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Metallic Electromigration Phenomena

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ABSTRACT

Metallic electromigration can be defined as the movement of metallic material, usually through or across a nonmetallic medium, under the influence of an electrical field. As such, it has assumed increasing importance in the performance and reliability of packaging systems that incorporate electrical contacts. The characteristics of the different electromigration processes will be discussed, including descriptions of related phenomena. The primary emphasis will be on electrolytically controlled processes that take place under low power and typical ambient conditions.

INTRODUCTION

Metallic electromigration has long been recognized as a significant potential failure mode in many electrical and electronic systems [1], [2]. Unfortunately, the study and understanding of this field has been complicated by the large array of interrelated phenomena, as well as by a number of effects that have only a superficial similarity to electromigration. One of the two main purposes of this paper then is to help clear up some of the prevailing confusion and misunderstanding by categorizing these phenomena and lending some degree of order to this important, but complex field. The second purpose is to outline the role of the various factors that determine the occurrence and extent of electromigration.

DEFINITIONS

As a first step, we would include in the term, *Metallic Electromigration,* all migration phenomena that involve the transport of a *metal-usually* through or across a nonmetallic medium-under the influence of an *applied electrical* ***field.***

Under this proposed definition, the material that migrates is considered to be in the metallic state, in that both its source (e.g., a plating, a clad stripe, a metal-loaded ink, or a base-metal substrate) and its *final form,* after migration, would function as metallic conductors. The migration of metallic elements in the form of corrosion-product compounds would not come under this definition, since such compounds do not exhibit full metallic conduction. Of greater importance, however, is the fact that this latter type of migration, as exemplified by copper tarnish creepage *[39],* [40], does not require an applied electrical field. Nevertheless, tarnish creepage effects are often confused with electromigration because both phenomena can exhibit dendritic morphologies-as shown by comparing the copper sulfide creepage dendrites in Fig. 1 and the dendritic copper sulfide crystals of Fig. 2 with the (metallic) silver migration dendrites of Figs. 3 and 4.

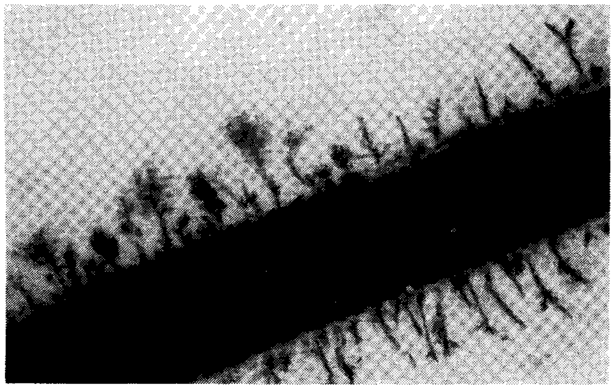

Fig. 1. Copper sulfide dendritic filaments growing from OS-mm (0.020-in) wide copper conductor between polyester sheets, without an applied voltage, after humid H2S exposure. 24 x .

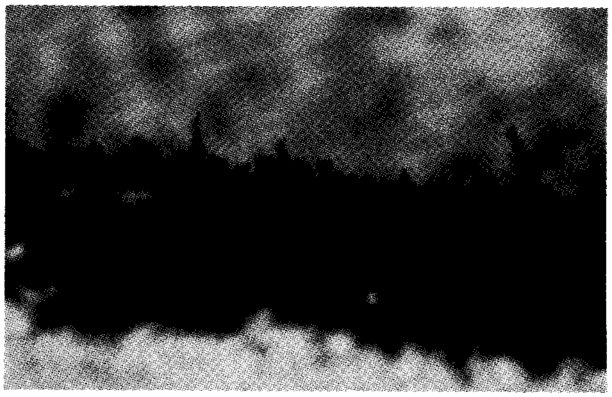

Fig. 2. Silhouette of copper sulfide dendritic crystals after copper exposure to 23 days in 50 ppb sulfur vapor at 87-percent RH with no applied voltage. 40 x .

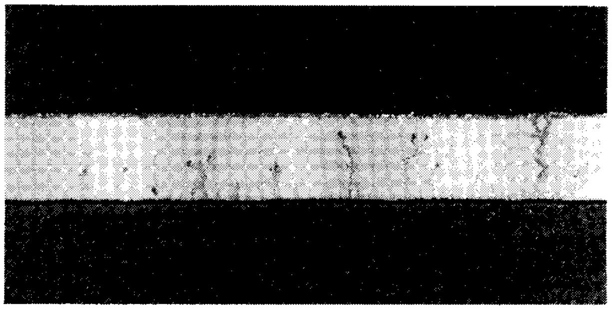

Fig. 3. Various stages, including one dendritic bridge of silver electromigration across 0.38-mm (0.015in) spacing on epoxy-glass PC board.

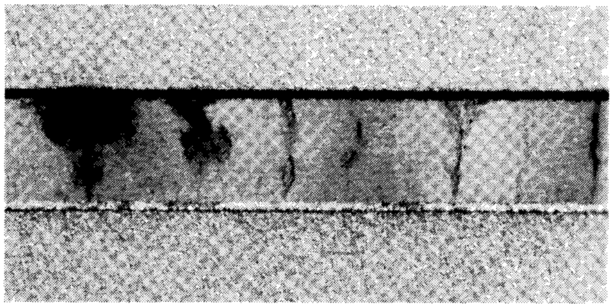

Fig. 4. Severe silver electromigration effects across 0.38-mm (0.015in) epoxy-glass spacing.

In the same way, the requirement of an applied electrical field differentiates electromigration from most tin whiskering effects, since the latter have been shown to be caused by mechanical stresses in the plating [53]. This is so even though both phenomena can produce failures by shorting across closely spaced metallic conductors.

ELECTROLYTIC ELECTROMIGRATION

As outlined in Table I, this type of electromigration is an *electrochemical* phenomenon that takes place primarily under normal ambient conditions, i.e., when the local temperatures and current densities are low enough to allow water to be present on the surface (contrast with the section on Solid-State Electromigration).

