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Review of the Thermal Contact Conductance of Junctions with Metallic Coatings and Films

M. A. Lambert* and L. S. Fletcher†
Texas A&M University, College Station, Texas 77843

The reliability of standard electronic modules may be improved by decreasing overall module temperature. This may be accomplished by enhancing the thermal contact conductance at the interface between the module frame guide rib and the card rail to which the module is clamped. The surface irregularities resulting from the machining or extruding of the components cause the true contact area to be much less than the apparent contact area, increasing the contact resistance. Some metallic coatings deform easily under load and increase the contact area and associated conductance. This investigation evaluates possible coatings and determines those most suitable for enhancing contact conductance based upon predictions using existing theories for thermal contact conductance of coated junctions.

Nomenclature

a = contact spot radius
b = radius of heat flux channel
H = hardness
h = thermal contact conductance
k = thermal conductivity
m = combined rms absolute asperity slope, $(m_1^2 + m_2^2)^{1/2}$
P = apparent contact pressure
R = thermal contact resistance
t = coating thickness
σ = combined rms roughness of both surfaces, $(\sigma_1^2 + \sigma_2^2)^{1/2}$

Subscripts

f = filler
M = metal substrate
t = total
1, 2 = surfaces 1 and 2

Superscript

$'$ = coating or coated contact

Introduction

CONTROLLING thermal contact conductance has become a subject of increasing interest and importance in recent years. The increased power capacities of modern microelectronics require greater heat dissipation. Spacecraft and satellites require effective means for distributing and dissipating heat generated by high-density power cells or absorbed through solar irradiation.

One of the most effective means of controlling contact conductance is through the use of interstitial materials between components. The choice of interstitial material and the use of the material for a particular application is governed by such factors as contact pressure and temperature, environmental conditions, and the degree to which it is desired to decrease or increase heat flow across the junction. Many thermal control materials are available, however, there are disadvantages for most materials used in metallic junctions.[1] Surface treatments, however, are generally used to improve contact conductance or provide thermal control. Treatments such as metallic platings, coatings, and vapor-deposited films are more permanent in nature than interstitial materials and may be suitable for applications involving repeated and/or sliding contact, depending upon coating properties and clearance. Therefore, surface treatments are the best choice for many applications.

A thorough search of the literature was undertaken to identify those investigations containing data and prediction techniques for the thermal conductance of metallic-coated contacts. In all studies considered, the coatings were deposited on a metallic substrate. The results of each investigation are summarized in the literature review.

Literature Review

There have been a number of investigations dealing with the thermal contact conductance of coated surfaces. Some of these investigations do not provide enough information to permit evaluation. Those that provide complete experimental data are reviewed along with those theoretical/analytical studies which are appropriate for coated surfaces.

Fried[2] and Fried and Kelly[3] described thermal contact conductance in the following manner. The contact heat transfer phenomenon, exclusive of the contribution of radiation, can be divided into the actual physical contact area determination and the contact heat transfer based on conduction across this actual area with and without an intervening film. The determination of the true contact area is very difficult because existing techniques are not suitable or practical. They stated that general elasticity and plasticity methods cannot be applied in most thermal contact problems for the following reasons:

1) The microscopic irregularities do not engage each other uniformly to form contacts, but do so in groups as the large scale macroscopic areas engage each other. The possibility of sliding contact cannot be excluded from this consideration.

2) The contact intersection is neither purely elastic nor purely plastic, but is elastoplastic or elastoviscous in character. Thus, as a load is applied, there is a redistribution of pressure among the load-bearing asperities.

3) The surface layers, particularly when machined and polished or when exposed and oxidized, have properties different from the underlying material.

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*Graduate Resarch Assistant, Department of Mechanical Engineering. Student Member AIAA.

†Thomas A. Dietz Professor, Department of Mechanical Engineering. Fellow AIAA.

They suggested that similar classes of materials having similar types of work history and surface finish should permit the use of statistical or semi-empirical prediction methods. Thus, although the thermal performance of a particular set of interfaces may not be specifically predicted, a method may be developed to estimate the performance of a particular class of contacts, provided the surfaces are well-defined.

Fried and Kelly[3] performed contact conductance experiments using 304 stainless steel specimens coated with vapor-deposited aluminum and magnesium. One trial employed aluminum coatings on both contacting surfaces, which were 1.5 and 1.9 μm (59 and 75 μin.) in thickness. The surface roughnesses were 0.6 and 1.0 μm (24 and 39 μin.). For a second trial involving the magnesium coating, a 2-μm (79-μin.) thick film was applied to one surface only. The roughnesses of the coated and uncoated surfaces were 0.6 and 0.3 μm (24 and 12 μin.), respectively. Contact pressures ranged from approximately 0.4 to 8 MPa (58 to 1160 psi). Both coating materials enhanced the contact conductance over that of bare joints by as much as an order of magnitude at high contact pressures.

The basic conclusions of the investigation applicable to coated contacts are listed below:

1) There appears to be no significant effect of trapped or adsorbed gases on contact heat transfer.

