at a potential of one volt across the plates. Capacitors used in most electronic devices are in the microfarad (μF) range. Capacitors are produced in a wide variety of forms and materials. Air, mica, ceramics, glass, paper, oil, and metal oxides are used as dielectrics, depending on the purpose for which the device is intended. This wide selection of materials creates a wide range of performance.

11.3.6 Capacitance

If two conducting objects are put near one another with a dielectric between them, and an electric potential difference (V) is applied between two conductors, there will be an electric charge. An electric field pushes negative charges in one direction and positive charges in the opposite direction as shown in Figure 11.5. A total positive charge (Q) would build up on the conductor of lower potential and a negative total charge ($-Q$) would build up on the conductor of higher potential. The dielectric polarizes and produces a net electric dipole moment per unit volume called the polarization. The most important mechanism of polarization is electronic and ionic polarization. The electric energy is stored in the dielectric polarization as mechanical energy is stored in a compressed spring. The magnitude (Q) of the charge on each conductor is related to the potential difference V with a constant factor called the capacitance (C).

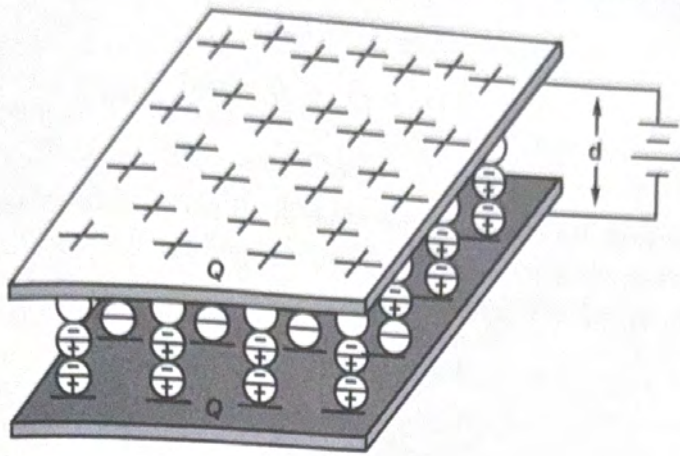


FIGURE 11.5 Capacitor configuration.

Capacitance is the ability of an electric circuit to store electrical charge. The capacitance of a vacuum dielectric, C_0 , measured in farads (coulomb/volt), is determined by the formula:

$$C_0 = Q/V = qA/V = \epsilon_0 EA/V = \epsilon_0 (V/d)A/V = \epsilon_0 A/d \quad (11.15)$$

where Q is the charge [in coulombs (C)] on one of the conductors, ϵ_0 is the vacuum permittivity ($8.854 \times 10^{-12} \text{ C}^2/\text{m}^2$), and V is the potential difference (in volts) between the conductors. When the dielectric materials with permittivity, ϵ , is placed between the conductors, the capacitance is:

$$C = \epsilon A/d = \epsilon_0 \kappa A/d = \kappa C_0 \quad (11.16)$$

where $\kappa (= \epsilon/\epsilon_0)$ is the dielectric constant (or relative permittivity) of the dielectric material between conductors, and A and d are the area and thickness of the dielectric.

Figure 11.6 represents a series and a parallel connection of three individual capacitive elements. In parallel connection, the voltage for each capacitor is the same, and the total current is the sum of the individual currents; thus, the total capacitance is the sum of individual capacitances:

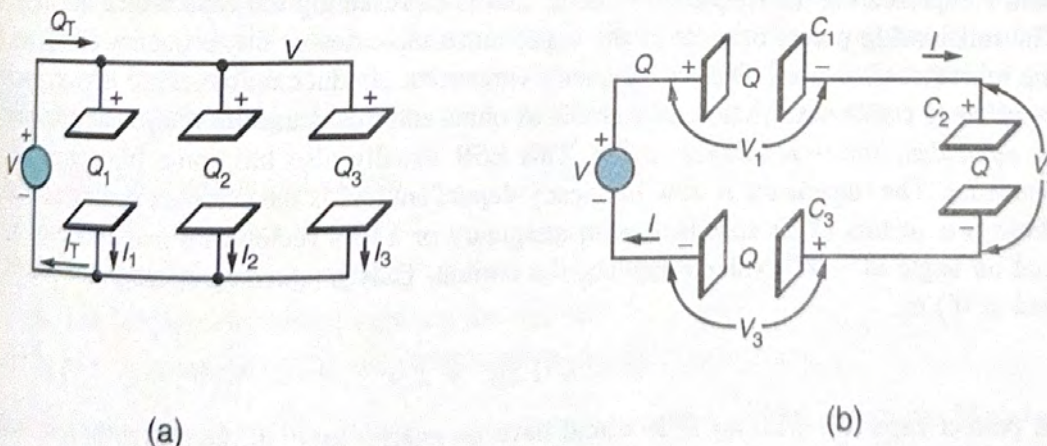


FIGURE 11.6 (a) Capacitors in parallel; (b) capacitors in series.

$$I_t = I_1 + I_2 + I_3 \quad (11.17)$$

$$Q_t = Q_1 + Q_2 + Q_3 \quad \text{and}$$

$$C_t = C_1 + C_2 + C_3$$

In series connection, the current is the same in all parts of the series circuit, and the charge on all parts is the same, since they are charged for the same time interval. The voltage is the sum of the individual voltages:

$$I_t = I_1 = I_2 = I_3 \quad (11.18)$$

$$Q_t = Q_1 = Q_2 = Q_3$$

$$V_t = V_1 + V_2 + V_3$$

Thus,

$$1/C_t = 1/C_1 + 1/C_2 + 1/C_3 \quad (11.19)$$

11.3.7 Impedance

The impedance that a capacitor presents to a circuit is related to the charging-discharging cycles. In a DC circuit, it is said to have infinite impedance once the charging currents cease. The measure of any minute amount of current in this DC state is defined as leakage current, as the insulative material does have some miniscule currents. For ceramic, glass and film capacitors, this leakage is so small (in the range of picoamperes), that this insulative property is expressed as insulation resistance, and usually expressed in gigaohms (1×10^9 ohms).

For an AC application, the impedance the capacitor offers is a complex association of the implied AC reactance and the real resistive losses (imperfect conductors in its structure and dielectric losses). The AC reactance, or capacitive reactance (X_c in ohms), is given as a relation of its capacitance and the rate of charge-discharge, or the frequency:

$$X_c = \frac{1}{2\pi FC} \quad (11.20)$$

with F representing the frequency in hertz, and C representing the capacitance in farads. The relationship points out that as the capacitance increases or the frequency increases, the reactance decreases. The loss elements (imperfect conductors, dielectric losses, etc.) combine to create a restriction measurable as ohms and this is usually relayed as *effective* or *equivalent series resistance* (ESR). This ESR usually also has some frequency dependence. The impedance is now frequency-dependent and is the complex summation of these two vectors (X_c is specified as an imaginary or a loss vector with magnitude of X_c and an angle of -90° , voltage lagging the current, ESR is a vector of magnitude ESR and at 0°) or:

$$Z = \sqrt{(\text{ESR}^2 + X_c^2)} \quad (11.21)$$

A perfect capacitor with no ESR would have no energy loss; all the charge is returned to the circuit. It is important to remember that there are no perfect capacitors, no perfect resistors, and no perfect inductors.

11.3.8 Loss Factor

Capacitors are specified by their capacitance, voltage and usually by some expression of the loss element. For film, glass and ceramic capacitors, the loss element is usually expressed as *dissipation factor* (DF). The DF of a capacitor is the ratio of its resistance to reactance at a given frequency. For the above-mentioned capacitors, the measurement frequency is at 1 kHz (some values below 1000 pF are measured at 1 MHz). The frequency is required, because the capacitive reactances, as well as the ESRs, change with frequency. For larger capacitance values found with electrolytic capacitors, the measurement is at 120 Hz. For the aluminum electrolytic, a common expression of this loss factor is "loss tangent," or the tangent of the complimentary angle formed by the impedance vector (or resistance divided by reactance).

For linear power supply applications, the frequencies of the rectified voltage pulses across the filter capacitors could coincide with the line frequencies, or double that. For the switch-mode regulators, the frequencies can be anywhere from 10 kHz up to 10 MHz. Losses given at 120 Hz would be of little significance, and capacitor manufacturers usually include information of the ESR at 100 kHz. In addition to the charging current in the capacitor dielectric, there is a loss of electrical energy due to the long-range charge migration and dissipation of energy from rotation or oscillation of dipoles. The amount of energy loss in the capacitor is defined as "loss tangent."

Other capacitor requirements are dielectric strength and leakage current. Dielectric strength is the maximum voltage that may be applied to the dielectric. The dimension of the dielectric strength is explained as voltage/mil or 10^6 voltage/cm. The leakage current represents the amount of miniscule current flowing, when voltage is applied to the two electrodes of capacitor. The larger the leakage current, the "leakier" the capacitor is. Leakage considerations are paramount when the device is battery powered, as higher leakage currents result in shorter battery life.

11.3.9 Inductor

An inductor is an impedance device comprising a coil, with or without core, for introducing inductance into an electric circuit. Both transformers and inductive reactors are included within the meaning of "inductor." Various inductors are shaped as coils wound on various core materials, such as ferrites. These cores multiply the inductance of a given coil by the "permeability" of the core material. The core may be in the shape of a rod or a toroid. For choosing an inductor for a specific application, it is necessary to consider:

1. The value of the inductance
2. The DC resistance of the coil
3. The current-carrying capacity of the coil windings
4. The breakdown voltage between the coil and the frame
5. The frequency range in which the coil is designed to operate

To obtain a very high inductance, it is necessary to have a coil of many turns. Winding the coil on a closed-loop iron or ferrite core can further increase the inductance. To obtain as pure an inductance as possible, the DC resistance of the windings should be reduced to a minimum. This can be done by increasing the wire size, which, of course,

increases the size of the choke. The size of the wire also determines the current-handling capacity of the choke, since the work done in forcing a current through a resistance is converted to heat in the resistance. Magnetic losses in an iron core also account for some heating, and this heating restricts any choke to a certain safe operating current. The windings of the coil must be insulated from the frame as well as from each other. Heavier insulation, which necessarily makes the choke more bulky, is used in applications where there will be a high voltage between the frame and the winding. The losses sustained in the iron core increase as the frequency increases. Large inductors, rated in henries, are used principally in power applications. The frequency in these circuits is relatively low, generally 60 Hz or low multiples thereof. In high-frequency circuits, such as those found in FM radios and television sets, very small inductors (of the order of microhenries) are frequently used.

Compared with resistors and capacitors, one of the main differences is what happens to electrical energy in them. Resistors dissipate electrical energy in the form of heat; capacitors store the energy in an electric field between the capacitor plates; inductors store the energy in the magnetic field in the coil. Inductors are closely related to capacitors; the rate of current change in an inductor depends on the voltage applied across it, whereas the rate of voltage change in a capacitor depends on the current passing through it.

11.3.10 Inductance

The inductance (L) of a circuit component (Figure 11.7) determines the magnitude of the *electromotive force* (EMF) induced in it as a result of a given rate of change of current through the component. Faraday's Law applied to an inductor states that a changing current induces a back EMF that opposes the change:

$$V = L \, di/dt \quad (11.22)$$

where V is the voltage across the inductor, and L is called the inductance and is measured in henries (or mH, μ H, etc.), and di/dt is the change in current over a small period of time. Putting a voltage across an inductor causes the current to rise as a ramp. For a capacitor, supplying a constant current causes the voltage to rise as a ramp; one volt across one henry produces a current that increases at one ampere per second. The in-

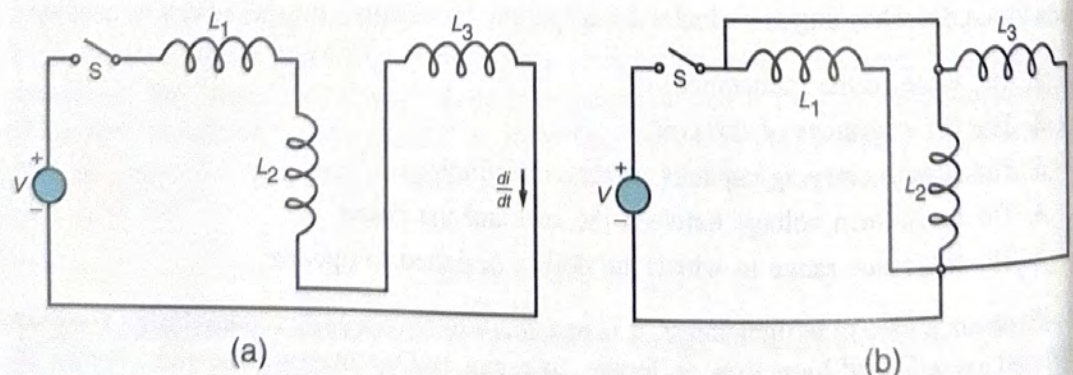


FIGURE 11.7 (a) Series inductors with no coupling between them (S = switch); (b) parallel inductors with no coupling between them (S = switch).

ductance will tend to smooth sudden changes in current, just as the capacitance smooths sudden changes in voltage. Of course, if the current is constant, there will be no induced EMF. So, unlike the capacitor which behaves like an open circuit in DC circuits, an inductor behaves like a short circuit in DC circuits.