TABLE I
METALLIC ELECTROMIGRATION

A. Electrolytic (Ionic)
Ambient temperatures (< 100°C) Low current densities (< 1 mA/cm^2) 1) Normal conditions-no visible moisture ("Humid" or Silver Electromigration). 2) Visible moisture across conductors ("Wet" Electromigration).
6. Solid State (Electron Momentum Transfer)
High temperatures (> 150°C) High current densities (>10^4 A/cm^2)

The actual mechanism of electrolytic electromigration is water-dependent, and tends to occur whenever the insulator separating the conductors (as on PC boards, flexible circuitry, chip carriers, or IC ceramics) has acquired sufficient moisture to allow electrolytic (ionic) conduction when an electrical potential is applied.

Electrolytic electromigration is primarily a direct-current (dc) phenomenon, although the direction of the migration can be reversed by reversing the polarity of the applied field (e.g., [52]). However, when a true ac voltage (60 Hz) was applied [3], "far less" migration was produced, and no electromigration could be detected at higher frequencies.

Although electromigration phenomena can occur with many metals, only silver-and, to a very limited extent, copper [3], [12]-[14], and perhaps tin [28], [45], [46]-normally undergoes these effects under noncondensing, but humid conditions [l]-[6], [27]. The other potentially susceptible metals generally require a visible layer of water (i.e., bulk condensation) for electromigration to occur at ambient temperatures [15]-[25]. From an "operating-conditions" viewpoint, therefore, these effects can be divided into two rough subcategories, according to whether the surface is covered by a thin invisible film of moisture ("Humid" Electromigration) or by a visible layer of condensed water ("Wet" Electromigration) (see Table I).

The essentially unique ability of silver to undergo slow electromigration at only moderate elevated temperatures in the absence of condensation has been commented upon in the literature [2], [24], [28], [47], and various explanations have been proposed. This is also the reason why many workers have used the term "silver electromigration" to describe the humid migration phenomenon.

A third category, that of "dry electromigration" of silver through glass, has been reported [48], [49]. Although no moisture is present and higher temperatures (150-200 "C) are involved, both the dendritic appearance of the migrating silver and the magnitudes of the electrical potentials, interconductor spacings, and failure times are essentially the same as those of normal silver electromigration. This would lead one to conclude that the function of the glass as a *solid electrolyte* is very similar to that of the invisible moisture films on other insulators (see below).

"HUMID" ELECTROMIGRATION

In the simplest case, metallic silver on the conductor with the more positive applied potential (anode) is oxidized to a more soluble form. The resulting positively charged ions then move under the influence of the electrical field through moisture paths on or in the insulator toward the more negative conductor (cathode), where they are reduced back to silver metal [2]-[4], [6].

If the migrating ions were deposited in a uniform manner (as in electroplating), there would be no discernible effect on the electrical properties of the circuitry, since transport of metal ions at the very low currents extant across the insulator would be too small to produce any significant changes in the contact or conductor spacings.

In practice, however, the electromigration mechanism produces two separate (though not always distinct) effects that lead to impairment of the circuit's electrical integrity. These are colloidal "staining" and filamental or dendritic bridging, both of which are shown in Fig. 4. Deposits of colloidal silver (or copper) often appear as brownish stained regions which originate at the positively polarized conductor but do not necessarily remain in contact with it (Fig. 5). They are assumed to result from reduction of the migrating ions, either by light or by chemical reducing agents on the insulator surface [2]-[5].

Fig. 5. Colloidal silver "stain-front" from positively polarized silver conductor on epoxy-glass PC board. 6.4 x .

Dendritic growth, on the other hand, results from the fact that the ions tend to deposit at localized sites on the cathode in the form of needles or spikes [35]. Once these nuclei have formed, the higher current density at their tips will greatly increase the probability of further deposition. This shows up as an accelerated growth outward from the tips in the form of thin black filaments of silver, extending from the cathode back toward the positive conductor (Fig. 6). In the course of this growth, branching usually occurs at definite crystallographic angles, resulting in a characteristic "dendritic" structure.

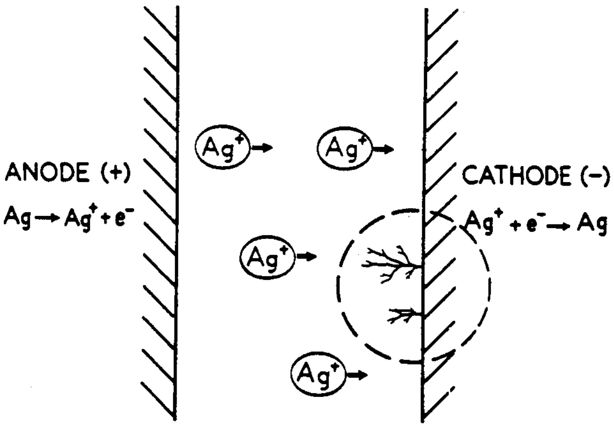

Fig. 6. Schematic diagram of early stages of dendrite growth. (From [8].)

When a filament finally bridges the gap between conductors, a sudden drop in resistance will occur. Although the magnitude of the initial resistance drop will be small (because of the small cross-sectional area of a single filament), thickening of the filaments and a rapid increase in additional bridges-as would be expected when dendrites are present-will soon lower the resistance sufficiently to produce circuit failures [1]-[4], [24], [25], [45], [47]-[51].

Bridging can also be produced by colloidal deposits from the anode, especially on contaminated surfaces [6], [7] and at higher temperatures and voltages [4]. A number of different phenomena have been reported in the literature, all of which appear to involve metallic electromigration from the anode [10]-[14], [21], [45], [46], often under conditions of comparatively high ambient temperatures (75 °C) or humidities (95 percent). In one series of papers [12]-[14], copper filaments were reported to be growing from anodic to cathodically polarized pads or plated-through holes after the glass-epoxy printed circuitry (with copper conductors) had been subjected to conditions that produced local physical separations of the epoxy resin from the glass fibers. The underlying mechanism for this effect-to which the authors of [12]-[14] gave the name "Conductive Anodic Filaments" (CAF)-was postulated as involving prior formation of moisture paths along those bare (hence water-wettable) glass fibers within the board that happened to bridge oppositely polarized conductors [13]. In other studies, we have found anodic silver in filamental form bridging 0.38-mm (15-mil) glass-epoxy spacings (Fig. 7), while higher voltage (100-300 V) work with aluminum-metallized integrated circuits produced practically instantaneous filamental bridging by the aluminum across 0.02-0.05-mm (1-2-mil) spacings on GaAs [10] substrates.

