ELECTRONICS, COATINGS

Coating technology can be defined as replacing air at the surface of a substrate to give a film structure having varying layers of different properties. This technology covers a wide range of products and processes (see Coating processes; Coatings; Paint). Electronics coatings refers to the wide variety of coated structures used in electronic devices.

There have been significant advances in electronics coatings technology in the latter part of the twentieth century, leading to rapid growth and high economic importance. These coatings have some unique aspects of formulation, production, and use. The ability to produce high resolution coatings, at high volume and low cost, has been the driving force for the revolutionary advances in a wide variety of electronic components, integrated circuits (qv), memory chips, magnetic storage devices, cathode ray tubes, optical storage disks, etc (see also Electronic materials; Information storage materials). Improved functionality of these components has led to advances in a wide range of consumer, industrial, and military products. Typical devices are television sets, video cassette recorders, cameras, fax machines, cellular phones, personal and lap-top computers, fly-by-wire control systems for airplanes, and the guidance system for such military ordnance as smart bombs and cruise missiles.

Significant advances have also been made in the more traditional area of wire and cable used to transmit the electricity needed for these devices (see Electrical connectors). The optical cables (see Fiber optics; Nonlinear optical materials) that are replacing the traditional copper (qv) cables for telephone usage require very sophisticated coatings to protect cable from light loss and deterioration. The ribbon cable and multiple coaxial cable assemblies used for cable television, stereo systems, and burglar alarms all depend on the cable coatings reducing interference with each other so that signal quality is maintained.

1. Economic Aspects

Electronic coatings are of significant economic importance, as are the finished products in which they go. The worldwide total value of the resulting products is $500 billion. Table 1 provides a geographic breakdown. The annual electronics coatings market value is estimated to be $5 billion. These coatings are manufactured in several countries. Some of the principal manufacturers of electronic coatings are

Company	Products
Minnesota Mining and Manufacturing	conformal coatings
W. R. Grace & Co.	dielectric and conductive adhesives, encapsulants, heat dissipating materials, manufacturing aid coatings
Union Carbide Corp.	Parylene conformal coatings, photoresists, developers, etchants, solder masks, potting compounds
Conap unit of American Cyanamid	potting compounds, conformal coatings
Du Pont Co.	conformal coatings, photoresists, manufacturing aids, electronic functional coating compounds
OGG Microelectronic Materials, Olin/CIBA-GEIGY venture	photosensitive polyimides, high performance semiconductors
Dexter	encapsulants
Dow Corning	potting and encapsulating compounds
Asahi	packing materials
Nippon Kayaku	packing materials
General Electric	packaging materials
Unilver	adhesives, dielectric coatings, protective coatings, dielectric interlayers, electronic functional coatings

2. Functions of Electronic Coatings

Electronics coatings can generally be classified as: (*1*) functional, ie, coatings that provide a variety of electrical, magnetic, optical, chemical, mechanical, and/or thermal properties enabling a device to function as prescribed; (*2*) manufacturing aids, ie, coatings that serve as an integral part of the manufacturing process to make a specific component or device; or (*3*) protective/decorative, ie, coatings that protect the component or device from environmental damage during its normal use cycle. As can be seen from Table 2, most electronic devices require coatings that perform more than one of these functions. A wide variety of chemical compounds or formulations are needed to meet these specifications.

2.1. Functional Coatings

Whereas there are many types of functional coatings, the basic properties or characteristics that give a device utility are its electrical, magnetic, and optical properties. The electrical properties can be defined by the ability of the material to conduct or hinder flow of electrons. This characteristic resistance is expressed by

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

where $R = \text{resistance}$ of conductor in ohms, L = length in cm, ρ = proportionality constant called specific resistance or resistivity in ohm·cm, and $A = \text{area}$ in cm^2. The resistivity is typically expressed in terms of the volume resistivity, ie, the ohmic resistance of a cube of material, having dimensions of 1 cm per side. This is expressed as ohm·cm. Good conductors, which do not impede the flow of electrons, have values of $10^{-6} - 10^{-8}$ ohm·cm. Poor conductors impede the flow of electrons and have values greater than 10^8ohm·cm. Figure 1 shows the comparative resistivity of a variety of materials.

Resistivity can be used as a guide to the role a material performs in a specific device. Materials having high values, such as Teflon, serve an insulation function (see Insulation, electrical). Metals such as silver and copper are excellent conductors. Organic compounds and polymers can cover a wide range of values, and the actual resistivity depends on exact composition.

