ROBUST MATERIALS AND PROCESSES: KEY TO RELIABILITY

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Achieving high reliability and yield in the design and manufacture of telecommunications products requires detailed assessment of the materials, product design, manufacturing processes, and use environment. The key prerequisites for eliminating the root causes of failure are both scientific understanding and engineering evaluations that use statistical experimental methods and accelerated-life tests to uncover potential failure mechanisms. This paper illustrates these principles through several examples that pertain to product design, materials selection, performance evaluation, and manufacturing processes. The examples were selected from our work with design, process, field, and system engineers and reliability practitioners throughout AT&T.

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Introduction

A requirement for market success with electronic equipment and devices is to achieve best-in-class reliability in materials, design, and processing. Figure 1 depicts a time-tested and proven strategy for delivering quality products that satisfy customers. (Panel 1 defines acronyms and terms used in this paper.)

The process begins at the earliest stages of product definition with a multidisciplinary assessment of all *materials*, *design*, and *manufacturing* technologies that will bear on the product's performance. The evaluation continues through the various stages of development and manufacture. There, one uses accelerated-life-test methods and statistically designed experiments to verify that the *performance* objectives were achieved.

If testing uncovers design, materials, or manufacturing deficiencies, then the root causes must be found and eliminated, preferably during prototype development. Neglecting this reliability assurance process often leads to costly development projects that do not succeed in the marketplace, or to failure analysis and repairs of field returns that cut our profit margins and dismay and lose customers.

Panel 1. Acronyms and Terms

Ag	silver
Ag-Cr	silver-chromium
Au	gold
CAD	computer-aided design
Cr	chromium
dc	direct current
Cl^-	negative chlorine ions
CMOS	complementary metal-oxide semiconductor
CVD	chemical-vapor deposition
H_2O	water
HIC	hybrid integrated circuit
IC	integrated circuit
ISDN	Integrated Services Digital Network
IR	infrared
M^+	positive metal ions
Na^+	positive sodium ions
NaCl	sodium chloride
PSG	phosphosilicate glass
RH	relative humidity
Si	silicon
UV	ultraviolet

For high-yield manufacturing of products that meet reliability expectations and are competitively priced, we must have the following:

- In-depth knowledge and an experience base in materials properties, performance, and interactions with the surrounding world, whether it be the ambient environment or other materials.
- Scientific understanding of the behavior of electrons or photons in devices.
- Commitment to robust designs. In the design phase, we must also consider the processing technology and its limitations. This will enable us to produce designs that have the desired properties in spite of process variability.
- An accelerated-life-test strategy that is aimed at all functional levels of a product including devices, components, interconnections, circuit boards, modules,

and the entire system.
- Commitment to robust manufacturing processes. Here, quality products are obtained even though incoming materials and process conditions may vary (in an anticipated way). To accomplish this, we establish the critical processing parameters and the relationships between materials variations and process variations through statistical evaluations. Then, these parameters and variations can be readily monitored for conformance.

Achieving reliability objectives in a real-world setting is a substantial challenge. Design engineers expect that the manufacturing processes will tolerate variations in structural parameters and materials, while the process engineer's job is made easier by designs and materials that tolerate process variations. A disciplined effort to eliminate structural, materials, and process variations that contribute to yield loss and prevent degradation processes in the field ensures a higher quality product. It also results in lower cost initially and over the life of the product. That lesson has been well learned. Quality is achieved and pays for itself if we ensure that a team of designers, materials experts, process experts, and statisticians is involved in all phases of the product life cycle, including design, manufacture, and operation.

In this paper, we use examples to illustrate experience-based strategies for achieving high yield and preventing field failures through proper attention to the reliability of materials, designs, and manufacturing. We selected these examples from our work with design, process, field, and system engineers and reliability practitioners throughout AT&T. (Many of the examples are contained in the *Designer's Companion*, a company-proprietary design and processing guide This guide emphasizes ways to avoid field problems t..rough proper design and informed selection and processing of materials.)

Some of the examples illustrate the importance of attention to details. Others show the value of examining the entire process of design, production, and product delivery. The examples also show that attending only to individual parts of the process can lead to disappointing

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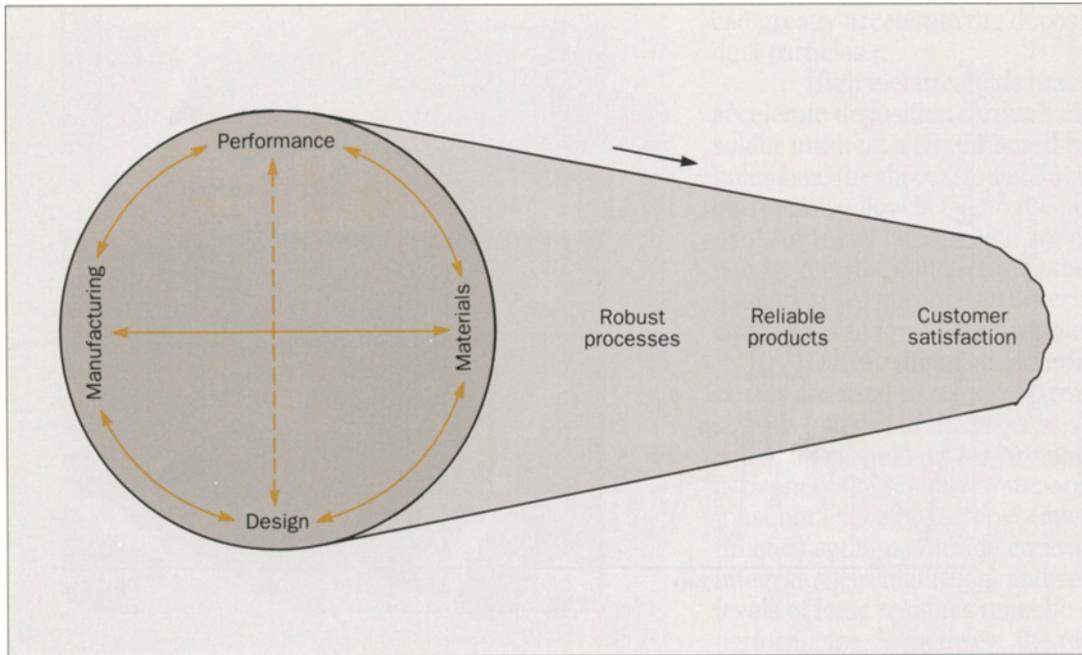
Figure 1. Strategy for delivering quality electronic products. The process entails assessing the design, materials, and manufacturing technologies that influence the product's performance and then eliminating deficiencies. Robustness at all stages translates into reliable products and satisfied customers.

results in the field.