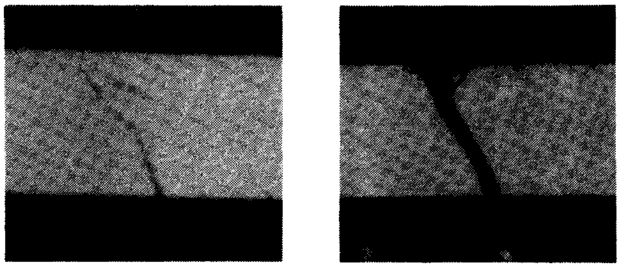

Fig. 7. Colloidal-silver anodic filaments on 0.38-mm (0.015-in) spacings of glass-epoxy PC boards. Anode is on top. 36 x .

A related silver electromigration phenomenon appears to take place electrolytically in a nonaqueous "solvent" at high (presumably dry) temperatures This is the reported migration of the metal from a silver-loaded polyimide adhesive that is used to bond diode chips to gold-plated headers. In this case [11], silver was found to migrate from the adhesive after 1000 h at 300 °C, when the diode was under a reverse bias of 10 V. Under these conditions, the gold/silver-adhesive system would be polarized positive (anodic).

Operating Conditions

The primary operating parameters that promote humid electromigration problems are as follows:

1) moisture (i.e., high relative humidity),
2) contamination on the insulator surface,
3) voltage difference between conductors,
4) narrow spacing widths,
5) elevated temperatures (at high relative humidity).

Detailed examples of how these factors affect both the speed and severity of the electromigration reactions for different insulator surfaces can be found in a number of publications [2]-[7], [9], [24], [26], [51]. The discussion given below will be primarily for the purpose of showing how these factors interact with each other, as well as in clarifying some of their less understood aspects. In discussing these points, it will be helpful to bear in mind the three basic electromigration steps that were previously described, i.e.,

a) oxidation or dissolution at the anode,
b) migration across or through the insulator,
c) reduction and deposition.

Moisture

For electromigration to occur, a comparatively low-resistance electrolytic path must exist between two conductors of opposite polarity. These paths need not necessarily be permanent. They may dry up and reappear with changing humidity, but their duration will be one of the factors determining the time to failure [4].

In the early experimental work with phenolic-paper laminates and other porous or fibrous substrates [l]-[3], the conductive solution was found to follow the pores or fibers, so that silver filaments would eventually be found within the insulator material itself. However, with nonporous substrates, such as glass-epoxy PC boards or ceramic microelectronic devices, the electrolytic path would be provided by, and generally restricted to, an adsorbed layer of moisture on the surface. Thus the presence of moisture and its effects will also be related to the nature of the insulator and to the type and quantity of surface contamination in its vicinity (factor 2), above).

Humidity and Insulator Material: It has been shown experimentally [2]-[9], [ll], [12], [18], [21], [27] that the higher the relative humidity, the faster the onset of electromigration and the greater the probability of low-resistance failures. However, for any one relative humidity, the tendency for moisture adsorption on the insulator surface will vary with the type of insulator material used and its surface condition. Insulator materials with strongly polar groups, like phenolics, nylons, alumina, or glass, have a much higher susceptibility to electromigration than “hydrophobic” materials with weak or no polar groups, like Mylar (polyester) or polyethylene [2], [3], [13], [26], since the latter materials have a much lower propensity for adsorbing moisture and retaining moisture films on their surfaces.

A particularly striking example of this effect is that of porcelain surfaces, as in porcelainized-steel circuit boards. When such boards with silver-ink circuitry were exposed to 75 °C and 90 percent relative humidity (RH), with 30-V polarization, significant electromigration was observed at the 0.38-mm (15-mil) spacings as early as the first week of the test. Within two weeks, significant bridging had occurred (Figs. 8 and 9), with a resulting drop in interconductor resistance of at least four orders of magnitude. The burnt-looking spots on the positive conductors in Figs. 8 and 9 are due to the dissolution of the white silver ink (over the black porcelain) in the initial stages of electromigration.

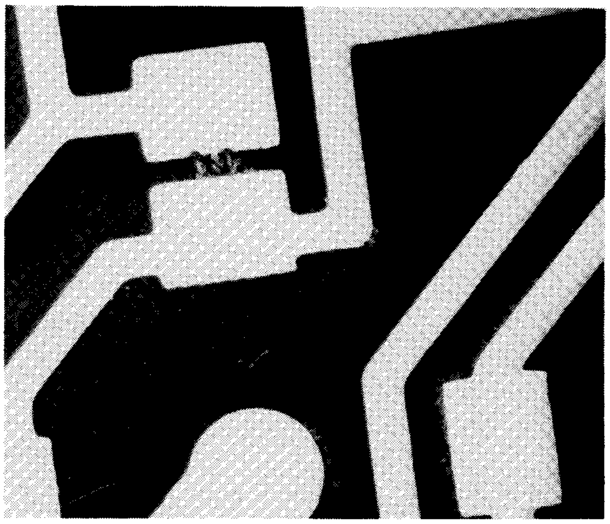

Fig. 8. Silver electromigration on porcelainized PC board. 4.8 x . Note dendritic bridging of 0.38-mm (0.015in) spacing, and orientation of dendrites on circular pad towards anodic conductor.

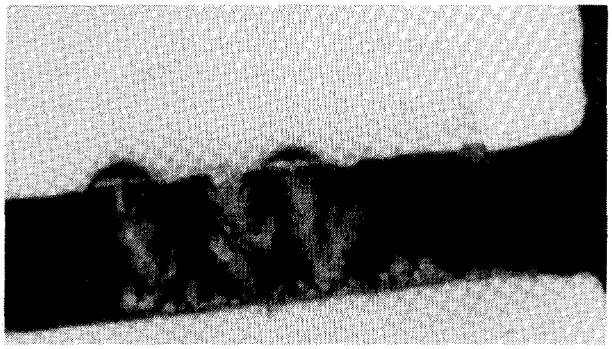

Fig. 9. Higher magnification (16 x) view of bridging across the 0.38-mm (0.015-in) spacing in Fig. 8.