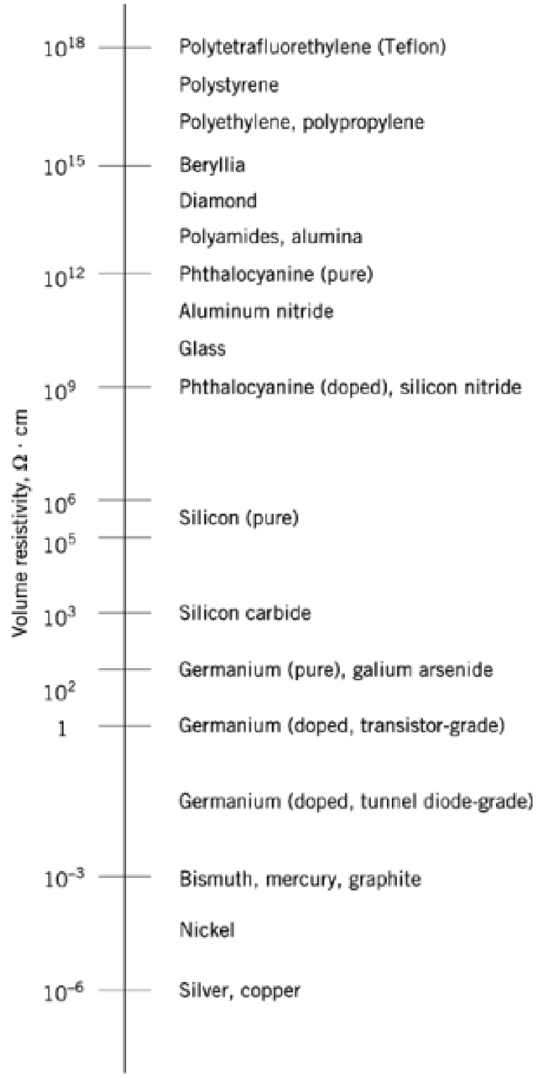

Fig. 1. Electrical resistance materials.

One factor leading to the growth of electronics coatings technology has been the ability to modify compounds to give very specific electrical properties. Variations in compositions and additions of trace materials can have a significant effect on resistivity, particularly in the chemistry of semiconductors (qv), where trace amounts of dopants can significantly change resistivity and thus the function. Polymers can be compounded with metals to increase the polymer conductivity while utilizing the polymer mechanical properties to give flexibility in fabrication of specific elements. The exact conductivity is, of course, a function of the dopant used. Polymers can also be custom synthesized to give increased conductivity. Typically, polymers having a high degree of conjugation and linear backbones tend to be better conductors than others.

Optical functions are important both to transmit information through fiber optic cables and to store information on optical disks. An optical fiber consists of a central core, such as silica [7631-86-9] surrounded by a series of coatings to protect the fiber and give it flexibility. Typically uv-curable acrylates are used for

Table 1. Worldwide 1992 Electronics Industry Value,[a] $\$ \times 10^9$

Market	Geographic area		
	United States	Japan	Europe
computers and office equipment	103	54	119
communications	36	12	36
consumer	35	20	32
semiconductors	17	24	11
capital and test equipment	10	6	4
Total	*519*		

[a] Ref. 1.

Table 2. Coating Requirements of Electronic Products[a]

Device	Coating function[b]
optical fibers	P,F
integrated optics	M,F,P
wires	P,F
printed circuit boards	M,F,P
passive components[c]	F
integrated circuits	M,P,F
liquid crystal displays	M
lenses	M,F
cathode ray tubes	M,P
projection TV screens	F
solid-state cameras	M,F
compact disks	M,P,F
LaserVision disks	M,F
optical recording	M,F,P
magnetic recording	M,F,P

[a] Ref. 2.
[b] F = functional, ie, electrical, magnetic, thermal, mechanical, chemical,or optical function; M = manufacturing aid; and P = protective.
[c] Components such as capacitors and resistors.

these protective coatings (see Acrylic ester polymers). To minimize light loss, the silica is doped with oxides of germanium or phosphorus to raise the refractive index.

Optical information storage is a relatively new method for storing large quantities of information. The compact disk (CD) and LaserVision are two well-known read-only formats that have been on the market since the early 1980s, whereas write-once and erasable (rewritable) recordable formats have been introduced more recently. Photopolymerizable acrylate compositions are used for abrasion protection of the metallic mirrors of CDs, as the information carrier in the replication of LaserVision video disks, and in the replication of aspheric lenses used in the optical heads of the drives or players. Numerous coatings have been developed for direct writing of the digital code onto recordable disks. These may be polymer/dye, metallic/semiconductor alloy, or even magneto-optic in composition. Writing occurs by a thermally induced optical change in the thin recording layer by a focused laser beam. Readout is typically done in reflection at lower laser power.

Because there are many other properties that also are important, coatings cannot be selected only on this basis. The mechanical and chemical properties of the coating, change of properties with temperature, dielectric and adhesion properties, and particularly the cost of fabrication are all important parameters. Coatings can also be used to transport heat created away from a component and keep the component functioning as designed, or to protect a component from temperature variations in the environment.