In keeping with the critical elements of delivering reliable products to our customers, we have organized the examples into sections on the design process, materials selection, performance evaluation, and manufacturing. We took this approach, realizing that all these areas must be intimately connected. These interconnections will be evident in several of the examples.

Environmental Constraints

Before we turn to the main thrust of this paper, let us review the environmental constraints that cause corrosion and short circuits in electrical devices. Performance evaluation requires that we understand the environmental factors that affect product reliability. Here, we describe the constituents of the environment that should be considered when planning environmental tests.

Water-soluble ionic contaminants are ubiquitous components of the environment. These contaminants could be: sea-salt particles or particles derived from fossil-fuel combustion or the incineration of municipal waste, commercial and residential fertilizers, soil dust, and salt used to melt ice and snow on roads.[1,2] The indoor concentrations of these substances can range from 10 to 80 percent of the outdoor concentrations, usually with office environments at the low end of the range and factories at the high end.

Particles in the environment exist in two distinct size regimes:[1,2]

- *Coarse particles* [i.e., > 2-μm (micrometers) diameter] consist largely of natural materials, especially in the outdoor environment. In the manufacturing environment, a variable fraction of these particles may be process related.
- *Fine particles* (i.e., < 2-μm diameter) typically result from fossil-fuel combustion, but they may also represent a process-related component in manufacturing environments.

Figure 2. Concentrations of contaminants at a typical IC manufacturing site. The indoor concentrations of sulfate in fine particles are typically 40 to 75 percent of the outdoor concentrations and track those levels.
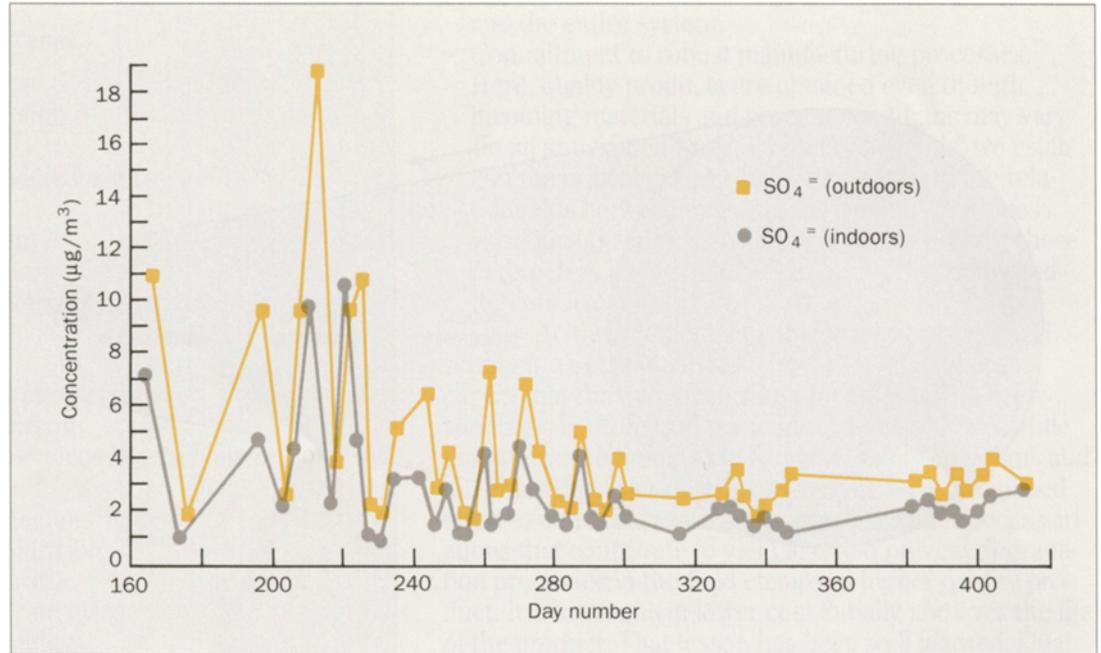
Because natural particles contain smaller concentrations of water-soluble ionic substances, they tend to be less corrosive than manmade particles. Air-filtration systems in office buildings and manufacturing environments are typically 30- to 85-percent efficient in removing coarse particles from the incoming air, but are less effective in removing fine particles.

Sulfate, usually as ammonium acid sulfate, is the most abundant substance in fine particles indoors and outdoors. Figure 2 shows the indoor and outdoor concentrations of sulfate in fine particles at a typical manufacturing location. Indoor concentrations of sulfate are typically 40 to 75 percent of the outdoor concentrations and track the outdoor levels.

Ionic contaminants are also present in the processing chemicals, which include electroplating salts, gases or liquids used for wet or dry etches, solder fluxes, acids and bases, and some cleaning solutions. Obviously,

these processing sources cause contamination by direct contact. But they can also raise the airborne concentrations of specific ionic compounds to levels several times higher than outdoor concentrations. If so, these ionic compounds may then be transferred by air to sensitive electronic components in other parts of the environment.

In the presence of atmospheric humidity, the ionic contaminants acquire moisture and thus form thin films of electrically conducting solutions. The result may be enough leakage current to cause crosstalk or soft errors. As we show in Figure 3, the leakage currents can also cause disintegration of conductor lines. Where high electric fields are present, component-damaging electrical arcs can also occur.