The humidity effect can also be explained in terms of phase equilibria between the gaseous moisture and the moisture adsorbed on the insulator and conductor. The RH, by definition, is the fraction of the saturation vapor pressure of water that is actually present in the operating environment. This saturation pressure (i.e., 100-percent RH) is, in turn, defined as the pressure of the vapor that is in equilibrium with the bulk liquid phase at any one temperature. Thus clean and smooth hydrophobic surfaces (polyethylene or polystyrene) would not be expected to acquire more than a few molecular layers of water until 100-percent RH had been approached, whereupon condensation of bulk liquid (as droplets) would occur. On the other hand (as explained above), insulating materials with water-attracting polar groups could begin to adsorb water as invisible films at much lower RH values [38], the extent of the adsorption increasing with rising humidity. In the same way, capillary condensation could occur in scratches, pits, and other high surface-energy areas, the net effect being the lowering of the minimum ambient RH required for adsorption, even on otherwise water-repellent materials.

This capillary effect was recognized during an extensive experimental program on silver migration on conventional epoxy-laminated glass-cloth, printed circuit (PC) boards [4], [7], [8], part of which involved examining the dendritic filaments under a scanning electron microscope (SEM). During these examinations, in which we found that the dendritic growth was always limited to the surfaces of these well-laminated boards [4], we also observed that the growths tended to follow low-lying channels or pathways on the epoxy-covered surface (Fig. 10).

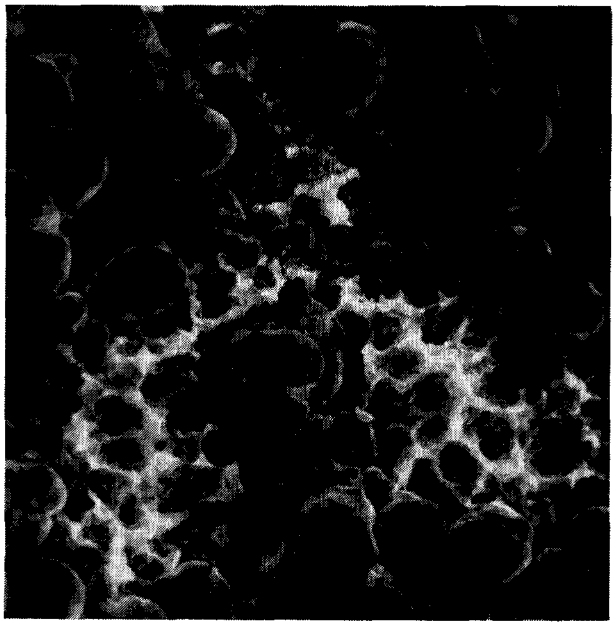

Fig. 10. SEM micrograph (800 x) of silver dendrite residue on epoxy-glass surface. (From [4].) (Note: In this figure the anode is at the bottom.)

An analogous phenomenon, involving *anodic* filaments, was observed with silver-ink conductors on Mylar polyester. After seven weeks in a 65 °C, 90-percent RH environment, with an applied voltage of 5 V, there was no significant resistance change and no sign of dendritic growth from the cathode. However, on some of the spacings, thin straight black needles were seen to be coming from the positively polarized conductors (Fig. 11).

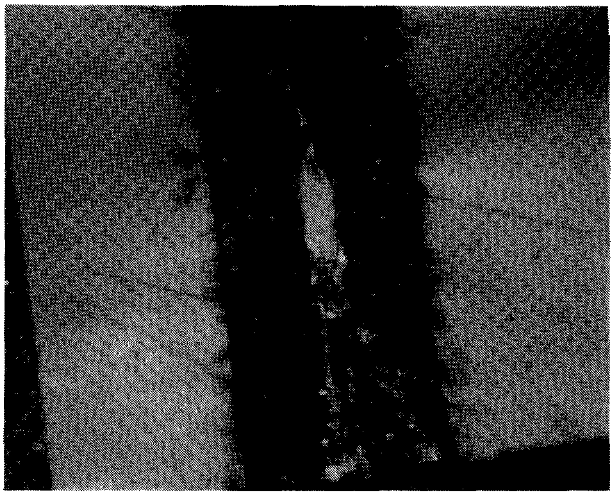

Fig. 11. Needles of colloidal silver from anodically polarized silver-ink conductors on polyester film. 15 x .

SEM microscopy and energy-dispersive spectroscopy (EDS) and X-ray mapping showed these needles to be composed of colloidal silver (Fig. 12) in well-defined scratches or craze-marks on the polyester surface.

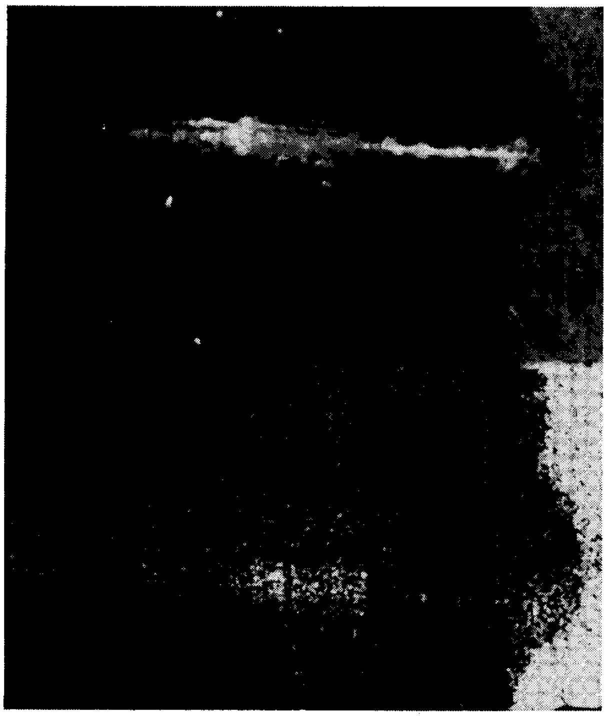

Fig. 12. 150 x SEM micrograph (top) and silver X-ray map (bottom) of silver needle, from Fig. 11.