When inductors are connected in series (Figure 11.7a), the current for each inductor is the same, thus dI/dt remains the same for each part. The total voltage is the sum of the individual inductor voltages. Therefore, as in the case of resistors, the total inductance is the sum of the individual inductances:

$$L = L_1 + L_2 + L_3 \quad (11.23)$$

In parallel connection (Figure 11.7b), the voltage for each inductor is the same, and the total current is the sum of the individual currents; thus the derivative of the total current is the sum of the individual derivatives. Hence:

$$1/L_T = 1/L_1 + 1/L_2 + 1/L_3 \quad (11.24)$$

Consider a simple inductor shown in Figure 11.8 in the form of a solenoid of area (A), length (l), and (n) turns per unit length, carrying a current (I). Then the magnetic field inside the coil is represented as:

$$B = \mu_0 n I \quad (11.25)$$

The stored energy per unit volume is expressed as:

$$B^2/2\mu_0 = \mu_0 n^2 I^2/2 \quad (11.26)$$

Total stored energy is represented by:

$$(\mu_0 n^2 I^2/2) Al = \mu_0 n^2 I^2 Al/2 = LI^2/2 \quad (11.27)$$

where μ_0 is the permeability of vacuum. Inductance is a quantity that measures the electromagnetic induction of an electric circuit component. The inductance:

$$L = \mu_0 n^2 Al \quad (11.28)$$

incorporates the dimensions of the inductor. Inserting an appropriate magnetic material within the coils of the inductor increases its inductance (L') and its stored magnetic energy by the relative permeability factor (μ_r), as defined by:

$$L'/L = \mu_r \quad (11.29)$$

The magnetic material in the core of the electromagnet increases the magnetic field inside the coil by the factor μ_r . An iron core with a relative permeability μ_r of 10^4 can significantly increase the magnetic field.

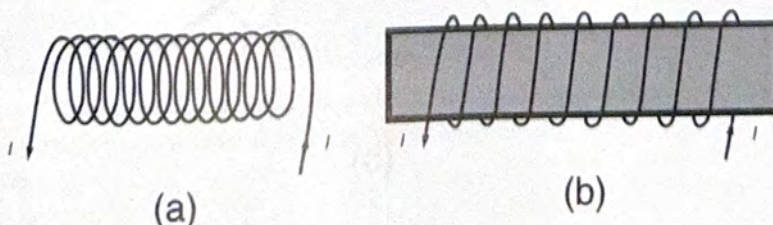


FIGURE 11.8 (a) Empty inductor; (b) inductor filled with magnetic material.

Another important parameter of the inductor is the quality factor, " Q -factor," which represents the ratio of energy stored to energy lost. For a series inductor and resistor circuit:

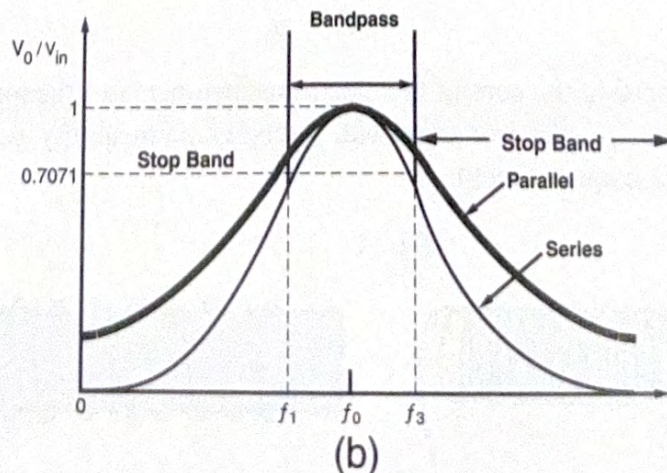
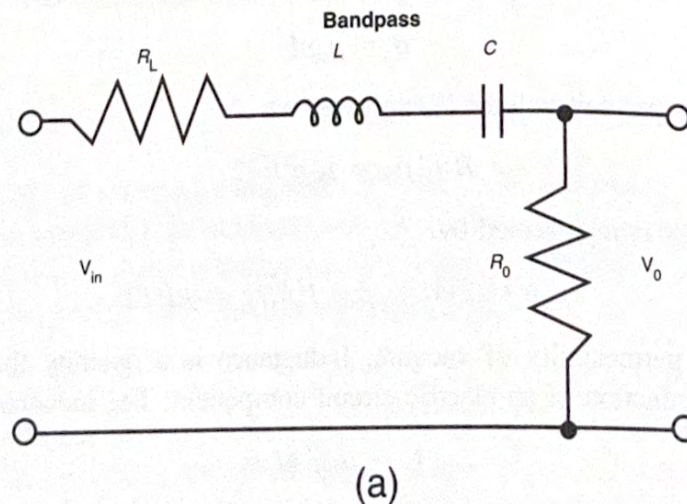
$$Q = \omega L / R, \quad R = \rho(l_w / A_w) \quad (11.30)$$

where R is the DC resistance, A_w is the cross-sectional area of the conductor, ω is the radian frequency, l_w is the length of the conductor lines, and ρ is the resistivity of the conductor material. To have a larger Q value, larger inductance and lower resistance of the conductor coil are needed.

11.3.11 Filters

A filter is defined as a transducer for separating waves on the basis of their frequencies. Filters can be designed to accept or reject frequencies containing the desired information, such as in an optical waveguide. Filters can function as active as well as passive networks. Passive networks consist of a series-parallel combination of R , L , and C . An active

FIGURE 11.9 (a) Circuitry of a series resonant bandpass filter; (b) amplitude response as a function of frequency.



network contains transistors and/or operational amplifiers in addition to R , L , and C to obtain the desired filtering effect. Four common types of filters are:

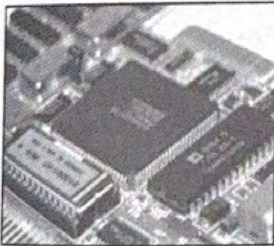
- Low-pass filter
- High-pass filter
- Bandpass filter
- Bandstop filter

The low-pass filter allows the signal to be transmitted up to a certain maximum frequency, f_c , above which the signal is rejected to a lesser or greater extent, depending on the design. Similarly, a high-pass filter allows frequency above the cut-off frequency, f_c , to be transmitted. Below this frequency, the signal is rejected. The bandpass filter selects a range of median frequencies to be passed. The bandstop filter rejects frequencies within a certain range and allows all frequencies below and above this range. Figure 11.9 shows the filtering effect.

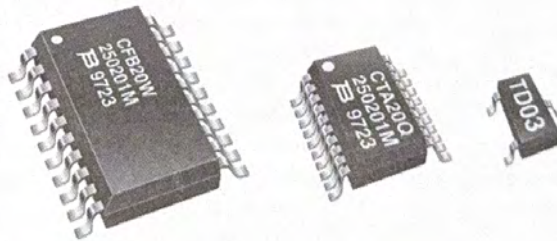
11.4 PHYSICAL REPRESENTATIONS OF PASSIVE COMPONENTS

There are currently three choices for passive components: discrete, integrated, and embedded (integral), as depicted in Figure 11.10. Integrated devices are packaged, and can

(a) Discretes



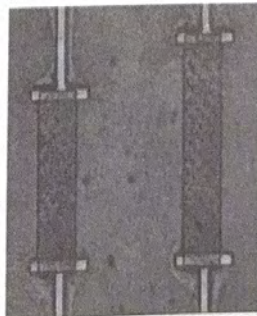
(b) Integrated Passive Devices (IPD)



(c) Embedded Capacitor



(d) Embedded Resistor



(e) Embedded Inductor

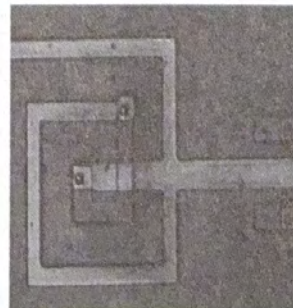


FIGURE 11.10 (a) Example of discrete device; (b) examples of integrated passive devices; (c) integral substrate with embedded polymer/ceramic nanocomposite capacitor; (d) epoxy/carbon resistor; and (e) copper spiral inductor fabricated on a PWB substrate.

be further subdivided by array and networks types. Below is a short description of discrete, integrated, and embedded passives. These devices are discussed in detail in the respective sections. The term "embedded passives" is becoming more widely accepted than "integral" passives. In this chapter, we will use embedded passives, since this is expected to be the nomenclature for the NEMI 2000 Roadmap. Table 11.3 shows a description of different passive component nomenclature according to NEMI. The On-Chip passive, as defined in Table 11.3, is beyond the scope of this chapter.

Discrete devices, are the simplest of devices, with leads or terminations affixed for surface mount application. The discrete is a singular device, one component only with the termination points defining the circuit connection. This definition would include screened-on resistors, capacitors or inductors. Screened-on resistors are very common in applications and also afford a trimming capability for tuning the circuit's performance. Discrete ceramic components are the obvious choice for passive components and constitute a large electronic ceramic market, estimated ~900 billion units a year.

TABLE 11.3 Passive component nomenclature.

Technology	Description
Discretes	Discrete passive devices are simply a single passive element (capacitor, resistor or conductor) in a leaded or SMT case.
Arrays	Arrays are multiple passive elements of like function (i.e., all capacitors or all resistors) in a single SMT case.
Networks	Networks are multiple passive elements of more than one function (e.g., capacitors + resistors) in a single SMT case. Typically a network contains from 4 to 12 elements.
IPDs	Integrated Passive Devices are multiple passive elements of more than one function and possibly a few active elements. (e.g., resistors + capacitors + diodes) in a single SMT or CSP. Typically an IPD contains more than 20 elements.
Supercomponents "Functional Modules"	Module-like packages incorporate 20 or more passives and provide for active mounting on its surface. VCO, Bluetooth, and GPS are some of these being designed.
Embedded Passives (Integral Passives)	Embedded passives are buried (embedded or integrated) into the substrate material itself. It does not matter if the substrate is a small piece of ceramic, a large FR4 board or small laminate package substrate. As long as the passive elements are considered to be an integral part of the substrate, then the elements are called embedded passives. The substrate is called an integral substrate. The deciding characteristic is that the passive component does not need to be mounted or connected to the substrate, since it is an inherent part of the substrate. It is distinguished from the "supercomponent" (module) because it acts as the "system board." The substrate may have one or more modules attached. <i>Within embedded capacitors, we can have a single capacitive plane that serves as a common decoupling layer; this is called planar distributed. Or we can have that layer broken up into different capacitors, in which case we call singulated.</i>
On-Chip Passives	An on-chip passive is a passive element that is fabricated along with the active elements as part of the semiconductor wafer (die). Since this roadmap only concerns itself with the passive components that are critical to the interconnect ("glue components"), we only count the discrete-like passives that were eliminated from the system, instead of the actual passive elements on the active semiconductor die.

Source: NEMI 2000 Roadmap.

Integrated components are packaged arrays or networks. These will consist of mixtures of capacitors, resistors and possibly inductors, forming termination or filtering functions with the terminations required only for input, output and common terminations. A "T-Filter" or "Pi-Filter" arrangement can be created in this package, to be mounted as a single piece with three terminations apparent, eliminating the requirement of handling, traces and termination pads for three discrete components. These integrated networks become more explicit in their design for a specific, repeated function. These devices might appear at common I/O interface ports such as RS-232 or Parallel Printer ports. As with the array, but to a higher degree, these devices eliminate handling larger numbers of discrete devices, saving board space and placement costs. Their availability and expense will be determined by commonality of circuit function, such as the more common I/O ports. Arrayed devices represent multiple components of a singular type (resistor, capacitor or inductor) of like or varied values within a package with multiple connections. Allowances in the termination scheme can create a common point, or all elements can be separate with two termination points for each. The most prevalent type of passives found in application would be resistor arrays in SIP (usually defining a "common" connection with a single termination), or DIP packages (usually all individual elements requiring two termination points for each element). Capacitor and inductor arrays might be found in parallel applications such as multiple data line filtering, but additional parasitics with wiring traces to various circuit locations would inhibit performance. In addition, by packaging these passive components crosstalk considerations with capacitive coupling through the substrate material or magnetic coupling prevent them from performing in widely separated functions for the circuit.

Embedded (Integral) passive components would create the passives as part of the substrate. In order to meet higher component needs, many miniaturized discrete surface mount passive components (resistors, capacitors, and inductors) have been mounted on boards and modules in a hybrid fashion. Such surface mounting introduces additional expense of manufacture, large board area, and additional parasitics into the system, thus limiting the system performance. These issues can be dealt with by integrating these passive components directly into a *multichip module* (MCM) substrate along with other IC chips. The size of the board can be reduced (especially if chips can be placed above the embedded passive components) and the parasitics associated with the passive components can also be reduced due to the elimination of leads and the shorter connections between passive components and other IC chips.