2.2. Manufacturing Aids

The use of coatings to aid in the manufacture of an electronic component is somewhat unique to electronics coatings. Most coatings, once applied, are part of the finished product, and remain with the coated structure throughout the majority of its life cycle. The manufacturing aid coating, however, is only temporary, and is used as part of the manufacturing process to help apply functional coatings in a desired path or to locate specific functions to give the component its desired characteristics. Historically, tubes, resistors, capacitors, etc, were placed on a board and connected using wires soldered in place. This methodology could not produce conductor paths below the 300 μm width needed for high performance devices. As a result, it has been replaced by processes that use temporary coatings, such as resists, to produce the conductor lines. The use of manufacturing aid coatings also allows manufacturers to rapidly and precisely apply a wide variety of newer types of coated materials that perform the same resistance and capacitance function previously done using discrete components. Electronics coatings technology can easily produce conductor paths of 1–5 μm, and even 0.35 μm is possible. The processes are easily automated, and have led to improvements in the quality, costs, and long-term performance of the resulting circuits.

Using electronics coatings technology, the temporary coating is applied to an underlayer or substrate, and a line or pattern copied to the temporary coating using uv light, x-rays, or an electron beam (see Lithography). The original pattern is prepared using computer design programs, and then transferred to photographic film (see Photography). The copying process can also significantly reduce the size of the pattern, so that the circuit can be designed in large scale and then reduced for the miniaturized part. The significant reduction in the size of lines produced yields an increased efficiency of all components.

The patterned coating leaves part of the underlayer protected and part unprotected. Conductive, resistive, or capacitive coatings can then be applied as needed to the unprotected portion to give functionality and conductor lines where desired. The temporary coating is then removed, and the process may be repeated using additional temporary coatings that give different patterns. This process may be used to apply or add other functions, to solder components in place, etch the underlayer, or apply dopants. When the component is finished, very little of the temporary coating remains.

Typical of the temporary or manufacturing aid coating systems is the RISTON dry film photoresist for printed circuit (PC) board fabrication. This was the first of these systems developed. The RISTON product structure and the basic steps in its use are shown in Figure 2. It consists of a photopolymer sheet laminated between a Mylar cover sheet and a polyolefin separation sheet. It is manufactured as a continuous web (see Coating processes, survey), and is supplied in rolls of varying width and photopolymer composition.

The steps in the process shown in Figure 2 are (*1*) clean the substrate by mechanical brush scrubbing or by using either spray or dipped solvents, vapor degreasing, or ultrasonic assist (microetchants may also be used); (*2*) laminate the photopolymer resist film to one or both sides of panel (the separator layer is removed just prior to lamination); (*3*) expose the board using a phototool through the Mylar cover sheet to harden the photopolymer to give the desired pattern; (*4*) remove the Mylar cover sheet and wash away the unexposed photopolymer using an alkaline water solution or an appropriate solvent; (*5*) apply the desired functional electronic coating; and (*6*) strip the photopolymer resist film from the circuit board, typically also using an aqueous alkaline solution. This process is highly automated and uses specific equipment to perform all of the functions, giving high productivity, low cost, and the precision needed.

In the production of integrated circuits where there is a need for very small ($<1\ \gamma$m) lines, which have to be very close to each other in order to achieve the miniaturization and small circuitry that is required, extreme cleanliness is required in all of the process elements. Dirt, particles, or defects in the temporary coating that are larger than 1 μm can be imaged, and ultimately give an electrical connection