Contamination

Many different types of contaminants and impurities may be present on the insulator and at the insulator-conductor interface. Although they can originate from a number of sources and may have varying effects on electromigration, most appear to function by encouraging moisture adsorption on the insulator surface, as well as by stabilizing the resulting surface solution and increasing its conductivity [2], [5]-[7], [12], [21].

In dealing with the diverse nature of the many potential contaminants, it is useful to divide them into two broad categories, according to their apparent origin, that is, 1) materials-based impurities, originating from the contacts, conductors, and insulator materials, and 2) extraneous contaminants from the environment surrounding the contacts or conductor-insulator system.

In making this semi-arbitrary division, one, of course, accepts the fact that there are some contaminants that do not fit into either category. One example is where the migrating silver itself originates as an impurity, as when silver-containing conductive adhesives are used to bond gold-plated surfaces in hybrid microcircuits [29], [32].

Materials-Based Impurities: Among the most common-and harmful-of these contaminants are chemical residues from the plating and etching operations, which,. fortunately, can often be minimized by proper and adequate rinsing. Ionic oxidants, such as ferric chloride etchant residues, have been found to encourage silver dissolution and a rapid buildup of colloidal silver on the insulator surface [7]. In other cases, wetting agents from the plating bath could decrease the hydrophobicity (or water repellency) of portions of the insulator surface while ionic residues would increase the conductivity of the adsorbed moisture film.

We have also found that differences in free cyanide content between two different silver-plating bath formulations can have a profound effect on the relative susceptibilities (to electromigration) of the resulting plated conductors. In this particular case [4], [7], however, it was the “no free cyanide” neutral silver formulation-which is free-rinsing and leaves essentially no residual cyanides on the finished plating [8]-that had the highest rate of electromigration. This apparent contradiction can be explained by noting that in the presence of moisture any excess free cyanide would tend to convert practically all other silver species into the very stable, negatively charged Ag(CN); complex **[36].** This would effectively inhibit dendrite growth, by preventing ionic migration to the negatively charged conductor, until the free cyanide concentration was reduced to a very small value.

The insulator material itself can also be a source of contamination. Many of these contain flameproofing agents or similar additives that can leach out to the surface. Thus with conventional glass-epoxy PC boards, the purer G-10 type was found to be less prone to electromigration than the flame-proof FR-4 variety [4].

Extraneous Contaminants: These may include airborne dusts, flux residues, gaseous pollutants **[6], [26], [28], [29],** [41], [42], fingerprint residues from improper handling, metallic particles and their corrosion products (including wear particles from conductor tabs), as well as fibers, plastic scrapings, and other materials that are introduced during connection or assembly.

Contamination can also be produced within a package or container that is otherwise protected from the outside environment. In many such cases, volatile compounds are emitted by plastics or desorbed from other inside surfaces of the package, processes that are accelerated by temperature changes. Some of the more common examples are HCl, acetic acid vapor, and ammonia or volatile amines **[29]**, **[43]**, **[44]**. Water, however, is the most common emission and desorption product observed in such systems. In certain cases, local buildups of this closed-system water resulted in the onset of "wet" electromigration phenomena **[16]**, [21], **[30]**, **[31]**. This effect may have also been involved in copper and tin-lead migration under certain solder-mask coatings, where the *external* humidity was **90** percent or less **[45]**, **[46]**.

Although the functions of extraneous contamination in supporting or inhibiting humid electromigration are similar to those discussed in the previous section, a number of additional points should be added. Many types of dust particles and almost all common corrosion products are hygroscopic; they will increase water adsorption in their vicinity. In an extreme example of this effect, DerMarderosian [21] found that placement of salt crystals in the insulator spacing produced visible water droplet condensation (leading to "wet" electromigration) at relatively low relative humidities. He also observed that the "critical humidity" (for water condensation on a particular surface) for a particular contaminant salt was approximately related to the threshold RH for dendritic growth.

In addition, many acidic pollutants, such as HCl and the sulfur and nitrogen oxides, are very soluble in both types of surface moisture films ("humid" and "wet") and will encourage electromigration **[6]**, **[26]**, **[28]**, **[29]**, **[41]**, **[42]**. One common gaseous contaminant that is often overlooked is ammonia **[29]**. Its importance to silver electromigration lies in its tendency to form stable positively charged complexes with silver ions **[36]**, thereby aiding the initial oxidation-dissolution step at the silver anode and supporting the ionic migration of silver towards the negative electrode.

Voltages and Spacings

A great many experimentalists have shown that the higher the polarizing dc voltage (or "bias"), the greater will be the rate and severity of the electromigration. In addition, an inverse relationship was almost always seen between the migration rate and the width of the interconductor spacing **[24]**, **[29]**, **[48]**, **[51]**. In a related extensive series of experiments, with redundent sets of three or more different spacings on the same board (Fig. **13)**, we found that the filaments or dendrites always began in the narrowest spacings **[4]**, and, in most cases, were never found on any of the wider spacings until bridging had first "shorted out" a narrower spacing. These and similar observations would indicate that the critical voltage variable is not the absolute value of the applied voltage, but rather the voltage *gradient* across the width of the spacing.

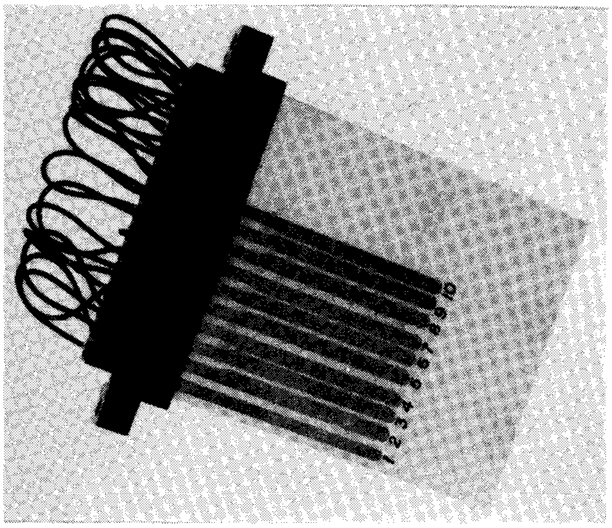

Fig. 13. Test board with redundant sets of three different conductor spacings. (From [4].)