Ionic contaminants may be deposited on sensitive surfaces during manufacture before protective coatings are applied. These contaminants, combined with exposure to atmospheric moisture, allow leakage cur-
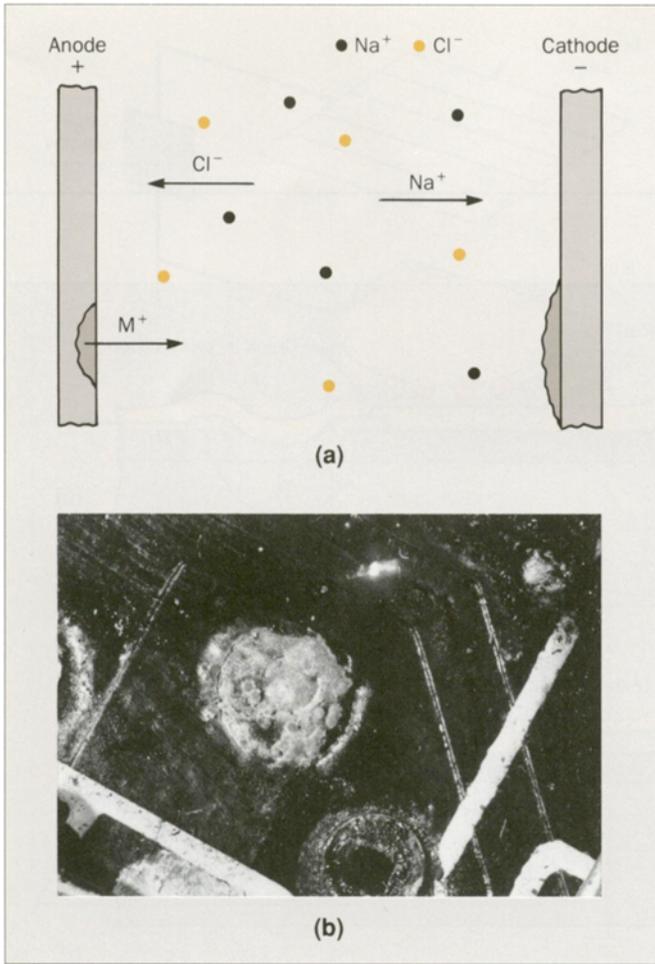
Figure 3. The electrochemical processes associated with ionic contamination on circuit boards, HICs, and devices. (a) In the presence of atmospheric moisture, contaminant residues (NaCl) form positive (Na$^+$) and negative (Cl$^-$) ions. As a result of the electrical potential between metal lines, the ions migrate to electrodes of opposite polarity. At sufficiently positive potentials, the anode corrodes. The anode metal dissolves, and positive metal ions (M$^+$) migrate toward the cathode. (b) This photograph shows an extreme example of such corrosion.

rents to flow under the coating. Ionic contamination deposited in the field allows leakage currents to flow over the top surface of the cover coat (i.e., solder mask) between the exposed bond pads or leads.

The increasing use of forced-air cooling to carry away the heat generated by high-power-density circuits can greatly accelerate the deposition of atmospheric dust particles.

High electric fields have also been found to accelerate deposition through electrostatic effects. If the solder mask on a circuit board has defects such as pinholes (see the discussion about solder masks), a leakage current may flow between the normally covered components or metal lines, which are now under a defect, and a nearby metallic conductor. Sometimes, a component-damaging arc may occur. Severe arcing can pyrolyze circuit boards to form conducting carbon bridges.

During the manufacturing phase, cleaning processes are used to remove harmful ionic contaminants at sensitive stages of the process. A commonly used specification on cleanliness for circuit boards is: After the board is cleaned, the residual water-soluble ionic contamination must not exceed 1 μg/cm^2 (micrograms per square centimeter) sodium chloride equivalent. For many hybrid integrated circuits (HICs) and semiconductor devices, the levels of ionic residues must be even lower for reliable performance. Sometimes, the required level of cleanliness is below the sensitivity limits of most surface-analysis techniques. (See the discussion of surface-ion effects on high-voltage devices.)

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To prevent leakage currents and corrosion in field environments, it is essential that:
- Solder masks are defect free. This can be evaluated by appropriate dust-exposure tests.
- Specifications for bond-pad and line spacings are strictly followed.
- The environment is maintained within design specifications.

Design Process

As mentioned earlier, the design must consider the process technology and its limitations. For example, a device's design can include safeguards that lessen or eliminate the effects of surface-ion contamination. Testing can both screen new designs and monitor process quality. Also, the design can allow for the effects of

Figure 4. Surface-ion effects in high-voltage devices. (a) Trace moisture on the outer insulating surface enables ionic charge to move in an electric field. The electric field of this charge results in high leakage currents or premature electric breakdown in the silicon below. (b) Metallic elements called field plates set the surface potential of a region to a safe level.
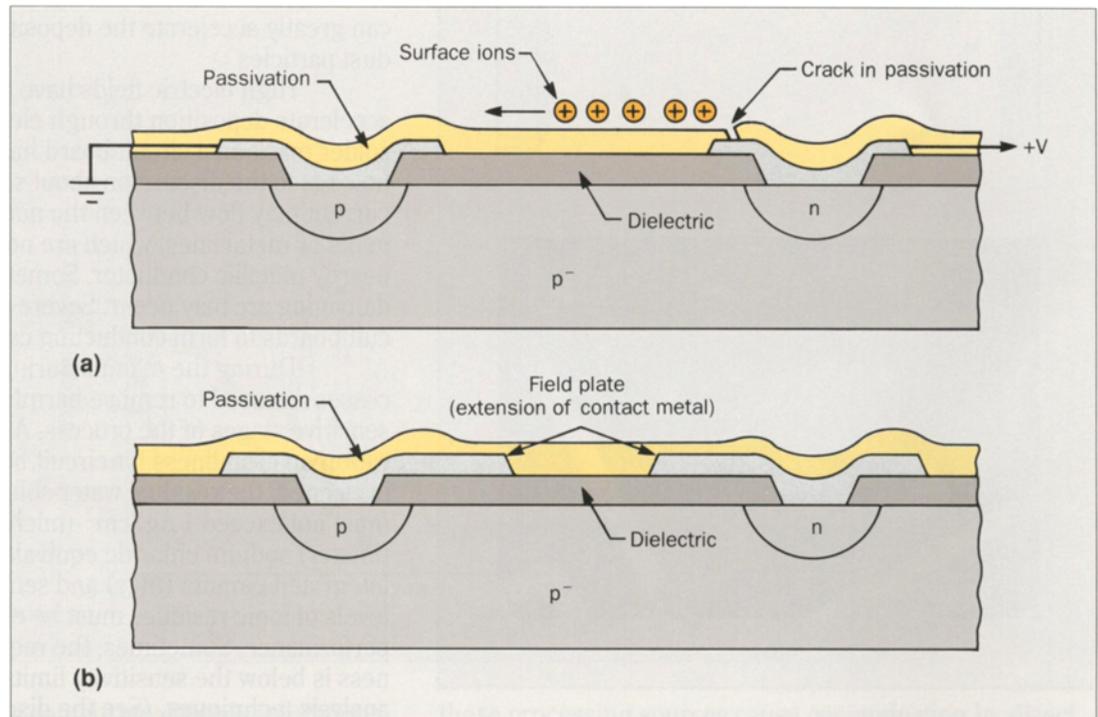

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subsequent processing, such as the effect of reheating on solder interconnections or of environmental corrosives on electroplated surfaces.