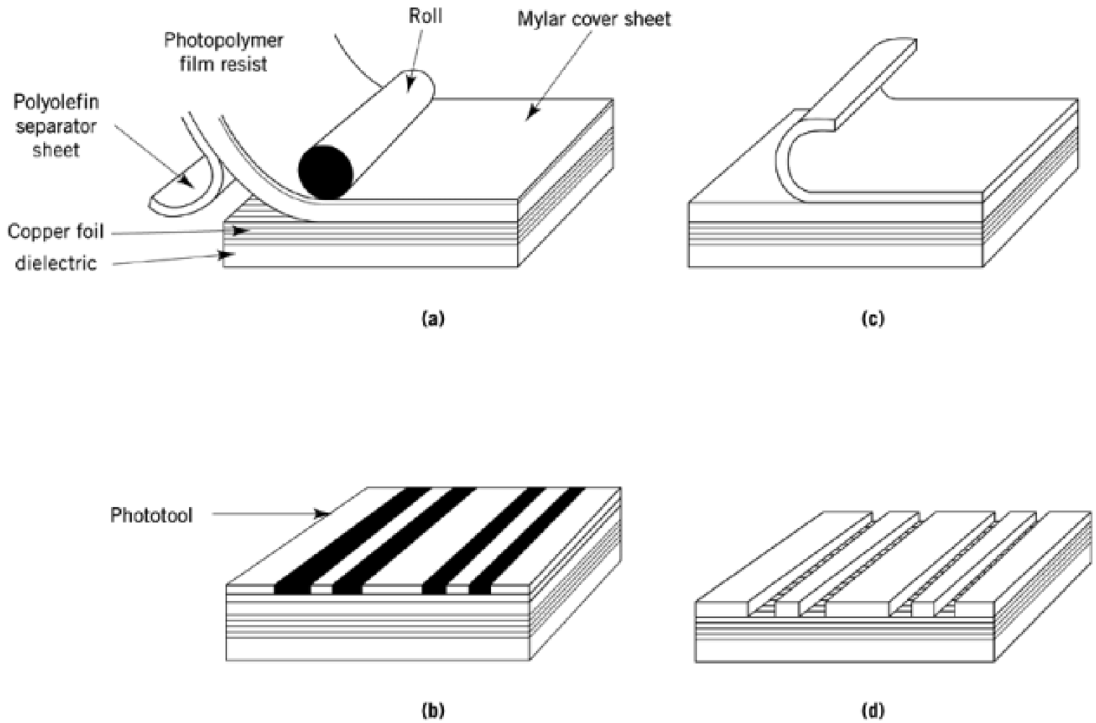

Fig. 2. Schematic of the RISTON dry film photoresist process. (**a**) Removal of polyolefin separator sheet and laminate resist to clean surface, using special laminator; (**b**) exposure to uv source using positive or negative phototool (positive to plate; negative for print-and-etch); (**c**) removal of the protective Mylar, which is readily removed by hand; and (**d**) development using a special processor (3).

between two lines that interfere with the functioning of the circuit. Thus all of the process components must be extraordinarily clean and free from defects and nonuniformities and the goal of all electronics coatings is to be defect-free. This sensitivity to contamination and the requirement for cleanliness are other differentiating elements from most coating processes, where much higher defect sizes can be tolerated.

To meet the cleanliness need, all elements of the process are controlled to minimize sources of contamination. Air normally contains a large volume of contaminants in the form of dirt, dust, and pollen. The human body sheds a large volume of particulate contaminants such as skin, phlegm, hair, etc. The importance of eliminating these contaminants can be understood by comparing the size of human hair (50 μm diameter) and a bacterium ($\sim$5 μm) to a 1-μm line such as used in a memory chip. To keep particulates from contacting the coating, all machines are maintained in clean rooms where air is filtered to remove contaminants; also, people entering the room wear protective clothing that does not shed particulates into the air. The clean rooms are rated by the number of particles present in the air. A class 100 rating indicates 100 or fewer particles $\geq$0.5 μm are present in 1 ft^3 (2.83×10^{-2} m^3) of air; a class 10,000 would have 10,000 or fewer 0.5 μm particles. The exact specification depends on need, but class 100 rooms are in routine use.

In addition, all of the process raw materials must be clean and not introduce contaminants. The raw materials and temporary coatings must also be defect-free, and these have to be manufactured under similar conditions so that no contaminants are introduced. The solvents used to clean the substrate and develop the resists must be filtered and pure. Care must also be taken to ensure that no trace compounds or elements are present that may affect the electronic properties. The specific type of coating aid, the type of functional coating, and the process used to apply the functional coating are all widely varied in actual practice.

2.3. Protective/Decorative Coatings

After the component or finished device has been fabricated, coatings may provide three additionally needed functions: protection of the component from the environment, to ensure the same performance throughout the component's useful lifetime; protection of the user and the environment from the component; and a decorative and characteristic appearance. Examples are the three copper conductor strands of wire in a typical electrical appliance. Each wire strand has a polymeric coating to protect the strands from contacting each other, thus preventing a short circuit and protecting the user when the cord is touched. The coating must also protect the copper from attack from the environment so that the metal does not corrode and fail. The coating should also enhance the appearance of the device. Wire coatings are color coded to ensure correct polarity when devices are attached. Black, red, blue, or yellow are the hot lead, power source; white is neutral; and green is ground.

The requirement for a protective coating for components depends on the environment in which it is going to be used and the potentially destructive capability of the various components present. In normal use, all devices are exposed to air, which contains water vapor and oxygen. Both react with the functional, electronic, magnetic, or optical coatings to change performance. Whereas it is possible to hermetically seal memory chips and integrated circuits during shipment and storage to eliminate these effects, it is not feasible to do this for the vast majority of uses. Thus protective coatings are used that retard the passage of moisture, oxygen, and sulfur dioxide. These are selected on the basis of low permeability and low water absorption as well as on aging performance. Several polymer classes, eg, polyurethanes (see Urethane polymers), polyimides(qv), poly(vinylidene chloride) (see Vinylidene chloride and poly(vinylidene-chloride)), are good for this application. If the device or component is to be used in a special environment such as the ocean, the ability to protect against salt water and corrosion resistance to salt become key factors.