From the viewpoint of electrochemical theory there are two fundamental ways in which the potential gradient can affect the electromigration. Both of these involve the rate at which the silver ions move from the anode to the cathode, and both assume that a film of moisture is continually present on the insulator spacing. In addition, both mechanisms are dependent on the temperature.

In the first mechanism **[34]**, which assumes a bulk solution and is therefore more applicable to "wet" electromigration, the velocity of an ion in an electrical field is directly proportional to the voltage gradient,. i.e.,

$$v_+ = u_+\vec{F}$$

where v, is the ionic mobility of a specific ion (Such as Ag') and *F* is the potential gradient, usually in units of volts per centimeter.

The second mechanism (which is superimposed on the first) involves the electrokinetic phenomenon of electro-osmosis, and is only applicable when the electrolyte is confined to scratches, narrow channels, or thin surface layers-such as would be postulated for humid electromigration. Under these conditions [33] the moisture layer will tend to flow towards the negative electrode, carrying with it the soluble silver species. (This is because the flow direction depends upon the relative dielectric constants of the water and insulator phases. In this case, since water's dielectric constant is much higher than that of plastics or ceramics, the liquid will acquire a positive charge and move towards the cathode [33].) This additional migration mode is also a function of the potential gradient, since the flow rate of the liquid II is directly proportional to it, i.e.,

$$\nu = \frac{D\vec{F}E_{\mathrm{ek}}}{4\pi\eta} \qquad (2)$$

where D is the dielectric constant of the liquid, η is its viscosity, and E_{ek} is the electrokinetic potential (which depends upon the properties of the solid surface and the solution).

From a practical point of view, however, it would be extremely difficult to evaluate the voltage gradient experienced by the migrating silver. This is because of the branching and tortuosity of the electrolytic paths as they actually exist on the insulator material. In addition, there are problems associated with the time-dependency of many of the properties associated with these surface electrolyte paths (such as cross-sectional area and solution concentration and conductivity). This would also include the ongoing decrease in the length of many of the paths once the silver filaments have begun to grow out from the cathode.

Temperature

All other things being equal, the higher the temperature the more extensive the migration, particularly at very high relative humidity values. This correlation has been observed for a variety of insulating materials with different silver migration susceptibilities **[3],** [4], [9], [12]. Unfortunately, the number of reports dealing with the effect of different constant temperatures within the normal operating range of electrical contacts, boards, and hybrids, is extremely limited. This is probably due to the long times required for each experimental run under these conditions, as well as the emphasis on standard testing (rather than operating) conditions. Thus most electromigration failure programs have been limited to comparatively high temperatures (as in 85 °C/85-percent RH exposures) or to thermal cycling-where the main effect would be to produce local humidity variations and condensations.

From a theoretical point of view **[34], [35],** the main effect of temperature would be to increase the conductivity of the electrolytic surface solution on the insulator and speed up the migration of silver ions towards the cathode (step (b)) in the introductory discussion of "operating conditions"). This increase in conductivity comes about through the increase in the value of ionic mobility (see (l)), and the decrease in solution viscosity (see (2)), with rising temperature. On the other hand, only a small part of any temperature effect would be attributable, theoretically, to the oxidation and dissolution processes at the anode (step (a)) of the introductory discussion). The anodic oxidation of silver is considered to be thermodynamically reversible, especially at the low current densities present across the insulator. One would therefore not expect any significant kinetically controlled processes (involving activation energies and exponential functions of the temperature) for this oxidation step. From a practical view, however, there seems to be doubt as to whether conclusions derived from electrodic oxidation equilibria in bulk solution can be extended to interfaces between silver conductors and a thin film of moisture on an insulator, although with "wet" electromigration (see below) they may be more applicable.

From our own observations, most of which have already been reported [4], [8], the decrease in time-to-failure at the higher temperatures seems to be connected to a comparatively rapid buildup of colloidal silver on the insulator and the movement of these "stains" towards the cathode. Examination of some of the failed spacings showed that the stains had bridged these spacings in some cases (Fig. 5) while in others, dendrites had grown from the cathode to the stain (Fig. 4). We had also previously reported [4] that at high temperatures (viz., 75 °C) a "stain front" could sometimes be seen parallel to the anodic conductors, similar to the one shown in Fig. 5. The advancing edge of this stain was often at the margin of farthest advance of the dendrites and may have served as a secondary source of silver ions for their growth [4].

"WET" ELECTROMIGRATION

When liquid water is present in the spacings between the conductors, the electromigration effects will increase in speed and severity by several orders of magnitude. In work carried out in the author's laboratory, for example, the time to dendrite inception at 45 °C, with an applied voltage of 10 V across 0.38-mm (15-mil) spacings, was at least a week at 90-percent RH. In addition, several more days were required for the dendrites to bridge the spacing. On the other hand, when a drop of water was placed between the conductors at room temperature, the time of inception was reduced to minutes (Table II), and subsequent bridging occurred in less than a minute. Other workers have reported similar accelerations [15], [19], [21], [24].

A second pronounced effect of condensed moisture in the interconductor spacing is the extension of all the previously discussed electromigration effects to many other metallic systems [15]-[22], [24], [25], [28]. Filament bridging from cathode to anode, under these conditions, has been observed for copper, gold, tin, nickel, lead, palladium, and solder, but not for metals with protective oxide films, such as chromium, aluminum, and tungsten [15], [24].

Wet electromigration has also become a quality-control problem with integrated-circuit (IC) devices and hybrid microcircuit systems, in general. Of particular importance was the finding that many "black-box failures" of gold-metallized circuitry were due to bridging of the narrow IC spacings by dendritic filaments of gold-which the reliability engineers who first discovered this effect [16]-[18] called Migrated Gold Resistive Shorts (MGRS). Although all of the failures were caused by condensed moisture, the presence of chlorides or other halogen-containing compounds was also considered necessary in order to convert the gold (at the anode) into a soluble complex form [16]-[18], [21], [22]. In the absence of such compounds, dendritic filaments were usually not produced. However, bridging by gold can still occur across the narrow spacings through the formation and migration of colloidal gold from the anodes [23].