To address the economic viability of embedded passives, the impacts of the following competing effects when integral passives are present must be addressed:

- Possible board area decreases due to reduction in the number of discrete passive components
- Decreased wiring density requirements due to the integration of resistors and bypass capacitors into the board
- Increased wiring density requirements due to the decreased size of the board
- Increased number of boards fabricated on a panel due to decreased board size
- Increase in board cost per unit area
- Decrease in board yield
- Decrease in board fabrication throughput

- Decrease in assembly costs
- Increase in overall assembly yield
- Decrease in assembly-level work

There has been a good deal of success reported with embedded resistors, as these are screened-on interconnects between vias that closely mimic the screened-on surface resistors. Embedded inductors have been created which include building a specific core structure within the layers. Embedded capacitors require a spotting of the higher dielectric constant materials within the area of the capacitor plates over several layers. Higher valued components or tighter tolerance devices are still forcing demands for discrete components. In 1995, almost all passive devices were implemented in electronic systems as discrete-like devices. In a typical circuit, 80% of the components are passives, taking up 50% of the printed wiring board area and requiring 25% of all solder joints, resulting in higher cost and potential reliability problems. Therefore, passive components substantially influence system cost, size, and reliability. Almost 95% of the current 900 billion passive components are discrete and integrated passives and about 3% are used in an embedded form.

11.5 DISCRETE PASSIVES

11.5.1 Resistors

Resistors are available in several common forms. For example, wire-wound resistors are formed from windings of fine wire; film resistors, commonly found in consumer electronic devices, use carbon or metal film deposited on a substrate; and carbon-composite resistors use a mixture of carbon powder with a polymer binder. In many cases, the resistor is not a component added to the circuit, but is a thick-film creation applied as a paste to the circuit board between two conductive pads. These screened-on resistors are usually made to be adjustable by laser-manipulating the path, such that the laser narrows or elongates the path to increase resistivity until a target value is achieved. Surface mount packages for these different types of materials are available.

Resistor Technology

There are basically two types of resistors: fixed value and variable resistors. Fixed value resistors can be carbon composition types, metal films, and wire-wound types. The variable resistor can be subdivided into rheostatic types and variable potentiometric types.

Molded carbon resistors are constructed of a resistive element, which contains a mixture of graphite powder and silica with a binder, and is made under heat and pressure. Lower resistance values are made by using higher graphite content. Values in the range of 0.1 Ω to 9.1 G Ω are commercially available. These resistors are color-coded. Metal film resistors have lower temperature coefficient of resistance, better reliability and precision. Wire-wound resistors use resistance alloy wires such as Nichrome. The resistor is first produced by winding resistance wire on an insulator form, which is then inserted in a ceramic case. The semi-variable resistors are wire-wound resistors with various tabs to target different resistance values.

Temperature Coefficient of Resistance (TCR)

All resistance materials exhibit some change in resistance with temperature. The TCR is defined as:

$$\text{TCR} = (1/R)(dR/dT) \quad (11.31)$$

The TCR is expressed in $\%/^{\circ}\text{C}$ or $\text{ppm}/^{\circ}\text{C}$. The TCR is important in circuit functions, because circuit temperature changes can cause unwanted circuit performance changes. TCR may be either positive or negative. A positive TCR denotes a decrease in resistance with a rise in resistance value with a rise in temperature, and vice versa. Pure metals have a positive TCR, while carbon and graphite resistors mixed with polymer binders usually exhibit negative TCRs. The TCR characteristics of a resistor are important to the designer and permit one to allow or compensate for the changes that will occur in the circuit being designed when it is exposed to temperature variation. With certain circuit functions such as voltage dividers, matching TCRs will be required.

Voltage Coefficient of Resistance (VCR)

Resistance value is not always independent of the voltage applied and may increase or decrease with the applied voltage:

$$\text{VCR} = (1/R)(dR/dV) \quad (11.32)$$

The units of VCR are $\%/V$ and may be converted to ppm/V . The measurement of VCR is particularly difficult, and suitable precautions must be taken not to heat the resistor, or the resulting measurement will have a component of TCR. The VCR can be measured by using pulsed DC and varying the duty cycle as the voltage is increased, such that the average power dissipation is constant. In films of practical thickness, the VCR is not a major factor, since it is of the order of 5 ppm/volt, which is usually smaller than the TCR effect due to the heating.

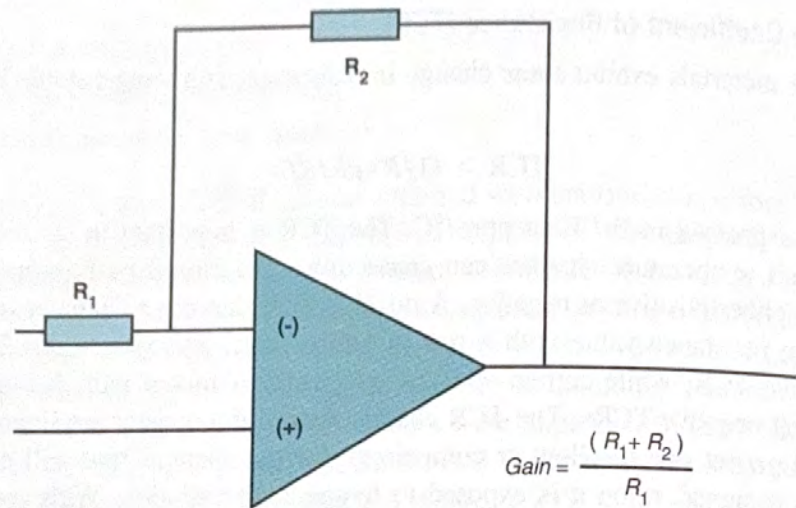
Resistor Applications

The applications for resistors include bias and dividers, feedback, termination, pull-down and pull-up, sense, delay, and timing. The bias, or divider, resistor circuit is intended to set the operating level of a third voltage defined somewhere in between two supplied voltages. The divider resistors can create this third voltage level by picking the correct ratio of the resistors to one another.

The feedback resistor is used to gain stability of an amplifier by reducing the output of an amplifier based on the magnitude of the input signal. For simple high gain operational amplifiers as shown in Figure 11.11, the gain of the amplifier can be controlled by the ratio of the summation resistance (input and feedback, $R_1 + R_2$) to the input resistance (R_1). For high frequency gain, it is the ratio of the impedances of these elements that establishes control, and the resistors can be replaced with combinations of resistors and capacitors.

The termination resistors are intended to terminate a signal line with an impedance match of the source to eliminate an echo produced otherwise. This is extremely important in digital circuits, where a square wave edge could create several high-frequency RF noise pulses that would appear along with the bus voltage to the entire circuit. Remember

FIGURE 11.11 Gain determination with input and feedback resistors.



that matching impedances not only eliminates the noise, but creates the most efficient transfer of power. Sense resistors can be found in almost all power supply circuits as these low value (usually film) resistors are used to generate a voltage signal proportional to the currents generated.

11.5.2 Capacitor Technology

The type of capacitor has an enormous impact on its behavior in many circuits. For the aluminum and tantalum capacitors, these devices are polar devices in that the dielectrics are electrochemically created materials that are oxides of the base metal. These dielectrics are extremely thin [in the range of 20 angstroms per volt ($\text{\AA}/\text{V}$)] and the cathode plate materials are either liquid or semiconductor materials that conform to the very irregular surface of the oxide material on the base metal plate or anode.

Aluminum Electrolytic

The aluminum construction involves an aluminum plate that is first acid etched prior to anodization. Large irregularities of the surface do not offer the major impediment to contact, as numerous tunnels are created into the surface, with some penetrating the full depth of the plate. These tunnels create an enormous increase in surface area, and thus the volumetric efficiency of the capacitor. The walls of the tunnels are anodized, and contact to these surfaces is through the cathode materials as they penetrate this structure.

Tantalum (Solid)

The tantalum starts out as a pressed pellet with enormous porosity and resultant surface area. After all the exposed tantalum surfaces are electrochemically treated to create the oxide dielectric, the cathode contact is created. This contact is either a liquid paste (the "wet" tantalum) or a processed material that is applied in liquid form and allowed to solidify. The "solid" tantalum is created by impregnation of manganese dioxide from the manganous nitrate solution, or more recently, by the polymerization of conductive film from the monomer solution.

With both of these electrolytic capacitors, the cathode material offers sufficient resistivity to the structure to create a "RC-ladder" effect in electrical performance. At low frequencies, all of the capacitive elements within the structure respond to the circuit, but as frequency increases, more and more of the capacitive elements gain too high of an RC time constant to respond. As such, the capacitance appears to decay, as frequency increases for these two devices. Improving the conductivity of the cathode material (as is done by using the conductive polymers) will cause this capacitance roll-off to occur at higher frequencies for a given capacitance structure.

Film

The film and ceramic capacitors are created with dielectric materials that are unique to the electrode materials. These nonpolar devices utilize an insulative film of plastic or fired ceramic as the dielectric. With the film capacitor, there are two possible constructions available: a rolled foil or stacked layers. With the rolled foil, there are two conductive electrodes that are separated from each other by a plastic film. These electrodes can exist as individual metal foils, or as thin metallization films deposited on the opposing faces of the plastic insulator. The film is then wound into a cylindrical shape in such a manner that the capacitor of extremely large area is compressed into a smaller cross-sectional shape. Lead attachment to these devices is with leads attached to each foil, extending out of the finished package.

The stacked film is processed with the plastic metallized film stacked in succession, with the electrode patterns extending to opposite edges for adjacent layers. Multiple layers are stacked to achieve a block structure, and the individual capacitor plates are then connected in parallel by means of a common metallization along the edges to which the plates extend. The manufacture of these devices is usually in a larger "motherpad" configuration, with the individual devices cut out of the motherpad after compression. These devices can appear as surface mount "chips" or with leads attached and packaged as through-hole devices.

Ceramic

The ceramic surface mount chip capacitor is the most dominant capacitor type in both volumes of pieces and percentage of market share. The device is built in a stacked configuration, much in the same manner as the film. The ceramic layer between electrodes is applied as a latex tape with ceramic in suspension, or as a wet "slurry" film squeegeed on each successive layer. The ceramic and metal ink layers are built in successive fashion, with the "wet" process requiring a drying before the next layer. As with the metallized plastic, the manufacturer uses a motherpad process, and the individual pieces are cut out of the finished pad. Figure 11.12 is an example of a ceramic SMT chip capacitor.

The ceramic must be fired (vitrified) after this process. This usually involves a kiln firing at temperatures anywhere from 1100 up to 1900°C. Because of these temperatures, precious metal compositions of platinum, palladium and silver, as well as combinations of these, dominate the metalizations for the electrode patterns. Recent process modifications have now allowed the use of nickel (which is less expensive) and copper electrodes.

The most recent developments for capacitors deal with the chemical or double-layer type capacitors. Their composition is such that they attempt to utilize a single layer of

TYPICAL MULTILAYER CERAMIC CAPACITOR

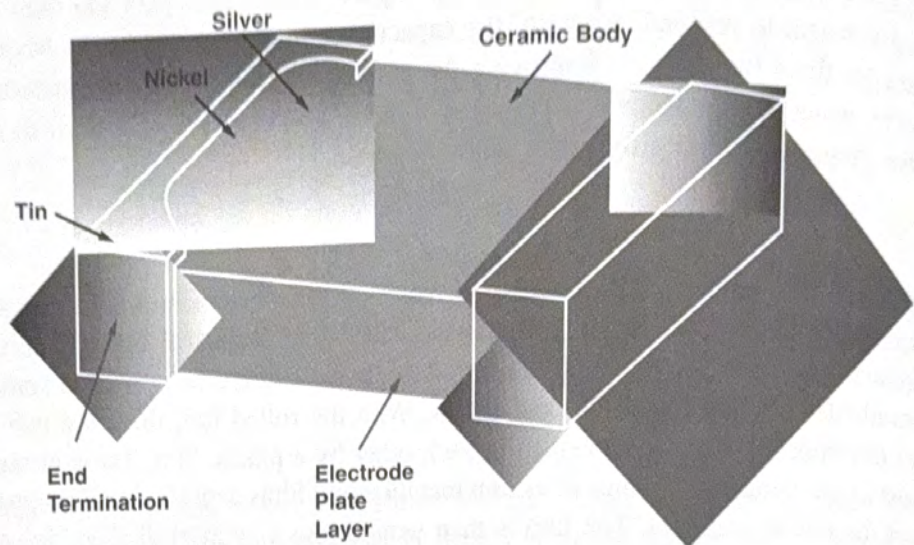


FIGURE 11.12 Ceramic SMT chip.

water molecules as dielectric. Regardless of the dielectric constant created here, you can imagine the enormous capacitive capability with the extremely thin dielectric. Typical capacitance values of 1–47 F are common. Based on the single molecule layer, this type also has an inherently low breakdown voltage of approximately 2.5 V DC. As such, these very large capacitances are available in lower voltages only (4–10 V) and the package usually involves cells that are connected in series within its structure.

Capacitor Performance

The biggest fault with capacitors in applications is with the engineer dismissing the capacitor as a simple device, and that a “capacitor is a capacitor” all the time. As with all passive components, this is far from the truth but may be more critical with these devices than others. A capacitor is dominated by its electrical attributes of electrical charge storage only within a specific frequency realm. The materials and the structure of the electrolytic capacitors show a decreasing capacitance with increasing frequency.

Temperature Coefficient

For most types of capacitors, there is very little change (less than $\pm 10\%$) in capacitance with temperature. For some film, glass and very stable ceramics, this change can be specified as ppm/ $^{\circ}\text{C}$, as these devices are very stable.