Electronic devices can also generate electromagnetic and radio frequency interference waves that can interfere with other electronic devices. These waves must be modulated and leakage to the environment prevented. Plastics, silicones, acrylics, and polyesters (qv) that are filled with conductive fillers, such as silver, nickel, and copper, are used for this application (1). Although nickel-filled polymers are low cost and efficient, these are not preferred because of the carcinogenic nature of nickel powder.

3. Coatings Properties

Material property specifications must be written by design and material engineers to control engineering requirements and to control incoming raw material quality. Material property requirements depend on various in-use functional needs in terms of electrical, mechanical, thermal, chemical, optical, and magnetic properties.

Electronic coatings can be classified as either organic, inorganic, or metallic. Organic coatings are typically polymeric in nature. A wide variety of polymer types are used. Although polymeric properties vary considerably less over the full range than those of the inorganics and metallics, both chemistry and molecular structure play a role because these dictate properties and coating behavior. A list of polymer uses in electronic coatings follows. More detail can be found in the literature (4).

Polymer	Uses
alkyd	polyesters for protective and decorative coatings; paints
acrylic	general purpose for molding, casting, and coating formulations; dip and sprayable PC board coatings
epoxy	protective and electrical-grade adhesives, electronic encapsulation, composites, and PC boards; solder masks
fluorocarbons	good chemical and electrical properties, protective coatings, release coatings, barrier coatings
phenolic	work-horse thermoset for adhesives; parts
polyimide	high temperature applications, glass-reinforced PC boards, flexible film and cable, interlayer dielectrics
polyurethane	tough, abrasion resistant for casting, potting, and encapsulation of connectors and modules; conformal coatings for PC assemblies
polyvinyls	chlorides, fluorides, vinylidene chlorides and fluorides, vinyl aldehydes, and polystyrene; used for moisture barriers, primary-wire insulation, corrosion protection, dielectric impregnants, and baking enamels
polyxylylene	conformal coatings for PC assemblies; insulation
silicone	available as solvent solutions, room-temperature vulcanizable (RTV) rubbers, and solventless resins; used as insulation for high temperature and high voltage parts

4. Components

4.1. Printed Circuit Functional Coatings

A printed circuit (PC) is an electrical connection or circuit board assembly fabricated using any of a number of graphic arts processes. The ability to be mass produced, high degree of reliability, and small size and weight, ie, increased circuit density, have made printed circuits the elements of choice in all kinds of electronic devices and equipment. Printed circuit applications can be printed wiring; hybrid circuits, ie, thick and thin film; or integrated circuits. Coatings are used in all aspects of printed circuits, from the base substrate materials, through fabrication, to final protection/encapsulation of the finished product.

4.1.1. Printed Wiring Boards

Printed wiring boards (PWBs) consist of one or more layers of conductive circuitry adhered to a dielectric (insulating) material or substrate. These may be simple single-sided copper wiring traces on a support, or complex multilayer assemblies having plated-through holes (vias), used in higher performance, higher density packaging (see Packaging, semiconductors and electronic materials).

4.1.2. Substrate Materials

The most common substrate is a copper-clad laminate. Fabrication starts with a base material, usually glass cloth, impregnated with a thermoset resin that is partially cured to give what is called a prepreg. The resin may be epoxy, but for more demanding applications such as the high density multilayer boards, high temperature polyimides are used. The prepreg is then clad with a thin layer of copper foil in a lamination or pressing step to give a rigid substrate suitable for and used in most applications. Demand for space savings has led to increased use of flexible substrate materials. These consist of a thin polyimide dielectric material clad with an adhesive and copper, and can be configured similarly to the rigid PWB (see Adhesives).

4.1.3. Resists

Resists are temporary, thin coatings applied to the surface of the copper-clad laminate. After patterning, these films act as masks that are chemically resistant to the cleaning, plating, and etching solutions used to define the circuit traces of the PWB. Both nonphotosensitive and photosensitive types are used.

4.2. Screenable Resists

Screenable resists or inks (qv) are applied to the metal-clad substrate through a silk (qv), nylon, or stainless steel screen on which a circuit pattern has been defined. The coating is squeegeed through the stencil onto the substrate, then dried. Depending on whether metal is to be removed or added, the board is treated with either etching or plating baths or solutions. Afterward, the resist is removed or stripped. Organic soluble resists have almost entirely been replaced by aqueous alkali strippable resists.

Screenable inks have a resin or polymer base and are of three types: organic solvent soluble, aqueous alkali soluble, and permanent. Primarily because of pollution requirements and higher solvent costs, the aqueous types have come into greater use. The permanent types are used as solder masks or for marking the boards. Uv-curable inks are also in use.