Fig. 14 shows early bridging by silver dendrites of a 0.76-mm (30.mil) spacing of a conventional epoxy-glass PC board on which a drop of deionized water had been placed. This micrograph was taken only a few minutes after we had applied a 5-V potential across the wet spacing. The bubbles (presumably of hydrogen gas) that can just be seen at the cathode-insulator interface were found to be a common feature of wet electromigration. In Fig. 15, for example, which shows a 0.76-mm (30-mil) spacing across which 10 V had been applied (and copper dendrites had bridged), the bubbling has increased considerably as a result of the increased voltage. In addition, the appearance of bubbles at both of the conductors (of thinly gold-plated copper) indicates that electrolysis of water is taking place at the higher potential. As explained below, the turbulence produced by bubble formation at the interface between the conductor and the water-covered insulator appears to play a major role in the apparent "saturation" of the failure rate when a certain level of applied voltage has been reached.

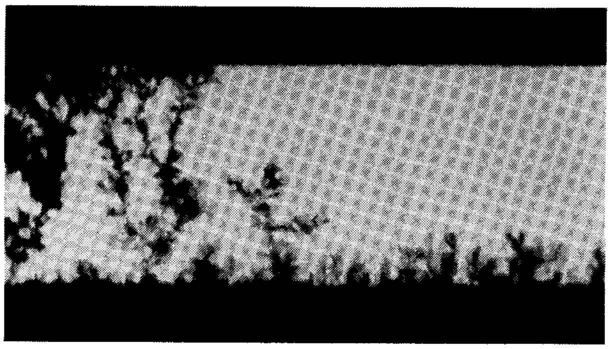

Fig. 14. "Wet" electromigration: Silver dendrites in deionized (DI) water on glass-epoxy PC board. Note gas bubbles at cathodic conductor. 24 x .

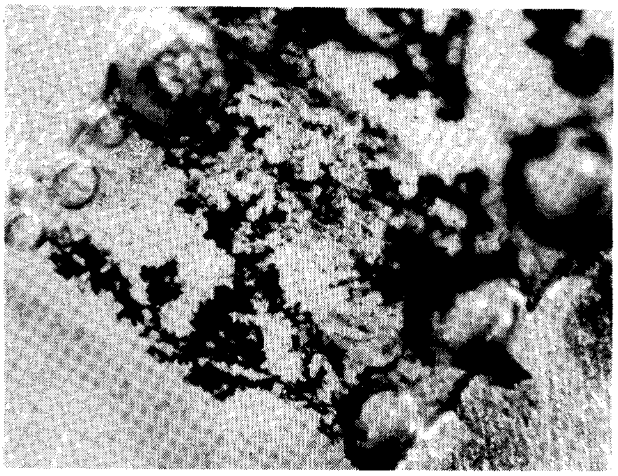

Fig. 15. Copper dendrites from thinly gold-plated conductors. DI water on glass-epoxy board. 32 x .

In a series of experimental programs with a relatively hydrophobic, Mylar-based flexible circuitry, the rapid onset of electromigration effects could be obtained at low applied potentials (down to 2 V) if a drop of deionized water was placed across either 25- or 50-mil spacings between tin-lead-plated conductors (Figs. 16 and 17). Analysis of the dendritic fragments that remained after evaporation of the water (Fig. 18) showed them to be composed of both tin and lead, with the same approximate composition as the tin-lead platings on the conductors. In addition, SEM micrographs of some of these fragments showed that the dendritic structure was present down to the micrometer range (Fig. 19).

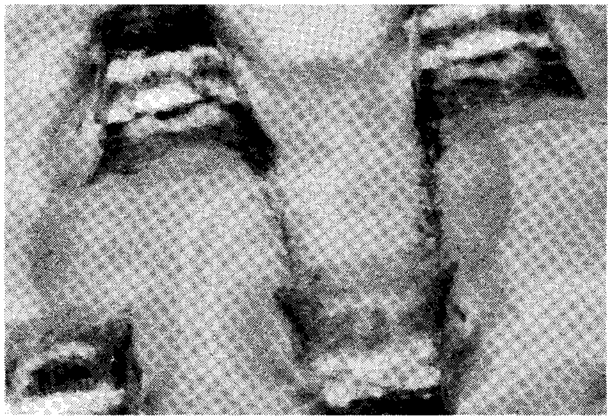

Fig. 16. Tin-lead electromigration in drop of DI water on polyester film. 23 x .

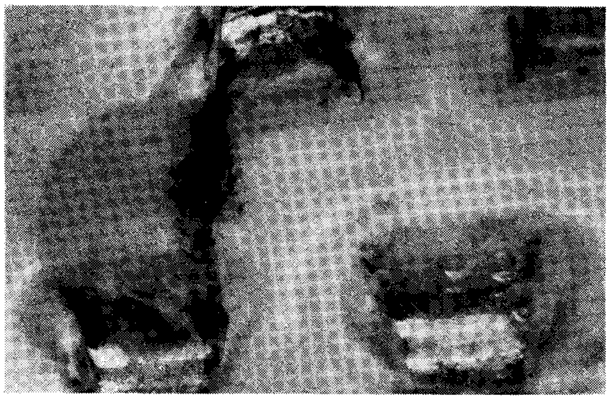

Fig. 17. Tin-lead electromigration in DI water drop on polyester film. Note gas bubbles on both anodic and cathodic contacts. 16.4 x.

Fig. 18. Dendritic fragments in 0.64-mm (0.025in) spacing after evaporation of water drop from polyester surface. 32 x .

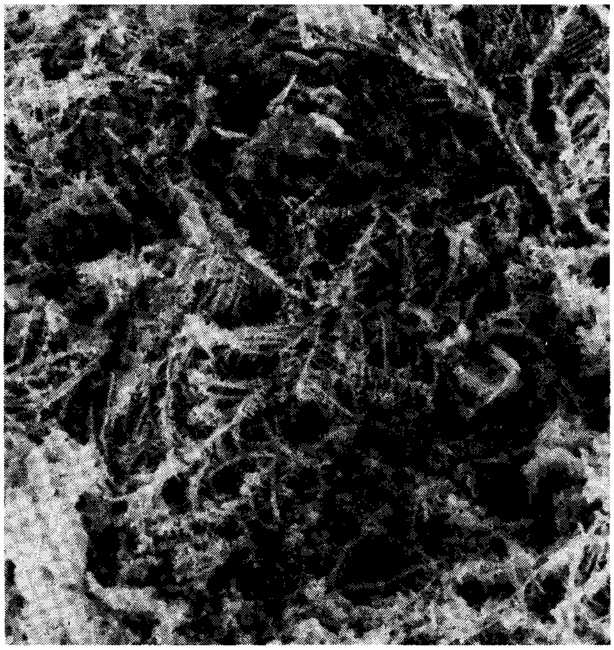

Fig. 19. SEM micrograph of some of the tin-lead fragments in Fig. 16. 600 x .