The ceramic dielectric composition can vary the most of any of the capacitor types. Extremely stable COG type dielectrics possess very stable temperature characteristics but have low dielectric constants (low capacitance values). For the higher dielectric constants, the instability may appear to be related to the magnitude of the dielectric constants. With Figure 11.13, the relative magnitudes of dielectric constant are shown versus temperature.

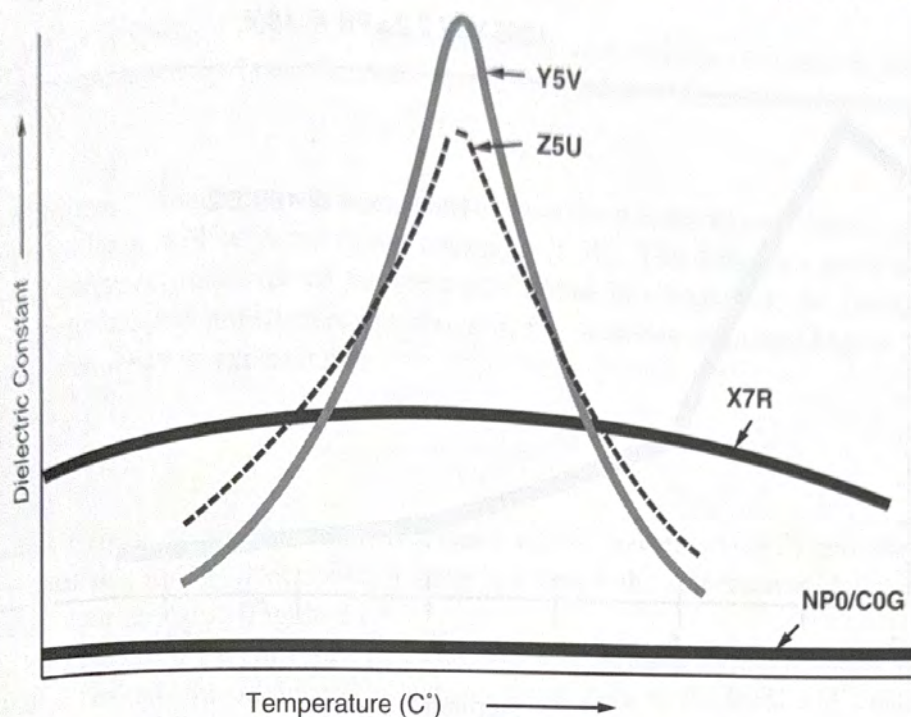


FIGURE 11.13 Capacitance vs. temperature.

and for the highest dielectric constants of Z5U and Y5V, the instability with temperature is greatest.

The three-character code (EIA standardized) of the dielectric type defines the boundaries of allowable capacitance change and the temperature range. The manufacturer may supply information on these.

Voltage Coefficient

Again, with most capacitor types, the change of capacitance versus applied DC bias is negligible, except for ceramics. As with the temperature coefficients being more dependent for the higher dielectric constants, the voltage coefficients are also greatest with the highest dielectrics. In Figure 11.14, with the capacitance for the high dielectric constant Y5V, dielectrics can lose as much as 90% of their capacitance value with the rated voltage applied. If the application applies a DC bias and at elevated temperatures, the ceramic dielectric type can decide if the capacitor is successful in its application. The voltage rating of a device has no significance to the dielectric type or voltage coefficients, but the manufacturer may provide these.

Aging

Ceramics show a decay or loss of capacitance with time, related to a relaxation of the crystal structure of the titanate materials. This decay is a natural decay phenomena with a constant loss of capacitance per decade hour (1, 10, 100, etc.) of time. The X7R dielectric typically loses about 1% of its capacitance at each successive time interval that is 10 times its predecessor. The high dielectric constant materials of Z5U and Y5V can decay from 5–15% per decade hour of time. This process is reversible as the ceramic is heated to a temperature above 150°C, and the initial crystal shape is reinstated. This

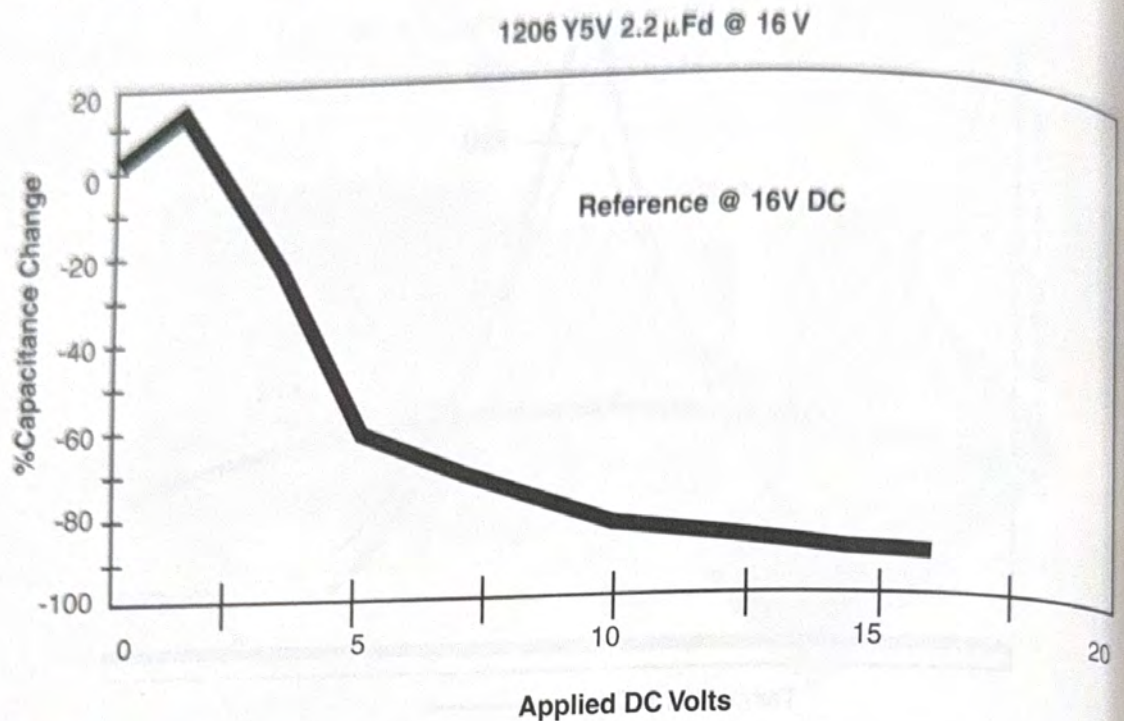


FIGURE 11.14 Voltage coefficient for Y5V.

aging may not cause concern with loss of capacitance over the expected life of a circuit, but because this process is reversible, the solder process may lead to unexpected high capacitance. Again, the manufacturer may provide this information.

Piezoelectric Noise

Ceramics as crystal-based dielectrics can exhibit a piezoelectric noise generation, as mechanical forces on the capacitor will generate electrical signals. These types should not be used where a mechanical isolation cannot eliminate these spurious signals from being generated in high gain applications.

Capacitors Becoming Inductors

Every capacitor has losses associated with the imperfect conductors and losses attributable to the dielectric. This establishes a parasitic resistance within the device. There is an additional parasitic element in the capacitor. As the current path through the device is fixed or constrained to a defined path of length, width, and thickness, there is an inductance associated with each. This element, known as *effective series inductance* (ESL), creates a reactance that is opposite ($+90^\circ$ or the voltage leads the current) to that of the capacitive reactance (-90°). The relationship of inductive reactance (X_L) to inductance and frequency is given as:

$$X_L = 2\pi FL \quad (11.33)$$

The inductive reactance is directly proportional to the inductance (L in henries) and frequency (F in hertz). This relationship with frequency is opposite to that of capacitive reactance, which shows decreasing reactance as frequency increases. In the lower frequencies, the capacitive reactance dominates to make the inductive reactance almost neg-

ligible, but as frequency increases, these opposing vectors begin to compete with each other. The impedance becomes factored by the difference of these two elements:

$$Z = \sqrt{R^2 = (X_C - X_L)} \quad (11.34)$$

There will come a frequency where these two opposing reactances cancel each other out, and the impedance will be equal to the resistance (ESR). This frequency point is known as the self-resonant frequency of the capacitor. Below this frequency, the capacitive reactance dominates the impedance, but above it, the inductive reactance begins to dominate. This frequency is expressed as:

$$F = \frac{1}{2\pi\sqrt{LC}} \quad (11.35)$$

Below this frequency, the dominant reactance will be negative (-90°) and above it, it will be positive ($+90^\circ$). It acts like a capacitor below the self-resonant frequency, but like an inductor above it (Figure 11.15).

The ESL for the different types of capacitors is dominated by the physical structure. With leaded devices, the additional inductance attributable to the leads will create higher ESLs. With tantalum surface mount molded devices, the leadframe extension into the plastic package adds to the ESL. Lower ESL can be achieved in ceramic packages where the aspect ratios (ratio of length to width) can be reduced by making the package shorter and wider (the 0612 chip size is a low inductance version of the 1206 chip size). There are also clever designs that feed the currents into the device in opposing paths that can create some inductive cancellations, using “inter-digitated” termination designs.

Capacitor Applications

The applications for capacitors include decoupling, filtering, coupling, timing and wave shaping, and oscillating circuits. Ceramic, aluminum electrolytic, tantalum, and film dominate the main types of capacitors available for these applications. For a great deal of time, these different types of capacitors were utilized to specific applications, each with a dominating niche for its specific application. The most prevalent of these types and

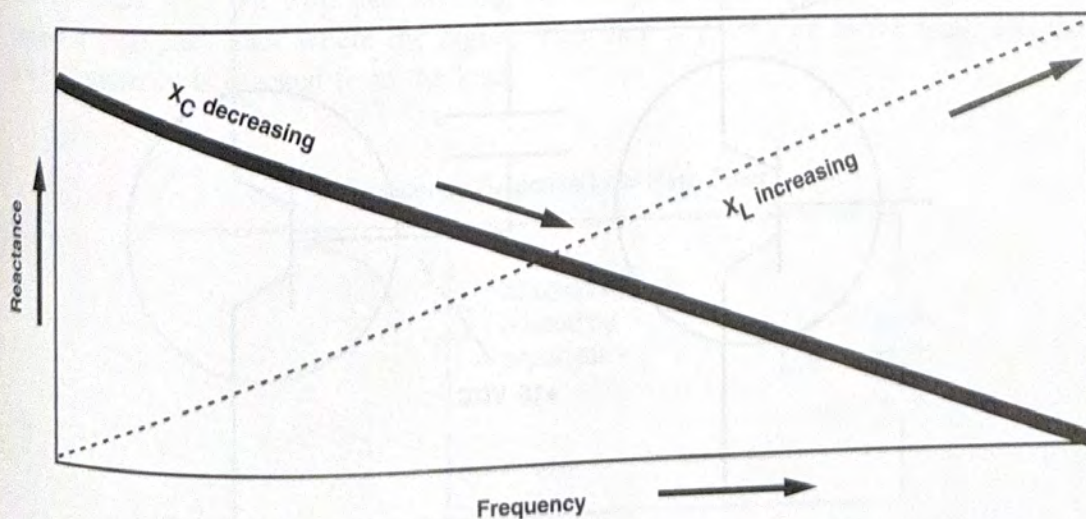


FIGURE 11.15 Series self-resonance.

applications would be the aluminum electrolytic capacitors used in power supply filtering applications. As such, they established "grandfather" footholds in these applications, and changing the type for any application would be considered only after a roadblock was established to prevent a design from working. Discrete capacitors are used more than any other passive components, so making them integrated would be advantageous. There are many capacitors depending on their functions such as decoupling, by-pass, tuning, filtering, converting, and protecting. Among them, low value ceramic chip capacitors (<1000 pF) used for decoupling, by-pass and other function capacitors are the primary drivers to integrate the capacitors into the printed wiring boards.

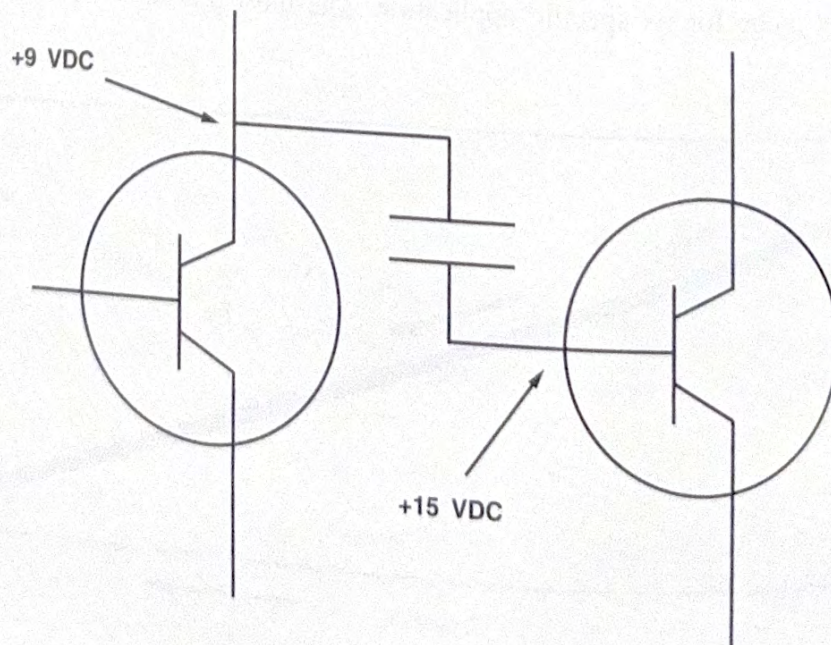
Coupling

Capacitors are limited in the amount of electric charge they can absorb for a given voltage; they can conduct direct current for only an instant (charging current) but function well as conductors in alternating-current circuits (constantly charging and discharging). This property makes them useful when direct current must be prevented from entering some part of an electric circuit, or creating a connection to disturb this imbalance. This defines the coupling capacitor's task as it passes an AC signal from one stage to another, and allows a difference in the DC bias states to stay independent of each other (Figure 11.16).