Although more direct than photoresist, this method, limited to line widths of 250–380 μm (10–15 mils) because of the limits of screen fabrication, is used primarily for low cost print-and-etch and plated PWBs (5).

4.3. Photoresists.

For high resolution circuit lines $\leq$125 μm (5 mils) photosensitive resists are used. These can either be applied as liquids and dried or laminated as dried films supported on a polyester support. When exposed to light, typically ultraviolet radiation, these coatings change chemically, and their solubility to certain solvents or developers changes. There are two types of photoresist: negative-acting and positive-acting. Negative resists typically consist of a mixture of acrylate monomers, a polymeric binder, and a photoinitiator. Upon uv exposure through a mask, the resist polymerizes and becomes insoluble to the developer. Unexposed areas remain soluble and are washed away. Positive resists function in the opposite way with exposed areas becoming soluble in the developing solvent. As for screenable inks, photoresists are available commercially both as solvent or aqueous developable, as well as permanent. A schematic of negative- and positive-working resists is shown in Figure 3.

4.3.1. Protective Coatings

Solder masks are resists designed to define or mask areas of a finished printed circuit board where components are to be attached by selective deposition of molten solder (see Solders and brazing alloys). In contrast to etching or plating resists, the cured solder mask film remains permanently. These coatings minimize bridging between close conductor lines and pads during soldering, provide protection from fluxing and other chemical attack during fabrication, and act as environmental and physical barriers for the life of the board. This is a demanding application having a number of rigidly specified requirements such as abrasion resistance, flexibility; adhesion to copper, tin–lead, nickel, and gold; thermal and flame resistance; machinability; low water absorption; and chemical and solvent resistance.

Earlier material systems were screened epoxies, but both laminatable dry-film and liquid uv photoimageable coatings are finding wide acceptance. These radiation-cured coatings offer high resolution and registration accuracy, and can be either epoxies or epoxy acrylates.

After all the components have been mounted, a conformal protective coating may be applied to the printed circuit board not only to provide electrical insulation, but also to help maintain performance and extend service life in harsh operating environments. Moisture is the main culprit, causing corrosion, degradation of insulating properties, or electrical shorts. Other benefits are protection from contaminants such as spray, salt, dust, grease, fuel, corrosive vapors, fungi, and, to some extent, mechanical vibration. Many electronic component assemblies are inexpensive and designed to be nonrepairable and throwaway. For these, if a protective coating is used at all, it is an inexpensive varnish or polyester. For more expensive modules, specialty coatings are used to ensure long-term reliability. These are typically acrylic, epoxy, polyurethane, silicone, or polyxylylene in composition and can be applied by numerous methods, eg, dip-coating, spraying, fluidized-bed coating, casting, or vacuum deposition. Individual components themselves may also be protected using conformal coatings. For expensive