Surface-ion Effects. In high-voltage devices, surface-ion effects are among the earliest documented failure mechanisms of semiconductor devices.[3] As Figure 4 shows, the presence of trace moisture, contamination, and an electric field on the outer insulating surface of a device causes movement of the ionic charge on that surface. (See the earlier discussion of environmental constraints.) This charge motion may cause a localized, net surface charge of either polarity. The presence of the surface charge induces a vertical electric field in the device insulators and, in particular, at the semiconductor surface. This electric field can result in surface inversion (a field-induced change in the sign of the majority carriers in the semiconductor), or in premature electrical breakdown in the semiconductor. As few as 10^{10} surface ions/cm^2 (ions per square centimeter) are enough to alter device performance. (This is less than 1 ion per 100,000 surface atoms.)

Design safeguards. The traditional design safeguards against surface-ion effects include the use of field plates, highly doped guard bands (i.e., diffusions), and thick insulators. *Field plates* are metallic elements that set the surface potential of a certain region at a safe level (Figure 4b). *Guard bands* are diffusions of a high enough doping level that the bands cannot be inverted at any potential normally applied to the device. *Thick insulators* provide an advantage because the surface ions are more distant from the semiconductor and, thus, have a smaller effect on it.
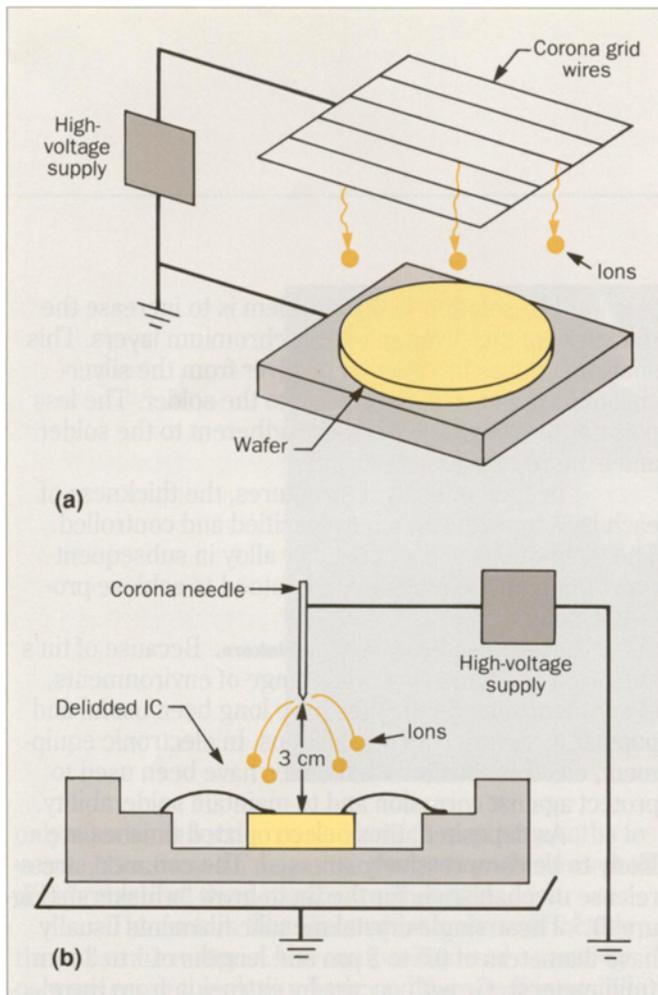
Figure 5. A dc gas discharge (corona discharge) at atmospheric pressure can be used to evaluate device susceptibility to surface-ion effects. The gas discharge deposits ions (a) on a device wafer or (b) on a single device.

All these safeguards can be incorporated into IC (integrated circuit) designs, using various computer-aided design techniques that determine the effect of circuit element potentials on the electric field at the silicon surface. In these methods, specific potentials are assigned to metal and semiconductor regions. However, insulator surfaces are usually treated as electrically neutral (i.e., they have no surface charge).

If we do not take surface-ion effects into account, the designs may be susceptible to surface-ion failure. Thus, it is not surprising that some high-voltage devices

or ICs have shown surface-ion effects (e.g., high leakage current or reduced breakdown voltage). Such weaknesses are normally exhibited after several hours or days of bias at elevated temperature, a test method known as *burn-in*.

Burn-in testing. Burn-in of some parts has been used as a screening process to remove from the population those parts that are susceptible to surface-ion effects. If the burn-in results are unacceptable for all lots, usually the product is redesigned. If acceptable results are obtained for most lots, then burn-in can be used as a lot-quality criterion and to remove susceptible devices from good lots.

Slight variations in the manufacturing process that reduce insulator thickness or alter semiconductor resistivity can make a particular design more susceptible to surface-ion effects.

Corona discharge testing. Burn-in testing is a lengthy and costly way to verify designs and monitor process quality. However, another method is available that has been used successfully to evaluate device susceptibility to surface-ion effects.

This technique uses an atmospheric-pressure dc (direct current) gas discharge (i.e., corona discharge) that generates ions and provides the electrical field to move them to the sample.[4,5] (See Figure 5.) By this means, ions are deliberately placed on the device in a controlled way to mimic the effect of surface-ionic net charge formed by surface-ion motion. The charge is deposited in tens of seconds and provides rapid evaluation of the effect of surface ions on the device.

This method has been used successfully to evaluate design alternatives, prove-in new designs, and analyze failures. It has pointed the way to improvements in field-plate design, dielectric properties, and insulator quality.