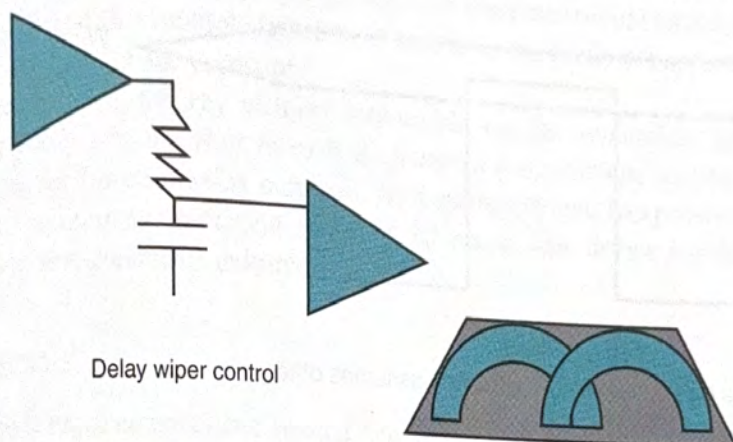
Timing and Wave Shaping

Since the capacitor builds up its charge by a small charging current, restricting this current will create a delay in the time to achieve the applied potential. This pinching effect is very much like narrowing the opening in a water jug. If the jug has a short height, wide diameter and an opening as wide as its diameter (like a cake pan), it fills quickly and can be emptied with no delay. Taking the same volume as the cake pan and using a configuration like a soda bottle with its taller height, smaller diameter and much smaller opening, takes additional time to fill and empty. They may have the same capacity, but

FIGURE 11.16 Coupling capacitors. The capacitor allows an AC signal to pass, and it stops DC.



RC charge scheme control by varying R

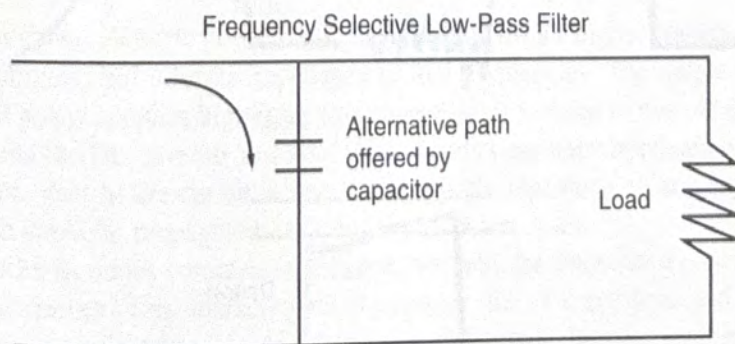
**FIGURE 11.17** Timing utilizing RC.

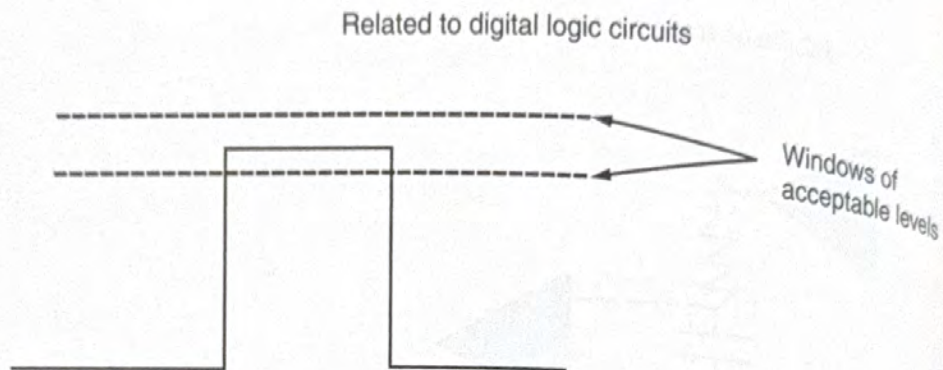
by restricting the flow, it takes more time to fill. Using a resistor in series with a capacitor can create a restriction to current flow, creating a time delay in charging the capacitor (Figure 11.17). This is the capacitor in a timing or RC (resistor-capacitor) delay circuit. The easiest presentation that we see today is in the delay wipers in automobiles. Reaching a specific voltage across the capacitor as it charges activates the wipers. We expand the delay between wiper actuation by adding resistance to the RC circuit.

Filtering

The impedance that a capacitor presents to a circuit is related to the charging-discharging cycles apparent. In a DC circuit, it is said to have infinite impedance. For an AC application, the capacitive reactance (X_c in ohms) and frequency relation dictates that as frequency increases, the X_c decreases [Equation (11.20)].

Because the impedance is related to the X_c , it also changes as frequency changes [Equation (11.21)]. The path through the capacitor can offer more impedance or less impedance than an alternative path. As such, this device shunting or parallel to a load can offer high impedance to lower frequencies, and lower impedance to higher frequencies; this configuration represents a low-pass filter (Figure 11.18). By putting the capacitor in series with the load and offering another path shunting, this arrangement can create a high-pass filter where the higher frequency is passed on to the load, and the lower frequency is blocked from the load.

**FIGURE 11.18** Filter capacitor: low-pass.



One level is tested for—absence assumes other.

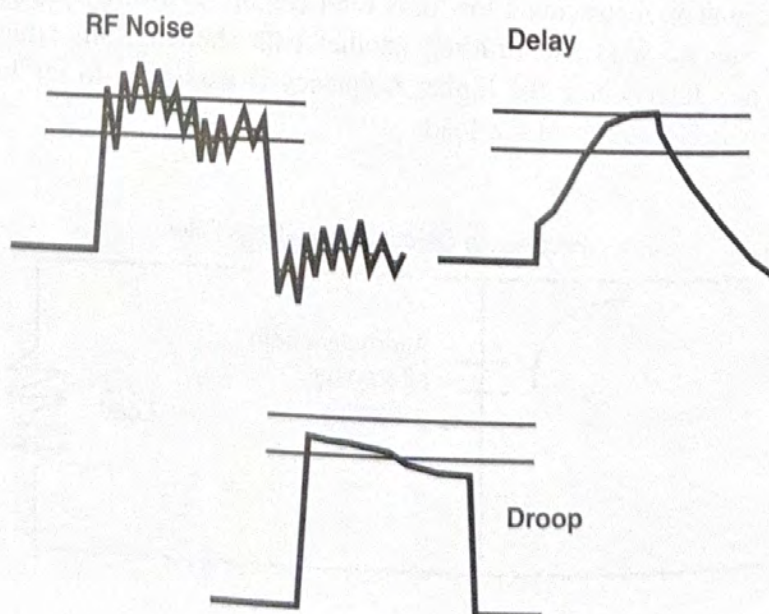
FIGURE 11.19 Digital level requirements.

Decoupling

This application deals with digital logic circuits. The voltage apparent at any gate is one of two possible states: either high or zero. The device tests the state of each gate by looking for the high voltage, and if it is not present, the low voltage is assumed. The window for reading the high state is defined in Figure 11.19, and voltages within this window will be read correctly every time. Voltages that fall out this window have a higher probability of being misread as the voltage falls lower and lower. These voltage states represent the binary states of "1" and "0."

Possible factors as illustrated in Figure 11.20, which can effect this voltage level, include high-frequency ringing, propagation delay (restrictive currents), and a common malady referred to as "droop" (Figure 11.20). This is where the voltage appears normal at first but as more devices draw energy off the bus, the voltage levels begin to decay. Any of these faults can lead to an incorrect reading of the proper voltage level. These faults show up as bugs in the programs but are not software related; rather, these are hardware-induced bugs.

FIGURE 11.20 Digital faults without decoupling.



The purpose of the decoupling capacitor is to offer a localized energy source for the IC from which to feed its energy requirements. This capacitor should have a large enough charge reservoir, so that multiple transfers of energy to the IC do not appreciably reduce the apparent voltage of the capacitor.

This application is the key element responsible for the tremendous growth of the ceramic capacitor industry. Next to each IC found in many circuits will be at least one ceramic capacitor for decoupling purposes. As a surface mount, inexpensive device with capacitance requirements sufficient for most IC needs, this device has shared in the growth of the semiconductor industry.

11.5.3 Inductors

Surface mount requirements have created new designs for inductors. First, plastic packages, in which the coil was inserted and the connector tabs were located on the plastic containers, were offered as *surface mount technology* (SMT) packages. More recently, multilayer connections within a ferrite block structure, with connecting terminations on opposite ends, have been made available. The appearance of these surface mount inductors looks dramatically like SMT capacitors. In fact, the package sizes being offered mimic those packages common to SMT resistors and ceramic capacitors.

Inductor Types and Compositions

An inductor may have a ferromagnetic core or an air core. Commercial inductors are available in a variety of fixed, adjustable and variable forms. Molded inductors are similar in appearance to resistors, and are commercially available for discrete and integrated circuits.

Inductor Applications

An inductor is specified by its inductance at a specific frequency or impedance, and a figure of merit (Q) or the ESR is specified as well. The Q defines the ratio of inductive reactance (X_L) to the resistance. Applications are usually in conjunction with a *capacitor element* (LC) or with a *resistor element* (LR). The LC combination takes advantage of a controlled resonance frequency [Equation (11.28)] that can create peaking impedance (parallel LC) or peaking admittance ["Y" admittance, Equation (11.23), from impedance created by series LC].

$$Y = 1/Z \quad (11.36)$$

As a simple choke element in a circuit, the inductor offers higher impedance to high-frequency currents, and a lower impedance to low frequencies. The output choke found in almost all power supplies highlights this capability; it is there to impede the AC ripple while allowing the DC currents to pass freely. Another common application of inductors is on the line input to the circuit where it offers high impedance to any high-frequency noise, which could be propagated back out to the power lines.

The inductor develops complex impedance, whereby the impedance is increasing with increasing frequency. This characteristic is opposite that of capacitors, and the inductor is used in many applications in conjunction with capacitors, to create a changeover point of control. The permeability of the core changes (usually declining) with increasing

frequency. There is a parallel parasitic capacitance, as well as a parasitic series resistance, which combine to alter the expected frequency response of impedance.

Many of the applications that were dominated by LC combinations for timing or delay-line applications are being taken over by timing ICs; they are less susceptible to changes, and the reliability is improved.

11.6 INTEGRATED PASSIVES

As the numbers of passives dominate the circuitry counts, the cost associated with these devices has a significant impact on the cost of the system. There is a trend that is generally given as a percentage of price reduction per doubling of the cumulative quantities, and this percentage is usually around 5%. The cost of the devices as they are newly released is high, then the pricing decays with the maturity of the product. A reduction in the size of the chips (0805 to 0603, to 0402, and to 0201) allows the manufacturers to reduce material costs (dielectric and electrode material costs). As these devices are manufactured in some manner of motherpad or multiple strip configurations, the smaller chip sizes allow more parts for the same effort, thereby increasing the manufacturing efficiency and reducing the costs associated with each.

On the circuitry side, moving to smaller passive chip sizes allows the circuitry to be condensed to smaller areas, but at a penalty to placement costs. The mechanical precision is good for 0805 and larger chips, but the dimension constraints begin with 0603 and smaller chip sizes. The 0603 can be placed with the best controls afforded with mechanical registration, but are easily controlled with optical. The 0402 chip size demands a refinement of the optical registration beyond that of the 0603, and the 0201 chips require still further refinement. These refinements add to the cost of the pick-and-place machinery, and the assembly houses amortize the cost of this equipment over a number of years, calculating the optimum usage, then costing each placement made. The pick-and-place equipment must be modified, or purchased as new, with each step into smaller chip sizes. Estimates for the placement cost per termination can be given from \$0.02 per termination, with some estimates as high as \$0.08 per termination. Getting the chip size down to where the device costs \$0.002 per device has little benefit if the placement costs rise from \$0.01 to \$0.08 per termination.

11.6.1 Arrays—Many of the Same

Multiple resistor packages first appeared as an assault on the costs of passive placements. Multiple resistors in SIP or DIP packaging were ideal for multiple data line circuits with required impedance matching demands. As the lines were usually paralleled together, these packages were soon being implemented in many digital circuit designs.

Capacitor arrays were soon to follow. At first, the ceramic packages were large and required special placement and handling considerations, but now there are popular SMT packages (Figure 11.21), the same size as a 1206 chip, with four paired terminations (eight in all). This device is actually comprised of four distinct capacitor elements. The array is also available in the 0805 package with three or four capacitors within. Again, for parallel digital lines, these arrays offer a good solution for matching impedances and for high pass filtering circuits.