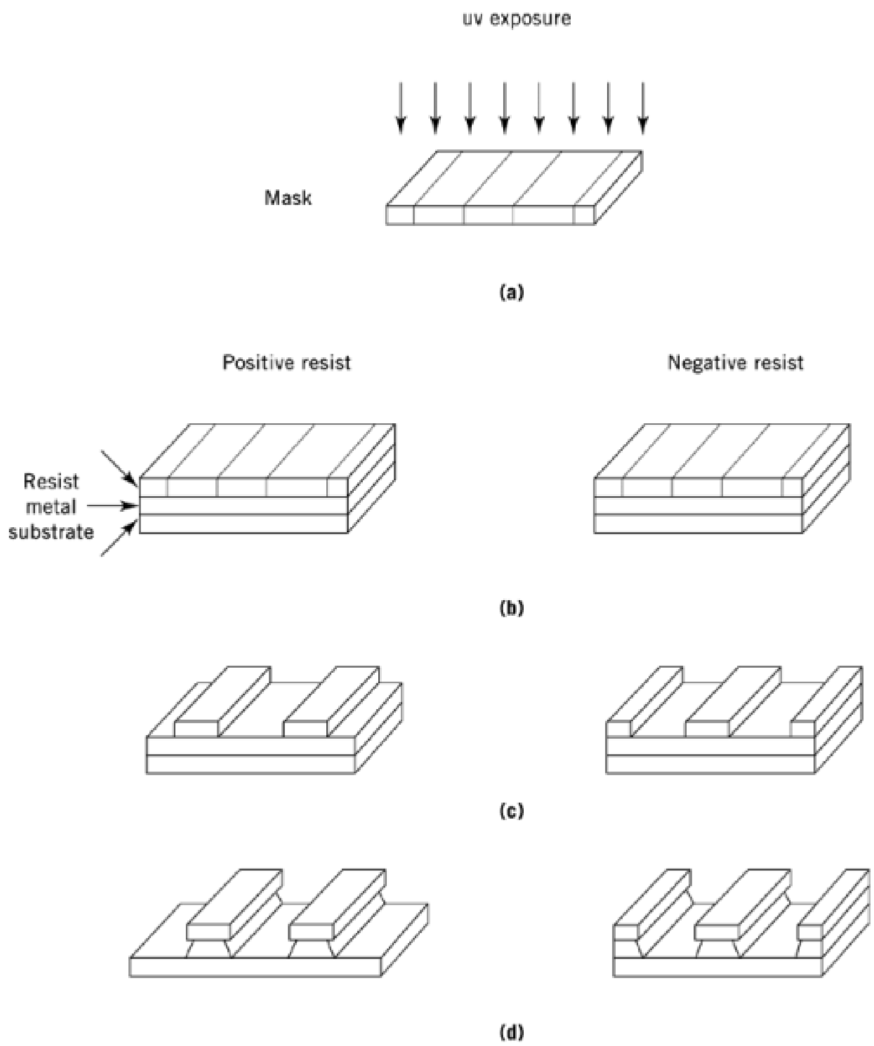

Fig. 3. Lithographic process using positive- and negative-resist systems. The element (**a**) is (**b**), exposed to uv radiation; (**c**), developed; and (**d**), the metal is etched (6).

assemblies, the coating must be removable to allow solder rework or replacement of defective components. This requirement places further demands on the coatings.

4.4. Hybrid Microelectronic Coatings.

Hybrid circuits are fabricated using two complementary technologies: thick- and thin-film printed circuits. Typically, simple thick- and thin-film hybrid circuitry and components packages, including integrated circuits (ICs), are integrated/assembled into a complex integrated unit on a ceramic substrate. The function of the hybrids is to connect and modify the component packages through use of various conductors, dielectrics, resistors, inductors, and capacitors. Because these can function at high temperatures and be hermetically sealed for some applications, they are typically used in demanding applications such as for the military, in space, computers, the automotive industry, and telecommunications.

Table 3. Electronics Coatings Application Methods[a]

Coating method	Advantages	Limitations	Typical uses
spray	fast, adaptable to varied shapes, low cost	difficult to obtain complete coating thickness, not uniform, poor reproducibility, high coating solution loss, solvent loss	motor frames and housings, electronic enclosures, circuit boards, modules, protective/decorative coatings
electrostatic spray	efficient coverage complex shapes, automated, less solvent loss	requires specially formulated solutions, high cost	heat dissipaters, decorative and protective coatings, enclosures
dip	thorough coverage of complex parts, inexpensive	viscosity stability affects coverage uniformity, environmental concerns	protective coatings on small- and medium-sized parts
roll	high speed continuous process sheets, excellent thickness control	requires continuous web, high cost	protective and decorative coatings, application of liquid photoresist to boards
fluidized-bed	thick coatings in one pass, uniform coating, no solvent, environmentally friendly	high temperature needed to fuse coating, limits substrate material	motor stators, insulation on castings, metal substrate for heat sinks, circuit boards
screen stencil	deposits coating in select area through mask, good thickness control	requires flat surface, need to prepare original pattern	circuit boards, masking for etchants, spot insulation between circuitry layers
spin	good thickness control for low coverage, reproducible	requires flat surface, discrete substrate, not continuous	photoresists for semiconductor devices and thin-film circuits, polymeric dielectrics, magnetic disks
electrocoat	good control of thickness and uniformity, can coat wet parts, good complex shapes	limited number of coating formulations, must be specially formulated, adhesion	protective and decorative coatings, complex castings
vacuum deposition	ultrathin, pinhole-free coatings, selective deposition through masks	thermal instability of plastics, needs vacuum control	optical coatings, thin-film IC layers

[a] Ref. 10.

Thick-film technology is an additive process and involves screen printing of functional inks, also called pastes or simply compositions. The paste formulation consists of a high $(20,000-250,000\text{mPa}\cdot\text{s}(=\text{cP}))$ viscosity thixotropic dispersion of fine particles of an electrically functional phase and a glass and/or ceramic frit binder. Also included for screen printing are a polymeric binder, a solvent or vehicle, and modifiers such as wetting and flow-control aids. After air drying to remove most of the solvent, the parts are fired at high (850–1000°C) temperature. During this process, the polymeric binder and other small molecule species decompose and volatilize. The glass frit fuses, wetting the surface of the functional phase, providing adhesion and sealing of the composite to the substrate. Because of the screen printing process, resolution is modest. Fired film thicknesses, which range from 10 to 50 μm (0.4 to 2.0 mils), are large compared to thin-film microelectronics. Some photosensitive pastes are also in use.