Soldered interconnections. Component metalization provides electrical contact to the semiconductor material in a device, and a stable means for connecting the signal or power to the external circuit. High-power devices often use solder as an interconnection between the semiconductor and the package leads. This requires

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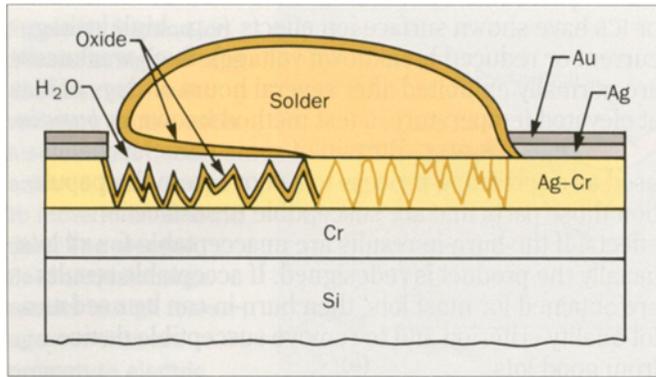
Figure 6. Effect of processing on the contacts of a hermetic diode. Metalization consists of layers of Cr, Ag-Cr, Ag, and Au. During the soldering process, the Ag and Au dissolve into the solder, leaving behind a porous layer of Cr.

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a metal contact that is solderable and compatible with the semiconductor material. However, the effect of soldering temperatures on such contacts must be carefully evaluated, because elevated temperature can degrade the integrity of the contacts and produce high resistance.

A recent problem discovered during qualification testing of a hermetic diode is a good example of the effect of processing on device contacts.

It was observed that the failure rate for these diodes increased with either temperature or current. The failure signature was high resistance at the interface between the semiconductor metalization and the soldered contact. As Figure 6 shows, the metalization consists of layers of chromium (Cr), silver-chromium (Ag-Cr), silver (Ag), and gold (Au).

During the next soldering process, the silver and gold totally dissolve into the solder, leaving behind a porous layer of chromium to which the solder bonds poorly or not at all. Because residual water in the package penetrates the chromium layer, oxidation of the chromium accelerates, enhanced by the applied electric field. Chromium oxidation increases the resistance and, eventually, causes an open circuit.

The solution to this problem is to increase the thickness of the silver and silver-chromium layers. This sharply reduces the fraction of silver from the silver-chromium layer that dissolves into the solder. The less porous chromium layer is more adherent to the solder and is more oxidation resistant.

In such multilayer structures, the thickness of each layer must be carefully specified and controlled. The interactions of each metal or alloy in subsequent processing or use must be understood to achieve product quality.

Shorts Caused by Metal Whiskers. Because of tin's corrosion resistance in a wide range of environments, electrodeposited tin finishes have long been useful and popular for a variety of applications. In electronic equipment, electrodeposited tin finishes have been used to protect against corrosion and to maintain solderability.

As deposited, these electroplated finishes are likely to be compressively stressed. The common stress-release mechanism is for the tin to grow "whiskers" (Figure 7).[6] These single-crystal metallic filaments usually have diameters of 0.5 to 5 μm and lengths of 1 to 2 mm (millimeters). Growth occurs by extrusion from the electrodeposited tin. The whiskers can be straight or kinked and have varied orientations with respect to the substrate. They can carry currents as large as 25 milliamperes and, therefore, can sustain potential drops up to a few tenths of a volt per millimeter before they burn out. Zinc and cadmium, which are also used for corrosion protection, exhibit the same whisker-growth phenomenon.

In electronic equipment, the growth of whiskers from electrodeposited tin usually causes failures in low-voltage, low-power circuits because electrical shorts are formed between closely spaced conductors. In high-voltage, high-current circuits, the whiskers are less likely to cause problems because they are quickly evaporated.

It usually is difficult to identify tin whiskers as the cause of the failure because the shorts are often intermittent and the whisker size is too small for unaided visual detection. In addition, whiskers generally grow
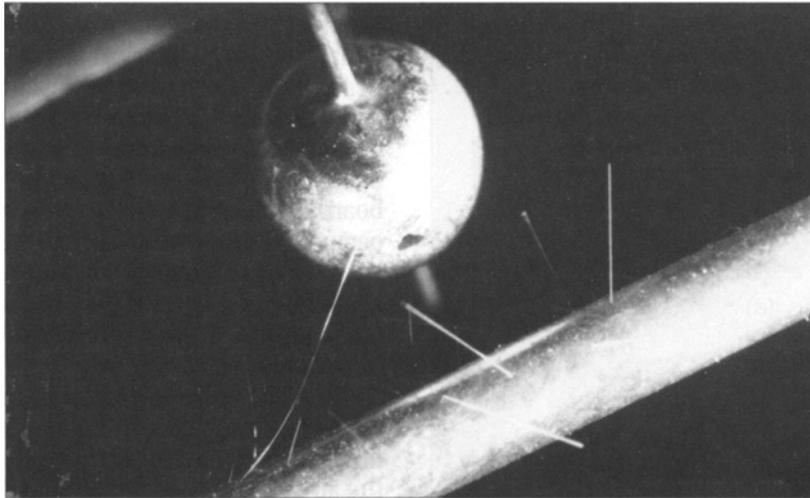
Figure 7. A common stress-release mechanism is for tin "whiskers" to grow spontaneously from an electroplated tin surface. Whiskers can cause leakage or short-circuit failures when gaps between conductors are bridged.

only after an induction period, which may be months to years. Also, most tin deposits never grow whiskers at all during the time the deposits are observed.

The factors that affect whisker growth include the substrate material, the composition and operating parameters of the plating bath, and the conditions under which the deposits are used. Many ways have been found to accelerate the growth of tin whiskers. But to date, no procedures have been established to assure that whiskers are absent from as-deposited electroplated tin under conditions that are practical for design and manufacture.

The addition of other metals, such as lead, reduces the occurrences of whiskers. Melting the electrodeposited tin or using a solder dip can relieve the built-in stresses and prevent whisker growth, if no strain is created or applied later. Tin coatings formed by hot-melt dipping are not prone to whisker formation because these coatings have much lower compressive stresses.

Materials Selection

When the use of new materials or designs is being considered or new processes are being developed, it is essential that materials and statistics experts be consulted. The knowledge required to develop or select reliable materials for use in robust processes should be defined early in the design process. These consultations will improve efficiency and quality, and provide confidence that past mistakes will not be repeated and foreseeable ones will be avoided.

If materials are to be used reliably in integrated circuits, discrete components, circuit packs, complete systems, and the manufacturing or assembly processes, then pertinent tests must be done to verify conformance to performance criteria. Product designs should adequately account for the natural changes in materials properties that result from processing and from physical and chemical aging of the materials.