BOARD SPACE SAVINGS USING ARRAYS

4 pcs 0603 Capacitors = 1 pc 1206 IPD Array

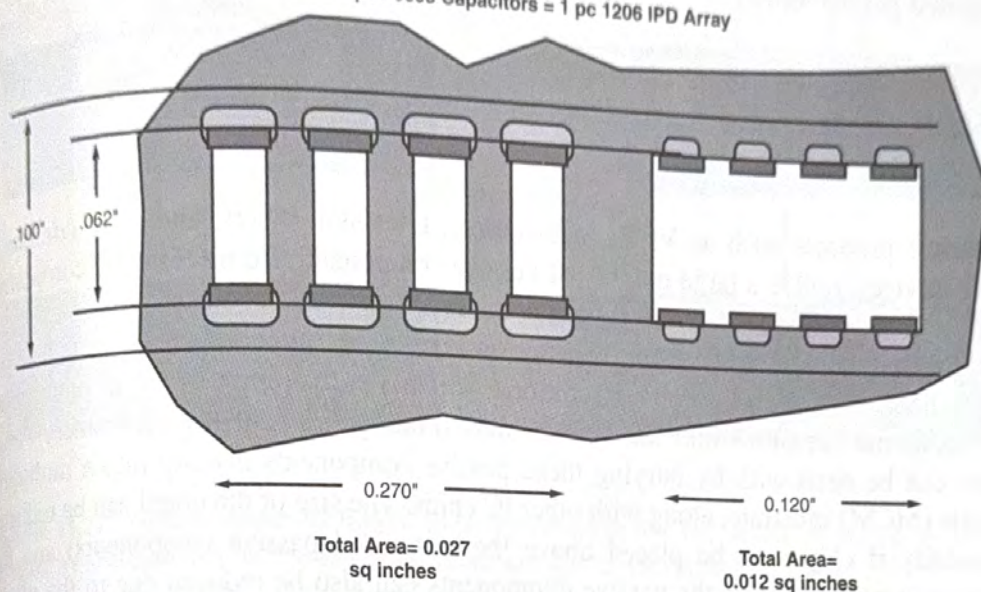


FIGURE 11.21 Capacitor array creates a single 4-in-1. (Courtesy of NEMI Roadmap-1998)

One of the most popular applications for resistors is impedance matching, and the multiple array configurations lend themselves well to these designs, as the data lines are printed in parallel. The most popular application for capacitors is decoupling, and the array does not lend itself well to this application. The array requires the multiple elements to be built within the same dielectric material as the distinct elements. This creates “cross-talk” coupling (capacitive) that allows a transfer of signal to the other elements within the package. This propagates itself as noise on the desired quiet line. In addition, decoupling is a circuit-dispersed requirement that demands close proximity to eliminate parasitics that add to the noise to distinct circuit locations widely dispersed throughout the printed wiring board. Having all of the capacitors clustered within a few packages defeats this requirement, as the wiring to this distended capacitor creates too many additional inductive and resistive elements.

11.6.2 Networks—Many of Different Types

The next progression of the multiple passive packaging involves mixing passive types within the same packages. These devices can coexist on a film, ceramic, or silicon substrate and contain at least two types of passive components. Typical designs can incorporate RC circuits for filtering or impedance matching, RLC circuits for filtering and timing, and LC circuit elements for delay line applications.

For ceramic substrates, utilizing the ceramic dielectric material as the substrate can allow the manufacturer to locate multiple capacitive elements through the substrate of the same or different values. The interconnects are accomplished by screening or sputtering the metallic links throughout the circuit, adjoining the individual components within. High-density replacement of a large number of RLC elements can be achieved within silicon substrates, allowing a singular chip to replace 45 discrete components in a parallel port I/O application.

Supercomponents such as module like packages (Table 11.3) can also be viewed as integrated passive devices.

11.7 EMBEDDED (INTEGRAL) PASSIVES

11.7.1 Benefits of Integration

Electronic products such as VCRs, camcorders, television tuners, and other communication devices, utilize a large number of passive components. To meet higher component needs, many miniaturized discrete surface mount passive components (resistors, capacitors, and inductors) have been configured on boards and modules in a hybrid fashion. Such surface mounting introduces additional expense of manufacture, large board area, and additional parasitics into the system, thus limiting the system performance. These issues can be dealt with by burying these passive components directly into a multichip module (MCM) substrate, along with other IC chips. The size of the board can be reduced (especially if chips can be placed above the embedded passive components) and the parasitics associated with the passive components can also be reduced due to the elimination of leads and the shorter connections between passive components and other IC chips. Integration of passive elements can also result in reduced assembly costs, improved electrical performance, improved packaging efficiency, mass production by batch fabrication, low power loss, low volume, low weight, and low profile. However, an integral substrate requires new design and test systems, manufacturing processes and materials. In addition, without *high density interconnect* (HDI), embedded passives are not feasible on printed wiring boards. Much research has been done to realize embedded passive components based on MCM-C (*ceramic*) and MCM-D (*deposited*) technology. In these approaches, it is necessary to undergo high temperature fabrication such as in *low-temperature cofired ceramics* (LTCC) and *high-temperature cofired ceramics* (HTCC).

Although discrete surface mount passive components (resistors, capacitors, and inductors) have been well developed, the development of embedded passive components suitable for integration with printed wiring boards is relatively recent. Since, in some applications, the number of passive components can exceed both the number and area of IC chips on a circuit board or in a package, such integration is desirable. To address these issues, integration technology for passive elements in the same manner as for transistors is necessary. An additional issue to be considered is that the fabrication sequence of all integrated passive components must be compatible if they are to be integrated on the same substrate. However, integration of these capacitors with resistors or inductors brings in numerous fabrication and compatibility issues such as:

1. Realization of a fully integrated R , L , and C on PWBs
2. Reduction in manufacturing cost
3. Low temperature fabrication process compatibility
4. Thermomechanical reliability
5. Crosstalks in a high density packaging
6. Appreciable packaging size reduction
7. Materials' compatibility

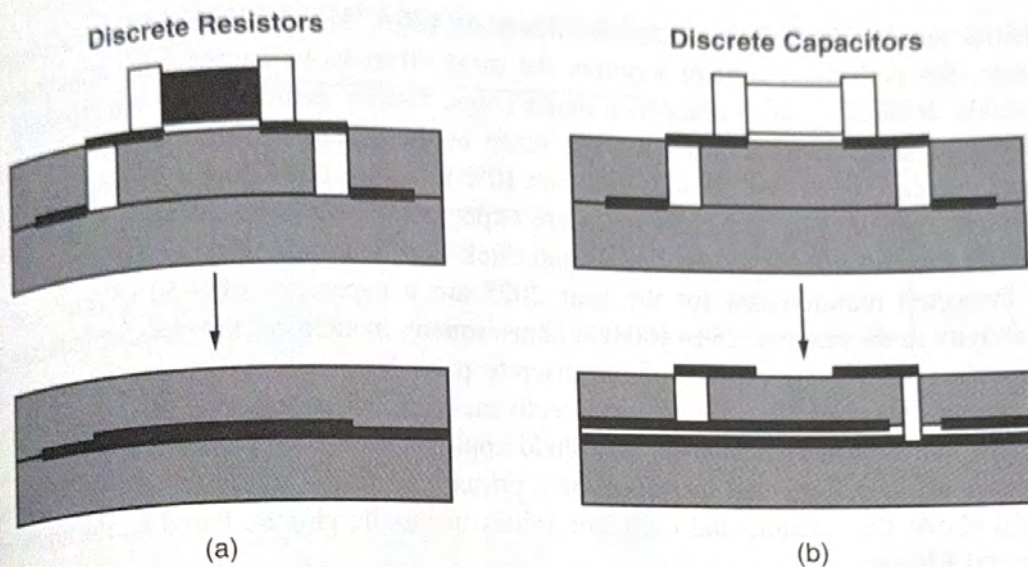


FIGURE 11.22 Embedded concept for R and C . (a) Resistors disappear from top, become part of an inner conductor; (b) capacitors (decoupling only) become vias dropping down to a common (distributed planar) layer.

Figure 11.22 shows the embedded versus surface mount concept. The integration of R , L , and C components on a ceramic substrate is depicted in Figure 11.23.

The primary driver for replacing SMT resistors with embedded resistors is faster bus speeds (>100 MHz). As the bus speeds exceed 100 MHz, the number of resistors re-

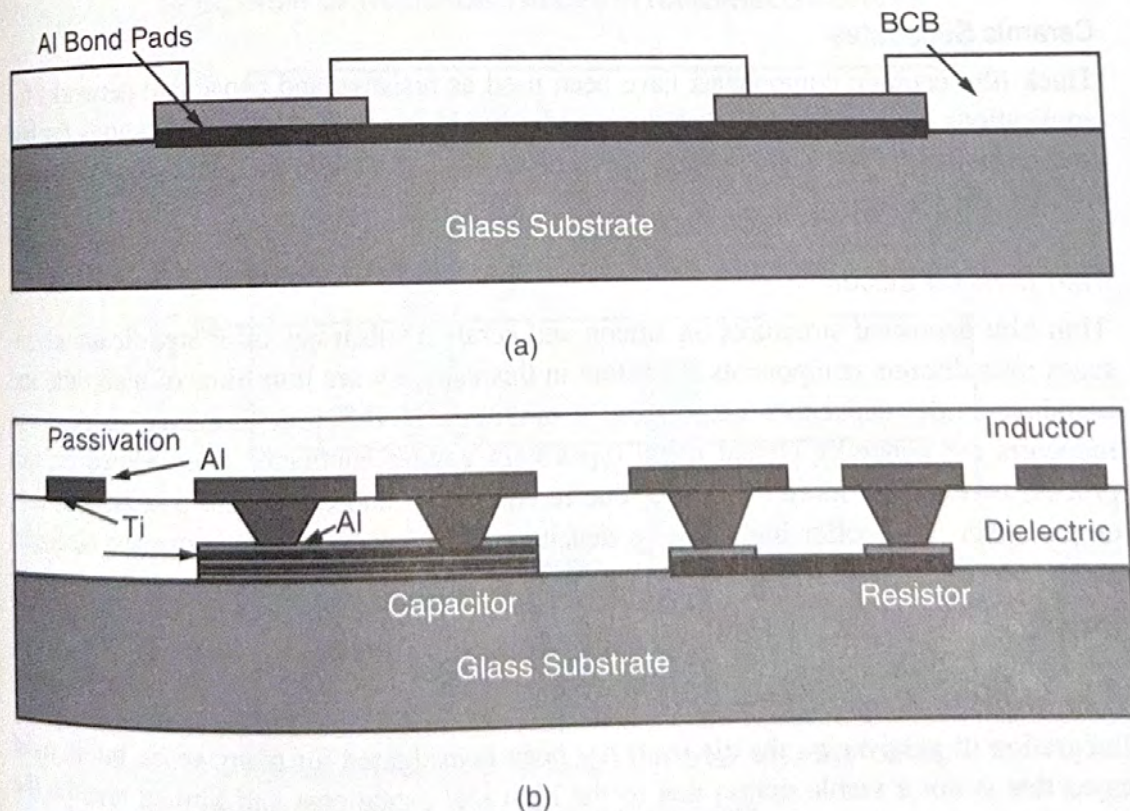


FIGURE 11.23 RLC network.

quired to manage these systems becomes quite large. Among required passive components, the embedded resistor requires the most effort to be successfully implemented quickly. Resistors can be embedded under chips, thereby reducing size, and reliability is increased since fewer connections are made at the surface. In general, the resistance ranges from 10 to 200 K Ω , with less than 10% tolerance depending on the applications. In large volume, thin film techniques are expected to be cost competitive with screen-printed inks on printed wiring boards and thick film hybrids.

Projected requirements for the year 2005 are a capacitance of ~ 50 nF/cm² and a resistivity in the range of 25 to 100,000 ohms/square. In addition, the parasitic inductance associated with the geometry of the discrete parts becomes increasingly important as frequency increases, decreasing the effectiveness of the capacitance. It is reported by NEMI that 40% of capacitors in hand-held applications are low value ceramic chip capacitors of <1000 pF, and these will be a primary target for integrated passives. Figure 11.24 shows the resistors and capacitor values in mobile phones, based on the study of General Electric.

11.7.2 Integration Options

Organic Board

Although embedded passives were realized on the PWB in the early 1980s, they were limited to mostly distributed capacitors and resistive layers in multilayer construction. The distributed capacitance planes are used in a number of high-speed digital systems, and resistive networks are used for high-speed telecommunication switches, workstations, and as termination resistors.

Ceramic Substrates

Thick film ceramic components have been used as resistive and capacitive networks for applications such as PCs, workstations, and other high-speed digital applications for bus line termination. For high volume applications, this can offer the price equivalency to discrete alternatives.