Table II lists the average time intervals between application of the voltage and the definite appearance of the first dendritic filaments of tin-lead at the negatively polarized conductors. It shows that these room-temperature inception times depend, as expected, on both the magnitude of the applied potential and the interconductor spacing. The table also gives some indication of the spread in the values for the different experimental conditions.

TABLE II
AVERAGE TIME BETWEEN APPLICATION OF VOLTAGE AND FIRST DEFINITE APPEARANCE OF METALLIC FILAMENTS

Voltage	Time Interval (min)	
(V)	0.64-mm Spacings	1.28-mm Spacings
6	0.92 ± 0.14 (3 runs)	2.4 ± 1.0 (3 runs)
5	1.0 ± 0.38 (2 runs)	3.3 ± 2.5 (4 runs)
4	0.93 ± 0.55 (4 runs)	
3	1.75 ± 0.35 (2 runs)	4.7 ± 1.0 (4 runs)
2	1.81 ± 0.59 (4 runs)	

Further examination of these results, particularly with the 0.64-mm (25-mil) spacings, shows what appears to be a maximum voltage above which no further acceleration in the electromigration effects would be obtained. In practice, this apparent leveling off in the rate of dendrite inception and growth is at least partly due to the increased turbulence in the liquid drop at the higher voltages which, as seen through the microscope, was produced by rapid eruptions of the gas bubbles. These tended to interfere with the nucleation of the first thin filaments at the negatively polarized conductors and especially with the unidirectional growth of the dendrites towards the positively polarized conductors. These same phenomena also occurred with the 1.28.mm (50-mil) spacings. However, their effect on inception time was primarily in the large observed variations in the time intervals for the different runs.

It should also be pointed out that when a filament or dendrite moves through the three-dimensional water layer of "wet" electromigration, motion within the liquid prevents the filament's path from going straight toward the anode, even allowing for branching. Instead-as observed both by direct stereomicroscope viewing and by examination of real-time videotapes-the filaments tend to take more tortuous and wiggly three-dimensional paths in response to the random motions of the liquid medium.

A WORD ABOUT PREVENTION

Problems with both wet and high-humidity electromigration are becoming much more prevalent as interconductor spacings become narrower and board loadings more complex. In addition to increasing the probability of capillary condensation of water in the very small nooks and crannies that arise from such loading, these discontinuities can also serve as traps for deleterious contaminants. It is therefore essential that those involved in testing, qualifying, and trouble-shooting such systems should pay even more attention to assuring the cleanliness and freedom from moisture of the entire package, if electromigration problems are to be avoided.

Because of the critical effect of moisture on electrolytic electromigration, it was felt that one could inhibit, or slow down, its effects by applying water-repelling coatings to the conductors and the insulator surface. Extensive work by different workers [3], [8], [24], [45], *[46], [50]* has shown that such techniques can be effective for certain conductor-insulator systems, but will also depend upon the magnitude of the voltage, temperature, and humidity to which the system is exposed. Another common method for mitigating electromigration (particularly of silver) is to inhibit the initial oxidation/dissolution step (step a) above) by reducing the thermodynamic "activity" (concentration) of the migrating metal. Techniques that have been tried with varying degrees of success [3], *[6], [22], [25], [28], [50],* [51] are overplating the silver with less "active" metals (such as gold, palladium, or even tin), alloying the silver (particularly with palladium), and tying up the silver or reducing its surface concentration through tarnishing or other chemical conversions.

SOLID-STATE ELECTROMIGRATION

The term "Electromigration" is also used in solid-state physics, where it describes mass transport in solids under the influence of high current densities. As such, it has received considerable attention in microelectronics because of its role in producing failures in integrated circuits [54]-[65], so that the Annual Symposia on Reliability Physics-sponsored by the IEEE Electron Devices and IEEE Reliability Societies-have included, over the past several years, special sessions on this type of electromigration.

In solid-state electromigration, the passage of a direct current produces migration primarily through the force of electrons impinging on the metal atoms. However, because of structural inhomogeneities such as grain boundaries, the resultant atomic flux is not spatially uniform, and its divergence leads to material depletion and material accumulation. Material depletion results in holes and eventual open circuits (conductor failure). Material accumulation, on the other hand, leads to hillocks and whiskers, which can cause short circuits or even corrosion, such as by breaking through protective coatings. In a recent case, hillock formation was even found to produce cracking in a silicon-dioxide ($SiO2$) overcoating [6l].

These two complementary phenomena may also be related to temperature differences on the metallization surface, with hillocks being associated with areas that are cooler than the average [65].

Although most solid-state electromigration failures in the literature have involved aluminum-based conductors applied directly over silicon-dioxide films, some have been reported for other substrate systems. One example is that of aluminum over titanium-tungsten (TiW) diffusion barrier films, where failures were ascribed to short-circuiting aluminum protrusions and whiskers [62]. In this regard, tin whiskers and filaments can also be produced by solid-state electromigration, provided that the current density is sufficient to raise the local temperature close to the melting point of tin *[66].*

Finally, the mechanisms and operational conditions for *solid-state* electromigration are entirely different from those of *electrolytic* electromigration. The former takes place under dry conditions, and becomes important at local temperatures above 150°C and, most importantly, at dc current densities of at least 10^4 A/cm^2 (Table I). These conditions are commonplace in the microscopic world of integrated circuits and thin-film conductors, but would cause melting and other damage to PC board conductors and similar macroscopic components [63]. On the other hand, such conditions would completely prevent the presence of moisture, thereby eliminating the primary mode of *electrolytic* electromigration.

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