Polymer thick films also perform conductor, resistor, and dielectric functions, but here the polymeric resins remain an integral part after curing. Owing to the relatively low (120–165°C) processing temperatures, both plastic and ceramic substrates can be used, leading to overall low costs in materials and fabrication. A common conductive composition for flexible membrane switches in touch keyboards uses fine silver particles in a thermoplastic or thermoset polymeric binder.

Thin-film technology offers the highest circuit/feature resolution, down to micrometer level geometries or even below, and film thicknesses that range from 0.01 to several micrometers (see Thin films). Although used in hybrid manufacturing, these processes are more typically found in the fabrication or manufacture of microelectronic, ie, integrated circuit devices. Coating is primarily done by either of two vacuum techniques:

evaporation or sputtering. Microelectronic photoresist application by spin coating and photodefinition is followed by etching, a subtractive process, to yield the circuit and device features. This contrasts with thick-film processes, which are additive. However, for many magnetic and optical applications, the thin film may be deposited only where desired through a stencil as in screen printing.

Device materials again may be conductive, semiconductive, dielectric, or resistive. Conductors are typically gold or aluminum, and resistors, silicon monoxide or silicon nitride. Tantalum nitride and nickel chromium are common resistor materials.

Vacuum evaporation consists of heating a reservoir of the source material to its boiling or sublimation point in a high vacuum. Material vapor travels a distance and condenses on a relatively cold substrate, forming a very thin uniform film. In sputtering, energetic ions are accelerated into a target material at relatively high pressures, and particles are kinetically driven from the surface. Several newer techniques are plasma polymerization and chemical vapor deposition(see Plasma technology; Vacuum technology) (7, 8).

Numerous protective conformal coatings are also used in the hybrid circuit industry. Most of the criteria that pertain to use in printed wiring also apply here (4).

4.5. Integrated Circuit Coatings

The integrated circuit (IC) is the basic building block in microelectronics. It is a semiconductor device having both passive and active components built both into and onto a silicon wafer. High reliability has led to numerous applications in aerospace, and for industrial and consumer equipment. Precisely formed multiple layers are deposited on top of one another and interconnected to form a three-dimensional circuit network. Circuit geometries are generally measured in the micrometer range. Circuit element thicknesses vary from a few hundredths to a couple of micrometers. A large integrated circuit chip often contains in excess of a million devices. Individual chips are linked together through packages on printed wiring boards or hybrid substrates to communicate with one another and the outside world.

Many of the fabrication processes for integrated circuits are similar or conceptually related to those used in the manufacture of printed wiring boards. However, because of the extremely fine device features, fabrication must be carried out in clean rooms having strictly controlled environments. Particulate and chemical contamination are minimized, and temperature, humidity, and even vibration are carefully controlled.

Resists used to define circuit patterns are radiation-sensitive and may be either positive- or negative-working. As a result of the fine lines, there has been movement away from optical lithography and into the mid- or deep-uv regions. Developmental work has also been focused on electron beam, x-ray, and ion-beam exposure devices and resists (9, 10).

Polyimides, both photodefinable and nonphotodefinable, are coming into increased use. Applications include planarizing interlayer dielectrics on integrated circuits and for interconnects, passivation layers, thermal and mechanical stress buffers in packaging, alpha particle barriers on memory devices, and ion implantation (qv) and dry etching masks.

A number of polymeric coatings, primarily polyimides, epoxies, and silicones, are used as adhesives and in other aspects of packaging, as well as for final encapsulation and protection of the integrated circuit.

5. Coating Application Methods

There are a wide variety of coating applications processes in use. The majority of these techniques are similar to those used in other coatings industries, and the same basic operating principles apply to these uses as to coating a photographic film or a coil of metal for a refrigerator.

There are, however, several differentiating characteristics of electronic coating processes as compared to general use. Typically, more discrete objects are coated as opposed to continuous webs, although wire coating, optical fiber, magnetic tape, metallized polyester, and optical fibers are continuous webs coated at very high volumes. A much wider range of coating weights and coating coverage is needed. The coatings and line width in an integrated circuit are very thin and low in coating weight. The protective coatings are relatively heavy, thus a wider variety of coating methods are in ongoing use in the electronics manufacturing industry than in most other industries. Spray, dip, brush, roller, fluidized-bed, spin, electrocoat, and vacuum deposition are all in routine use. Table 3 summarizes these methods for electronics coating applications.

In addition, cleanliness is far more important at all stages of the electronics coating process than generally necessary for nonelectronics coatings. There is also a wider range of coating compositions used, and because most of the processes are fluid coating application processes, many diverse solvents are in use. This contrasts with the paper and photographic industries where water is almost always the exclusive solvent used. The wide use of high volatility solvents in a coating application is of concern, however, because of the increasing environmental needs.

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