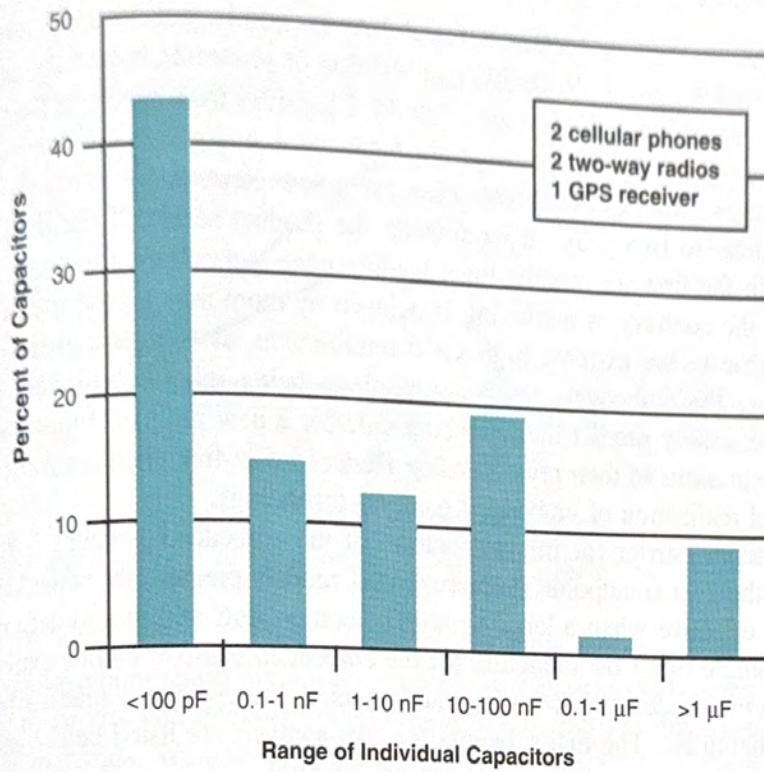
Thin films on Silicon

Thin film deposited structures on silicon and ceramic substrates offer significant advantages over discrete components. Resistors in this category are thin films of nichrome and tantalum oxide; capacitors range from a multitude of different inorganic oxides, and inductors are generally etched spiral types with copper conductor lines. However, this process is relatively more expensive, due to equipment and cleanroom processes which, on the other hand, offer high passive densities, tight tolerances, and superior electrical performance. Standard resistor network, R/C filter or R/C diode combinations can be realized using thin films on silicon.

IC Integration

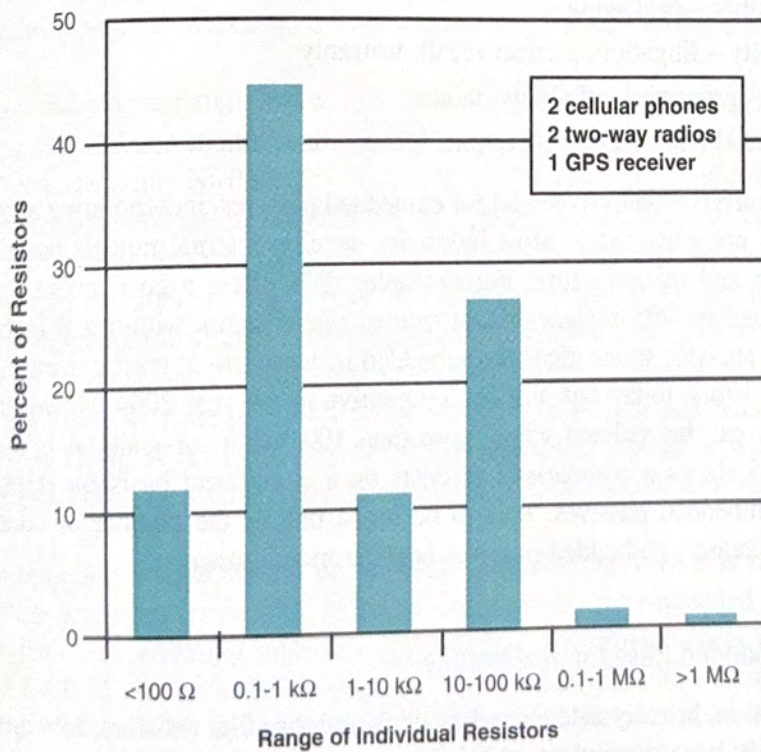
Integration of passives on the die itself has been investigated for many years, but in most cases this is not a viable option due to the high real estate cost and limited area on the chip. On-chip terminating and input/output matching passives are incorporated in the high-speed digital applications.

SPECTRUM OF CAPACITOR VALUES IN HAND-HELD DEVICES



(a)

SPECTRUM OF RESISTOR VALUES IN HAND-HELD DEVICES



(b)

FIGURE 11.24 Capacitor values in hand-held devices.

11.7.3 Barriers to Embedded Passives

Several inhibitors such as technical feasibility, economic justification, reducing engineering and manufacturing flexibility, qualification of processes, materials, and products, and need for industry standards keep embedded passives from reaching their market. In addition, time-to-market for a new product can be a major concern for realization of embedded passive devices. The cycle time for a new electronic product usually ranges from six months to two years depending on the product sector. If the product is marketable within the first six months for a leading edge technology, the profit margin can be hefty. On the contrary, if marketing is delayed by more than a year, the loss could be substantial. Due to the extreme high yield requirement, as well as experience required for developing the embedded passive technology being relatively limited, it is rather difficult to accurately predict the launching date for a new product. Embedded passives are inflexible in terms of their reworkability. Hence, defect-free yield is almost mandatory for successful realization of embedded passives technology.

Another major barrier for implementation of the embedded passives is their justification from the cost standpoint. Numerous cost models predict that embedded passives become cost effective when a large number of components within a system can be fabricated in a single run. Cost modeling for the embedded passives can be extremely complex due to a multitude of contributing parameters. A life cycle cost analysis incorporates all possible liabilities. The major factors for cost analysis are listed below, along with a subset of contributing parameters within each category.

1. Design—design tools, training, design library, iterations, design modularity
2. Materials—raw material, shelf life, substrate, qualification, standards
3. Manufacturing—capital equipment, training, yield, waste disposal or recycling
4. Assembly—packaging
5. Liability—litigation, product recall, warranty
6. Tests—properties, reliability, failure
7. Overhead—inventory, inspection, specification, time-to-market

Thus, a universal analysis model for embedded passives, incorporating all factors listed above, does not exist today. Most industries develop internal models based on product specification and infrastructure. For example, IBM offers a cost model for embedded resistors based on 795 replaceable surface mount resistors within a 9 inch $\times$ 12 inch board. Cost analysis shows that the embedded resistors are at least twice as expensive as the SMT resistors, today but will be competitive in the year 2004. However, significant cost savings can be realized when more than 100,000 ft² of material is used per year. Figure 11.25 shows a comparison of costs on a component basis for discretes, arrays, IPDs and embedded passives. It is to be noted that as the number of components per unit area increases, embedded passives become more attractive.

11.7.4 Embedded Resistor Technology

Resistors can be broadly categorized as thick and thin film resistors. In the case of thick film materials, usually conductive polymer composites are used. Epoxy-based thick-film

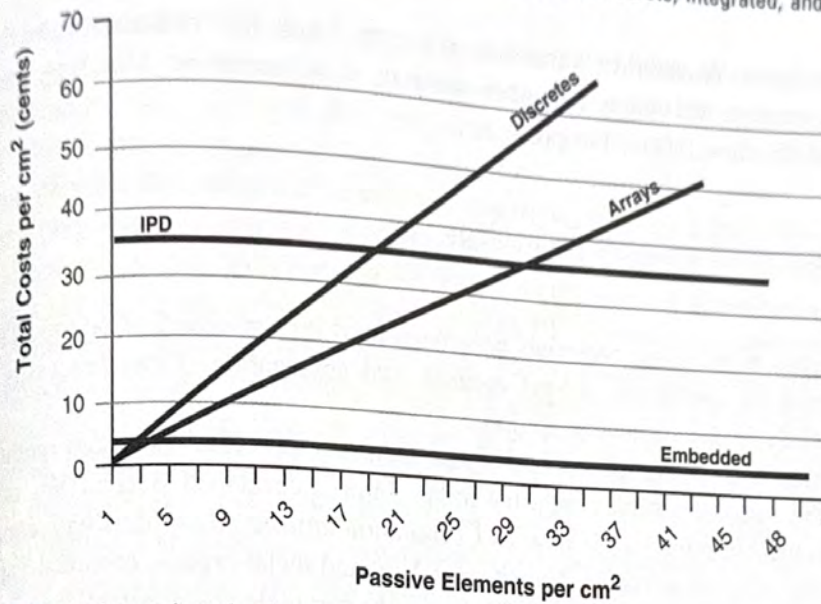


FIGURE 11.25 Cost comparison of various technologies on a component density basis.

materials can have high resistivity but have poor tolerance, especially stability over time. Controlling resistivity and thickness tolerances is a goal that has not been met by thick film resistor materials. Wide sheet resistance thick film materials in the range of 100–1,000,000 Ω/sq are available.

Thin film materials have good stability but low resistivity and only fair tolerance. Thin film resistor materials with sheet resistance of 25–100 Ω/sq are available, and 10,000 Ω/sq materials are under development. CrSi thin film resistors with DC values of 600 Ω to 14 K Ω were fabricated on flexible films. A thin film tantalum nitride, with near zero TCR values, was fabricated on a high density interconnect (HDI) dielectric polyimide layer.

Electroless and electroplating are widely used for patterning conductor lines for the inductors and depositing resistive layers on PWB and silicon substrates. Ohmega Technology has been marketing Ni-P resistive materials on various organic substrates for over 20 years. Sheet resistance on the order of 25, 50, 100, and 250 Ω/sq are commercially available from Ohmega. Intarsia Corporation, Boeing, NTT, and GE have utilized Ta₂N films for thin film resistors with resistivity values in the range of 10–125 Ω/sq . AT&T Bell Labs and Singapore Institute of Microelectronics reported TaSi films with resistivity in the range of 8–40 Ω/sq . The Sheldahl Corporation and the University of Arkansas deposited CrSi films with sheet resistivity ~ 360 Ω/sq , and TaN and NiCr films with resistivity ~ 100 Ω/sq . W. L. Gore and Associates deposited TiW films with resistivity in the range 2–4 Ω/sq . Deutsche Aerospace utilized NiCr materials with resistivity 35–100 Ω/sq .

Although there are a wide variety of materials available, the choice is limited when low temperature processes are desired. Materials requirements for embedded resistors can be largely satisfied by choosing materials systems that will provide sheet resistance in the range of 5–50 Ω/sq , 500–1000 Ω/sq , and 5 to 20 K Ω/sq , with a temperature coefficient of resistance (TCR) on the order of ± 50 ppm/ $^{\circ}\text{C}$. Besides materials, there are challenges in process integration, such as large area fabrication with good reproducibility

and yield, materials stability, variations in length, width and thickness of the deposited thin film, contact resistance, smoother substrate to reduce noise, trimming, and development of low-cost fabrication processes.

11.7.5 Embedded Capacitor Technology

Inorganic Materials

Various types of inorganic materials have been used for embedded capacitors. These can be deposited by sputtering, sol-gel method, and anodization. These processes are described briefly in the following section.

Sputtering is a widely used resistive and capacitive thin film deposition method practiced in the microelectronics industry today. Fujitsu developed $\text{Ba}(\text{Zr,Ti})\text{O}_3$ thin films with dielectric constant ~ 145 ; Intarsia Corporation utilized Al_2O_3 films with capacitance $\sim 50 \text{ nF/cm}^2$. *Chemical vapor deposition* (CVD) and metal-organic chemical vapor deposition (MOCVD) are also used for fabricating higher dielectric constant capacitors such as SrTiO_3 and $(\text{Ba,Sr})\text{TiO}_3$. A plasma enhanced MOCVD method has been applied to deposit and pattern PbTiO and $\text{Pb}_x\text{La}_{1-x}\text{TiO}_3$ films for high value capacitors. These materials have thicknesses in the range of 50–1000 nm. Feasibility of incorporating a low temperature MOCVD process in large area packaging has been studied. Recently, thin TiO_2 film with a dielectric constant ~ 34 and a capacitance density $> 110 \text{ nF/cm}^2$ has been deposited on PWB substrates at temperatures below 180°C . However, these MOCVD deposited inorganics exhibit higher loss, and the dielectric constants in these materials decrease rapidly with increasing frequencies.

The sol-gel technique has been employed in depositing thin film of PLZT type materials with higher dielectric constants. Sandia National Laboratory reported a dielectric constant of 900 in a PLZT system. AVX Corporation has recently developed sol-gel derived PZT materials with capacitance in the range of 1–5 nF on a one micron thick film with a nominal dielectric constant of ~ 1000 , thus providing a good commercialization opportunity. Sol-gel technology has been widely applied to the synthesis of fine high permittivity particles, organic/inorganic hybrid materials, and thick film glass/ceramic capacitors. However, sintering temperatures of the sol-gel powders are much higher for application in the MCM-L technology.

The anodization method has been used with vacuum deposited aluminum and tantalum films to form thin dielectric oxide layers. Sputtered tantalum films are oxidized thermally or electrolytically to thin Ta_2O_5 capacitor films. The University of Arkansas and the Sheldahl Corporation achieved a dielectric constant ~ 22 and a capacitance in the range of 50 to 110 nF/cm^2 within acceptable leakage and breakdown voltages. General Electric reported anodized Ta_2O_5 films with capacitance $\sim 200 \text{ nF/cm}^2$. The anodization technique has found limited applications due to the fact that most anodizable materials have low breakdown voltages at temperatures above 100°C .