We also need to consider environmental factors such as temperature, humidity, light, atmospheric pollutants, vibrations, and mechanical stresses. Appropriate tests should be devised to evaluate the durability of the materials and materials combinations for the full range of use environments. (See the earlier discussion of environmental constraints.)

Some processes produce components that already have high levels of stress imparted to the materials. We must carefully evaluate such considerations

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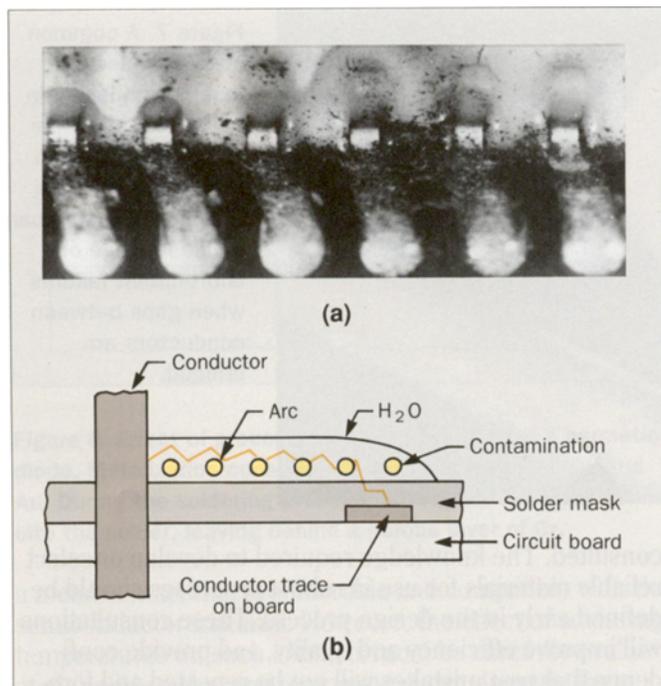
Figure 8. Airborne dust in a forced-air cooled system may accumulate on circuit-board components and leads. (a) This photograph shows the contaminant bridging between pins. (b) In high-humidity environments, water saturation can occur on a dust-contaminated board. Because of the conducting film of water, all the high voltage appears across the solder mask and causes an arc.

when specifying the manufacturing process.

The creative use of in-situ process monitors and feedback controls based on detailed statistical evaluations is beneficial for controlling and optimizing material performance and should be exploited.

Solder Masks on Circuit Boards. The proper selection of solder masks for circuit boards illustrates the need for careful assessment of the interactions between electronic design, circuit-board processing, and the use environment. The solder mask prevents the application of solder where it is not wanted, and may have an additional role as an electrical insulator.

Certain system applications require on-board voltages that are well above 250V (volts), and the complex, dense nature of modern telecommunications equipment demands that the conductors be closely spaced on the board. Under certain conditions, destructive arcs can occur between conductors. These conditions involve both ionic contamination of the circuit board and unusually high humidity that may occur in the field.

Airborne dust, particularly in systems cooled by forced air, may accumulate on circuit-board components and leads (Figure 8a). At locations of high potential gradient, dust deposition is enhanced by the large electric fields that act on the normally charged dust particles in the air stream. As mentioned earlier, the dust contains various ionic compounds that can become saturated with water. A saturation humidity of 85 percent is common for dusts accumulated under normal field conditions (e.g., an air-conditioned building with filtration). But exposure to relative humidity as low as 60 percent may be enough to cause electrical leakage and arcing.

If a dust-contaminated board is exposed to enough humidity that water saturation takes place, then an arc can occur (see Figure 8b). The conducting film of water causes all the high voltage to appear across the solder mask. When the applied voltage exceeds the breakdown capability of the solder mask, an arc will occur between the two conductors. The resulting current spike may damage low-voltage circuits, such as logic devices, that are connected to one of the conductors.

We can use various strategies to prevent such incidents, including:

- Paying careful attention to lead spacing and voltage
- Using suitable insulating coatings for exposed leads
- Using good filtration in forced-air cooled systems
- Changing building practices to minimize the occurrences of high humidity and the accumulation of harmful contaminants
- Executing environmental-stress tests during product development.

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The evaluation of solder-mask materials is an example of one such strategy.

Initial tests of the breakdown voltage of various solder-mask materials showed large differences among materials. One material had extremely low and variable breakdown voltage, and analysis showed that the cause was pinholes inherent in the process. Other materials had breakdown voltages that were 100 times higher. In particular, the tests showed that a recently developed low-cost material was fully adequate.

After candidate materials with high dielectric strength were selected, a synthetic dust formulation was applied to them for environmental tests. The synthetic dust mimics the harmful properties of typical worst-case natural dusts and has also been used for evaluating circuit boards for environmental robustness.

High-Reliability Connector Materials. Our next example concerns the selection of high-reliability, separable connector materials for the 1990s and materials to be avoided. (A *separable connection* is not permanent and can be disconnected when necessary.) Traditionally, gold has been the material of choice for the contact surfaces of separable connectors in high-reliability applications. Because of gold's high cost, research has focused on finding ways to reduce or eliminate its use, yet still maintain low and stable values of contact resistance.

In recent years, palladium and palladium-nickel contact surfaces have been used successfully in several applications.[7] Also, a new nickel-phosphorus contact surface with a high degree of microscopic roughness has been found to perform well in accelerated-life tests, especially when coated with a very thin layer of gold.[8] We expect to see the palladium-nickel and nickel-phosphorus/gold finishes used increasingly in the 1990s as lower cost alternatives to gold with almost comparable reliability.

Tin and solder alloys have also been examined for some applications. However, these alloys are susceptible to wear-enhanced corrosion (i.e., fretting corrosion) caused by micromotion between contacting surfaces.[9] When tin or solder are paired with each other or with
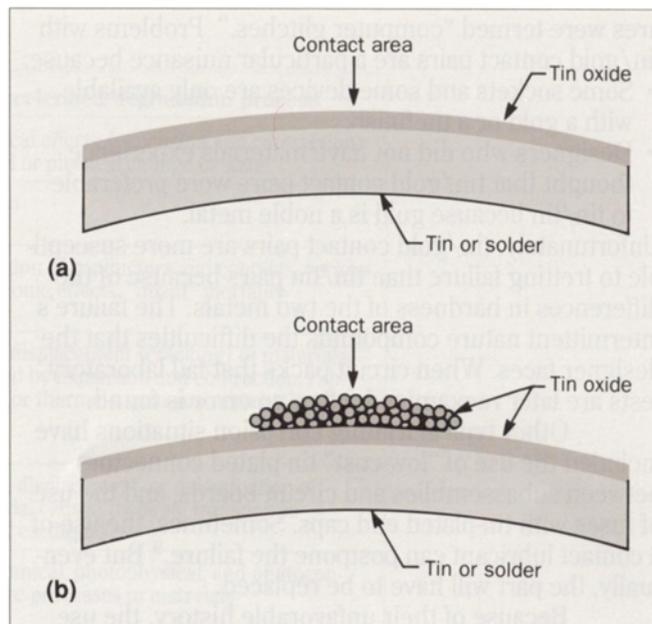
Figure 9. Motion from ordinary vibrations can produce enough oxide debris (fretting) to cause contact failure. (a) Cross section of a connector contact surface with an oxide layer over the tin or solder. (b) The same surface after fretting has generated tin-oxide particles that prevent intimate contact with the opposing contact surface (which is not shown).

gold, separable connectors that use tin or solder contacts exhibit intermittent high resistance or open circuits because wear products of tin oxide build up on the contact surface. As Figure 9 shows, motion induced by ordinary vibrations can produce enough oxide debris to cause contact failure.

Before 1970, few failures involved tin and solder contacts because most equipment used gold or other high-reliability, noble (i.e., nonreactive) metal contacts. In the mid-1970s, many component suppliers switched from gold to tin or solder contacts to reduce costs, and fretting failures became common. Frequently, these fail-

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ures were termed "computer glitches." Problems with tin/gold contact pairs are a particular nuisance because:
- Some sockets and some devices are only available with a gold or a tin finish.
- Designers who did not have materials experience thought that tin/gold contact pairs were preferable to tin/tin because gold is a noble metal.

Unfortunately, tin/gold contact pairs are more susceptible to fretting failure than tin/tin pairs because of the differences in hardness of the two metals. The failure's intermittent nature compounds the difficulties that the designer faces. When circuit packs that fail laboratory tests are later reexamined, often no error is found.

Other typical fretting corrosion situations have included the use of "low-cost" tin-plated connectors between subassemblies and circuit boards, and the use of fuses with tin-plated end caps. Sometimes, the use of a contact lubricant can postpone the failure.[9] But eventually, the part will have to be replaced.

Because of their unfavorable history, the use of tin (solder) in combination with tin (solder) or gold (i.e., tin/tin, tin/solder, solder/solder, tin/gold, or solder/gold) should be avoided. Gold contacts offer high reliability but at a high cost. Among the new and emerging materials that offer high reliability at reduced cost, palladium, palladium-nickel, and nickel-phosphorus/gold are good choices.

Performance Evaluation

Performance evaluation is the measurement of a product's overall quality, including reliability and robustness, and is applied both to purchased or manufactured parts and to the final product. A final-test procedure measures all the design features of the product. *Reliability* is a measure of the time that a product can be used without experiencing failure or degradation under a specified set of use conditions. Reliability testing is the application of various stresses to parts, assemblies, and the entire system so that we can predict the product's useful life.

To assess reliability, we need valid accelerated tests that substantially shorten the time to failure. Reliability evaluation applies stresses that accelerate various physical and chemical mechanisms that lead to failure. Because products (i.e., systems) consist of many different parts, the reliability of each part must be high if the total assembly is to be reliable. Although we can classify the various stresses used in reliability assessment according to the stress mechanism (Table I), there is likely to be a synergistic relationship among them.

To induce thermal stress, we apply an elevated temperature to a part or assembly. This tends to accelerate mechanisms that involve a chemical or physical change of state. For some failure mechanisms, reduced temperature is an accelerant.

To induce electrical stress, we apply a voltage or current to a part, device, or assembly. Often, excess voltage or current is used with thermal stress to accelerate the failure mechanism.

Mechanical stress is applied in many forms to a wide variety of parts to evaluate mechanical integrity while the part undergoes expansion and contraction. Mechanical wear (i.e., rubbing) is used to test finishes and load-bearing surfaces. Various forms of mechanical shock, vibration, and acceleration assess a part's mechanical integrity.

Often, thermal tests are used to assess mechanical integrity. These tests usually involve either slow cycling between two widely different temperatures or rapid changes in temperature obtained by immersing the component alternately in hot and cold liquids.

The effects of radiation (both nonionizing and ionizing) can be evaluated with accelerated tests. For example, we can assess the effects of sunlight on finishes or on the strength of polymers by applying intense UV light. But we must also know the effects of ionizing radiation from various sources. For example, materials used for IC packages often contain small amounts of impurities that emit alpha particles. To test device and package designs that reduce to harmless levels the soft-error rate

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Table I. Stresses Used in Reliability Evaluations

Stress	Typical tests	Accelerated degradation process
Thermal	Temperature cycling (high and low) High temperature	Mechanical effects (expansion and contraction) Chemical or physical change of state
Humidity	Exposure to 85-percent RH Pressure cooker	Corrosion
Electrical	Application of voltage or current at or above the rated levels, usually at elevated temperature	Degradation of conductors and contacts, various electronic effects, "infant" mortality
Mechanical	Exposure to vibrations with variable amplitude and frequency Temperature cycling Thermal shock Centrifuge (constant acceleration)	Physical displacement (cracking) of materials caused by expansion and contraction, rubbing, or thermal-expansion mismatch
Shock	Dropping, impact with flat surface Sudden acceleration	Fracture, displacement, or delamination of material caused by being transported Effects of earthquakes
Radiation	Exposure to more than 10 to 100 times the normal amount of UV, IR, or ionizing radiation	Photochemical, photophysical, and photoconductive processes in materials
Corrosive gas	Exposure to 10^{-5} to 10^{-1} percent sulfur dioxide, nitrogen oxide, hydrogen sulfide, or hydrochloric acid in air	Corrosion of metalization and electrical contacts; electrical shorts and opens
Corrosive particles	Exposure to 50 to 100 $\mu g/m^3$ of test dust using forced-air flow	Corrosion of metalization and electrical contacts; electrical shorts and opens

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generated by alpha particles, we use alpha fluxes that are enormous compared to expected levels.