Organic Materials

Polymers with higher permittivity (ϵ_r) are ideal candidate materials for MCM-L compatible embedded capacitors. The single-phase neat polymer system eliminates complexities arising from mixing and dispersion that are prevalent in the multiphase systems. Research in developing high ϵ_r polymers has been initiated by numerous institutions, but

a stable and processable high ϵ_r polymer system is not yet available. An electric field can induce preferred dipolar and domain orientation in ferroelectric polymers such as polyvinylidene fluoride, vinyl cyanide copolymers, and polyvinylchloride. Recently odd nylons (nylon 7 and nylon 11) showed electrical polarization analogous to the polyvinylidene fluoride. Delocalization of π -orbital electrons offers very high permittivity in conjugated polymers. For example, polyacetylene offers a dielectric permittivity of 5.5. Dielectric constant in polyacetylene can be further increased with introduction of polar side groups via copolymerization. Synthesis of a PVDF electroactive copolymer with a dielectric constant ~ 100 was recently reported by Pennsylvania State University, through a combination of radiation treatment of the PVDF copolymer films, followed by poling under an electric field. High dielectric constants in PVDF systems were also reported by poling alone, without the radiation treatment. The increased dielectric constant in PVDF is due to the distortion of the crystallites before poling, which can yield a dielectric constant as high as 100 in the pure polymer phase. However, limitations of this approach in large area embedded capacitor fabrication are cost, area of exposure, low yield, and compatibility with the sequential build-up process.

Polymer-Ceramic Composites

The lower dielectric constants of the commercially available polymers can be greatly compensated by incorporating higher permittivity ceramic fillers. The combination of such processable polymers, together with fine ($<1 \mu\text{m}$) ceramic powders, results in a polymer-ceramic nanocomposite. The two-phase nanocomposites have found application in resistors, capacitors, and inductors. Typical dielectric constant values are 10 to 100 and have capacitance of 4–25 nF/cm².

The dielectric constants of a two-phase composite can be expressed by the classical Maxwell equation. These equations were derived with the planar arrangement of two phases oriented either parallel or perpendicular to the specimen electrodes. In the case of particulate composites, Maxwell equations can be implemented as (1) phase one being dispersed, while phase two is continuous, and (2) phase two is dispersed in the continuous phase one. Figure 11.26 is a graphical representation of dielectric constants vs. filler volume fraction, where dielectric constants of the individual phases are widely different, such as the case with polymer/ceramic nanocomposites. In this figure, the dielectric constant ratio of the two phases is taken as 1000. The rule of mixtures, modified by Lichtenecker, is shown by the solid line. The outer curves represent a laminated structure arranged parallel and normal to the measuring electrodes. The dispersed two-phase composites are encompassed within this boundary. Maxwell equations predict better results in the dilute solutions. The dotted lines show that the dilute dispersion condition is no longer valid in the mixture. It is evident that the composite dielectric constant can be increased by:

1. Increasing dielectric constants of polymers and fillers
2. Higher filler loading
3. Directional anisotropy of the filler particles with respect to the measurement direction

The effective dielectric constant of a composite can be maximized by selecting higher dielectric constants of filler and matrix phases, higher filler loading, and reinforcing the

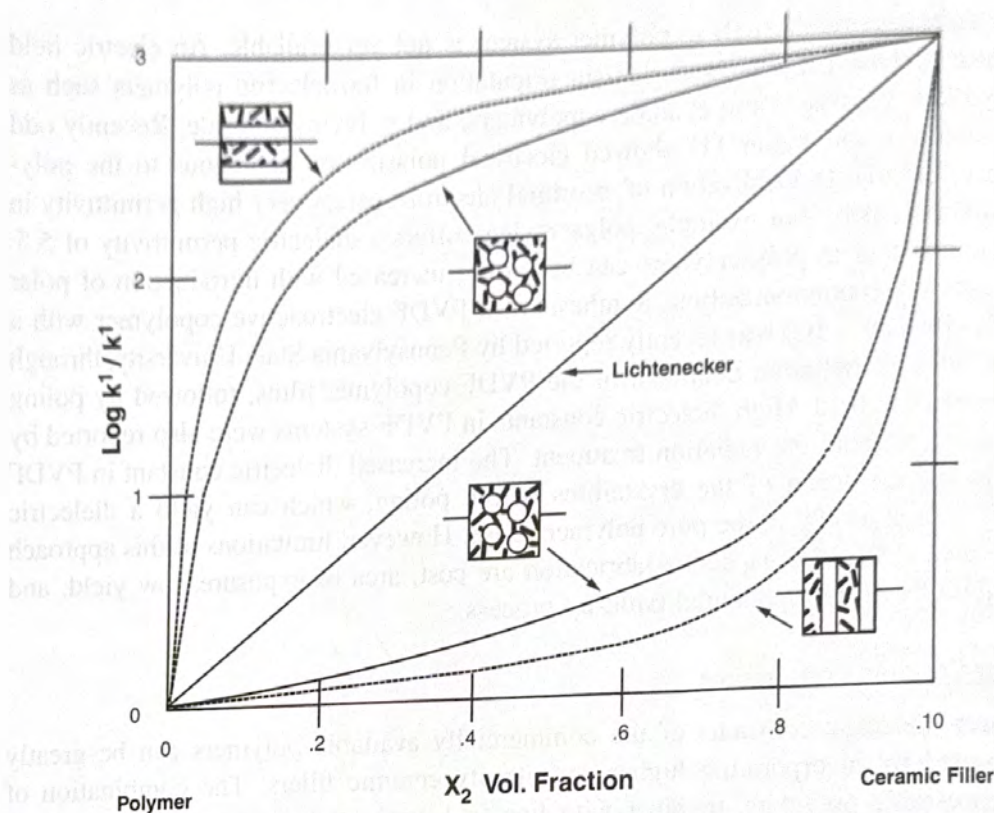


FIGURE 11.26 Calculated dielectric constants of a two-phase material.

dielectric contribution of the filler particles through their morphological and structural optimization.

11.7.6 Embedded Inductor Technology

Currently, values lower than 100 nH can be achieved by the embedded passive technology. Discretes are recommended in values higher than 100 nH, due to the increased cost in developing special materials and compatible processes. Discrete devices are usually solenoid type which offer high inductance, high- Q factor, and low-DC resistance. The high leakage current, particularly at increased frequencies, and poor packaging due to increased size, are major disadvantages. On the other hand, parasitic effects resulting from conductor line spacing and dielectric constant of the substrate are major concerns. For higher frequencies, soft magnetic materials with high resistivity are required to reduce eddy current losses. Other desirable requirements are high saturation flux to obtain high saturation current, higher permeability for increased inductance, and closed magnetic circuit to minimize leakage flux. Although integration technology has become useful in resistors and capacitors, embedded magnetic components are not well developed for the MCM-L compatible process. Inductors with varied geometries have been fabricated using the LTCC process, which is relatively expensive due to the high temperature requirement.

Electroplated magnetically soft alloys such as permalloy (Ni80Fe20), orthonol (Ni50Fe50), amorphous CoFeCu, and supermalloy (NiFeMo) have been fabricated for cost driven applications. Screen-printed polyimide filled NiZn and MnZn ferrites were developed for this purpose. Polymer ferrite core materials also offer additional EMI

shielding. The fabrication process consists of depositing a seed Cu/Cr layer, patterning with photoresist, electroplating or screen-printing a magnetic core, and wet release of the bottom seed layer.

For conductor lines, multi-level metal conductors are electroplated on the magnetic core material using a seed layer which is difficult to remove due to the spatial hindrance. Mesh-type seed layers were used for the lower conductor lines and vias. After the fabrication process was completed, the edges of the mesh-type seed layers were exposed and removed by the plasma etch. Top conductor lines were deposited by electroplating. Inductors with special geometries such as (1) planar wire-wound inductors, (2) multi-turned core with and without air gap, (3) bar type inductors, (4) EMI filter inductors with vertically stacked spiral-type conductor lines using permalloy cores, and (5) spiral and meander type inductors with sandwich ferrite core, were fabricated. For low frequency applications (<1 MHz), inductors with a geometry of $4\text{ mm} \times 1\text{ mm}$ with 0.13-mm thick device achieved inductance in the range of $0.57\text{--}0.67\text{ }\mu\text{H}$ with Q -factor in the range of 1.4 to 1.8 with permalloy core. With ferrite core inductors, inductance of $\sim 0.6\text{ }\mu\text{H}$ and a Q -factor of 15–17 at 15 MHz were obtained. Motorola, Lawrence Livermore Laboratory, Intarsia Corporation, and GE adopted electroplating to form copper lines on inductors. The inductance was in the range of 5–50 nH, and the Q factor varied between 10 and 30 at the frequency range of 1–3 GHz.

11.8 SUMMARY AND FUTURE TRENDS

Passive components play an important role in all electronic circuitry. This chapter begins with a definition of passive components from the fundamental as well as from the functional standpoint with a clear distinction from the active components. Applications of passive elements in digital, RF, and mixed-signal packages are provided with current and future requirements. Fundamental equations relating to the conceptual definition of passive components are provided. The many forms of passives such as discrete, integrated, and embedded are addressed with examples in each of these three broadly defined nomenclatures. The technology trend toward the emerging embedded passives and the options for embedding passives into substrates have been argued from the advantages and challenges.

The electronics industry is going through miniaturization in consumer electronic products. The current demand is for lighter and highly integrated ultra-thin packages at reduced cost. Embedded passive technology provides a window of opportunity to meet the current demand. The general consensus in embedded passives today is that resistor technology is viable, capacitors need further research and developmental work, and inductors are beneficial only for relatively low values ($\sim 100\text{ nH}$). Projected requirements for the year 2005 is a capacitance of $\sim 50\text{ nF/cm}^2$ and a resistivity in the range of 25 to 100,000 Ω/sq . It is reported by NEMI that 40% of capacitors in hand-held applications are low value ceramic chip capacitors of $<1000\text{ pF}$, and these will be a primary target for integrated passives. Currently, discretely are recommended for high value resistors, capacitors and inductors.

Although embedded passives have been realized in the laboratory prototypes, there are several unresolved issues for commercialization. Yield in the manufacturing process is a big concern, since the embedded passive technology does not offer the luxury of reworkability, as in the case of discretely. A single defect could result in discarding the

entire board with hundreds of pre-fabricated components. The critical concerns in electrical design are front-end design and back-end tests. A long design cycle of over two weeks is attributed to simulation tools, design rule check, and iterations before the design can be validated. Electrical test is also expensive, due to the lack of efficient test procedures. Crosstalk becomes an important issue due to the higher component density. Product qualification, component specifications and tolerances, trimmability, and ultimate component density are important issues for standardization of embedded passive technology. The good news is that, according to the NEMI Roadmap, 900 billion parts were shipped in 1997, projecting the passive component market in excess of \$18 billion. However, only 2.6% of these passives were buried components. The study indicates that embedded passive technology may have a unique opportunity for capturing a huge market share in the near future. The fastest growing sector is likely to be within the integrated passive components used for high performance filtering application and ESD protection, and standard wireless modules for VCOs, power amplifiers, and transceivers.

11.9 HOMEWORK PROBLEMS

1. Wires are fabricated with the following four different materials with their associated resistivities: nickel ($6.9 \times 10^{-6} \Omega\text{-cm}$), copper ($1.724 \times 10^{-6} \Omega\text{-cm}$), iron ($9.71 \times 10^{-6} \Omega\text{-cm}$), and aluminum ($2.62 \times 10^{-6} \Omega\text{-cm}$). If the wire size is 22 gauge (circular area of $3.355 \times 10^{-3} \text{ cm}^2$), what would be the resistivity per unit length of these four (Ω/M)?
2. As you add wires in parallel, the cross-sectional area increases by the cross-sectional area of one wire. What is the resistance of the four types of wires from problem 1, if they are each built with 5 strands of 22 gauge each?
3. Ceramic capacitors are built with stacked plates, and the stacking effect is the same as adding an additional plate area for each element of the stack. Consider a capacitor built with 40 stacked layers, each layer with an area of 1 cm^2 . If the dielectric constant is 4000, and the thickness of the dielectric is 10 microns, what would the capacitance be? If the layers are increased to 80, what is the capacitance?
4. Placing equal capacitors in series is the same as retaining the same area and dielectric, but increasing the thickness by a factor of two. If two of the same $1\text{-}\mu\text{F}$ capacitors were placed in series, what would the final capacitance of the pair be equal to? Since the dielectric thickness defines the voltage stress capability, how does the voltage rating of this series connection relate to the voltage rating of each capacitor?
5. In a circuit application, an inductor of 100 nanohenries (nH) is subjected to a current pulse that goes from 0 to 16 amperes in 10 nanoseconds. What is the voltage developed across the inductor at time $t = 0$, and at time $t = 10 \text{ nsec}$?
6. A notch filter consists of a series capacitor and inductor pair. If the inductor is 100 nH, and the capacitor is $10 \mu\text{F}$, assuming there are no parasitics with these devices, what is the resonant frequency of this pair? Is the impedance or admittance peaking at this frequency? If the resistance of this circuit is 10 milliohms, what is the impedance at the resonant frequency?
7. A tank circuit consists of a parallel arrangement of the capacitor and inductor. If the same capacitor and inductor from question 6 were used in a tank circuit, what is the resonance frequency for this arrangement? Is the impedance or admittance peaking?

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