Finally, we should evaluate the environment in which the product will be used and assess the robustness of the parts, assemblies, and entire system. Experience has taught us that environmental testing of the entire system is particularly important. These stress tests involve exposure under accelerated conditions (such as elevated temperatures) to higher concentrations of water vapor (high relative humidity), gaseous chemicals, and airborne particles than expected.

Key to predicting product reliability is to determine the amount of acceleration over use conditions achieved by the various stresses. This determination can be done in several ways. If data exists, we can compare the results of tests run under accelerated conditions and field results for similar parts or assemblies. Or, we can test at a series of stress levels and then use extrapolation to estimate reliability under field conditions. In some cases, the chemical, physical, and electrical details of the failure process are understood well enough that the prediction of reliability can be accurately calculated from known physical laws.

Manufacturing

Existing manufacturing processes and their control features also need to be evaluated early in the design process. Sometimes, the key to product reliability may

be in the design of the manufacturing process and its controls. For example, the existing processes may not be capable of meeting the product's requirements. If so, a process may need to be redesigned or its controls redefined, or new processes may have to be designed.

Here, one example shows how a process can be optimized, while the other discusses altering a process.

Manufacturing Process Optimization. Customer demand for new ISDN capability in the sixth generic of the 5ESS® switch requires the design and manufacture of new circuit packs with increased functionality, using smaller components arranged more densely on the boards. A new soldering technology was required for assembling these circuit packs. Specifically, the requirements include the use of:
- Topside components with surface-mounted, gull-wing leads on a 25-mil pitch, assembled using IR (infrared) reflow ovens
- Backside components assembled by wave soldering.

New circuit-pack assembly technology that uses surface-mount soldering with closely spaced pads (i.e., small pitch) presents new challenges in designing for manufacturability and in achieving a low incidence of initial solder defects and high long-term reliability. We found that existing manufacturing controls were inadequate to meet these needs. Because many possible factors could be varied and studied, we needed a statistically designed experiment to achieve this goal.

The following physical design variables are among those considered important for 25-mil pitch, surface-mount soldering:
- Shape and dimensions of the pad
- Spacing between devices
- Nominal position of the device lead on the pad
- Geometric location of the device on the board, such as near the leading or trailing edge
- Thickness of the stencil (through which the solder paste is applied) and the size and shape of its openings
- Type of solder mask applied to the board
- Surface structure of the pads.

Any of these variables can be changed at the design stage, but many are fixed once the printed-wiring boards have been built and arrive at the assembly plant.

Process variables should also be considered during design. Such variables include:
- Type of solder paste used
- Settings, such as pressure and speed, of the machine that applies the solder paste
- Reflow-oven temperature
- Frequency of cleaning the stencil.

The goal is to find a combination of design and process variables that optimizes the soldering process.

From the many possibilities, six design variables were selected. Four of the variables had four different parameter settings each, and two variables had two settings each. This choice gave us a total of 1024 possible combinations using just 6 variables (i.e., $4\times4\times4\times4\times2\times2 = 1024$).

Clearly, an experiment that used all 1024 combinations was not feasible. However, we could use the principles of statistical experimental design to reduce this number considerably, yet obtain useful information for all variables. Thus, we found a highly fractionated design that used only 16 different combinations but permitted us to estimate the main effects for each of the 6 variables.

The 16 combinations of variables were evaluated using a special test board. Process variables and certain design variables, such as solder mask and pad surface, are constant over the whole board. Different combinations of these variables were varied among different boards in a statistically designed way, so information about them could also be obtained economically.

We followed an iterative approach: Several small lots were run and the data from each lot was analyzed to help us determine what conditions should be studied in later lots. Early results led to several revisions to the original plan. For example, the sizes and shapes of the stencil openings appeared to be important. Therefore, we decided to vary these factors over a wider range of values than had been planned originally. Thus, a series of

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separate experiments was designed and run using new stencils with a greater variety of openings.

After the initial experiments, the board was redesigned using the earlier results as a guide. We now wanted to focus on optimum values. Eventually, two large lots were run. The results showed that, under the best levels identified for these variables, we can obtain solder-defect levels of less than 100 parts per million for the 25-mil pitch, surface-mount product.

Additional benefits accrue from this effort to separate the factory introduction of new technology from product introduction. All pieces must be in place early in the process so we can build the test circuit packs that the experiments require. Then, problems that might not be detected until we scale up to full production can be discovered, when they are much less expensive to fix.

In this example, we encountered several problems that altered the experimental program from what was originally planned. However, all the problems provided valuable information and suggested important new work that needed to be done.

Blisters Formed by Trapped Gases. To avoid problems associated with gases trapped in thin films, one requires a detailed understanding of the process chemistry. However, the complexity of material and process interactions makes such understanding difficult.

For gate and interconnect metalizations, CMOS ICs use silicide films (e.g., tantalum silicide, cobalt silicide, titanium silicide) over polysilicon to achieve lower resistance than is possible with polysilicon alone. These silicides are normally applied using an argon-sputtering process. A phosphosilicate glass (PSG) film is then deposited over the patterned silicide as an insulator between the silicide interconnect and the next deposited layer, usually an aluminum interconnect.

To achieve a smoother topography, we flow this PSG layer at elevated temperature. At these temperatures, tantalum silicide films can blister, which causes the PSG layer to lose adhesion. In addition, loss of adhesion sometimes occurs at the silicide-polysilicon

interface during high-temperature treatment. The high temperature causes the release of argon, which was entrapped in the film during sputtering.[10] High-energy ion implantation of dopants into the silicide films sometimes increases the gas evolution and adhesive loss. Similar gas-entrapment effects have been observed in the boron nitride films[11] used for fabricating X-ray masks.

The prevention of film bubbles and delamination requires process conditions that minimize entrapment and subsequent release of gases. Appropriate control of the argon pressure will minimize argon retention.

Summary

This paper has examined the process for achieving high reliability in materials, design, and manufacture for electronic equipment and devices. The delivery of quality products that satisfy customers requires a multidisciplinary assessment of all factors that are likely to affect manufacturing and product variation. This assessment begins at the earliest stages of product definition. It continues throughout the product delivery process using performance evaluations that verify the achievement of objectives.

Process evaluations and accelerated-life tests of the devices, components, interconnections, circuit boards, modules, and the entire system—using statistically designed experiments—are essential for producing robust products. Experience-based strategies for achieving high reliability have been illustrated through a series of examples.

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