2) Coarsely finished surfaces appear to permit more reliable contact heat transfer predictions and provide more reproducible test data. Conversely, very finely finished surfaces (such as optically polished surfaces) result in the least reproducibility and predictability.

3) The presence of soft metal platings substantially improves joint conductance.

4) Statistical prediction methods appear to hold promise for the thermal performance of inexactly defined surfaces.

Mal'kov and Dobashin[4] investigated the resistance of Kh18N9T stainless steel specimens with electroplated coatings of silver, nickel, and copper. All coatings were 25 μm (0.001 in.) in thickness. Surface roughnesses varied from 0.85 to 1.9 μm (33 to 75 μin.), and deviations from true flatness ranged from 5 to 40 μm (0.0002 to 0.0016 in.) Apparent contact pressures ranged from 0.48 to 5.6 MPa (70 to 810 psi), and testing was performed in a vacuum. The test temperature range was 250–550°C (482–1022°F).

They found that the microgeometry of the coating surface is determined to a large extent by the microgeometry of the underlying metal surface. Although the thickness of the coatings applied in this set of experiments was 12–15 times the height of the asperities, the surface characteristics of the coatings remained practically unchanged from those of the substrate for the case of the silver coating. The surfaces of the copper and nickel coatings were somewhat rougher and smoother, respectively, than their underlying stainless steel surface.

Mal'kov and Dobashin[4] noted that for the given pressure range, the thermal contact resistances of the coated joints were reduced by factors of 2–10 from the value for the uncoated contact. The resistance of specimens that were lapped after being coated became negligibly small with increasing contact pressure. Increases in surface roughness and waviness resulted in increased resistance; however, the contact resistance was less affected by pressure for increasing waviness. Coated or uncoated lapped surfaces had lower resistance than unlapped surfaces, which they attributed to the decreased roughness and waviness. The coatings became decreasingly effective with increasing waviness.

Mikic and Carnasciali[5] developed an analysis for the thermal contact resistance of an elemental heat channel (single contact). They argued that the analysis for an elemental heat channel can be used for evaluation of contact resistance for multiple contacts between nominally flat, rough surfaces, or directly applied to calculation of macroscopic constriction resistance for wavy, smooth surfaces. They noted that highly conductive platings may significantly reduce the resistance. Platings may also be used to alter the geometry of the contact for a given interfacial load due to the generally different yield strengths of the plating and substrate.

Mikic and Carnasciali[5] further suggested that the plating of only one contacting surface should have only a limited effect on the resistance, since the entire constriction on the unplated side still has to take place in a low-conductivity material. When both surfaces are plated, the combined effects of the change of thermal conductivity in the constriction region and the change in geometry of the contact are fully realized, and the contact conductance is most improved.

Their model for predicting the ratio of the coated-to-uncoated contact conductance uses three ratios as input information: 1) t/a, 2) a/b, and 3) k_1/k_2, where k_1 and k_2 are the thermal conductivities of the plating and substrate materials, respectively. The resistance ratio for the coated-to-uncoated contacts (R_t/R) is reduced by increases in each of the three previously listed ratios.

An experimental verification of the theory was conducted by Mikic and Carnasciali[5] using a macroscopic model of a single constriction. The plating and substrate materials were copper and 303 stainless steel, respectively. Cylinders of each material were soldered together to simulate perfect bonding of the plating to the substrate. Then, a portion of each copper cylinder was turned to a smaller radius to simulate a constriction. Experiments using ratios of a/b and t/a from 0.5 to 2.0 ($k_1/k_2 = 23.0$) yielded reductions in the resistance ratio by a factor of 10–20. Their experimental results demonstrated close agreement with the theory. However, no information on surface topography was provided that would permit comparison of their results to those of other investigations.

O'Callaghan et al.[6] present a theory which predicts the optimum thickness of a metallic coating for maximum thermal contact conductance. It assumes that ideal plastic deformation occurs at the interface of a rough and smooth surface. It further assumes that the material within intersections of the surfaces (i.e., parts of the asperities protruding into the coating) has no effect on the contact conductance. They indicate that if the filler material were fully ductile it would extrude from the asperity intersections into noncontact regions and result in greater values of thermal contact conductance than the theory suggests.

They suggested that if the filler is softer than the base materials, the real contact area will be increased for a given pressure compared to the same interface without filler. They also contend that the degree of improvement depends on the ratio of the conductivities of the filler and base materials, and the optimal filler thickness is expected to be of the order of the surface roughness.

O'Callaghan et al.[6] conducted experiments using stainless steel (En58b) specimens with ion-deposited tin coatings ranging in thickness from approximately 3 to 106 μm (0.00012 to 0.0042 in.) Their theoretical prediction exhibited fairly good agreement with the data.

Snaith et al.[7] identified a general criterion for determining whether a filler material of suitable thickness will decrease contact resistance

$$H_M k_f / H_f k_M > 1$$

where H_f and H_M are the hardnesses of the filler and substrate, and k_f and k_M are the thermal conductivities of the filler and substrate.

The optimal thickness is expected to occur when filler thickness t is on the order of the rms surface roughness σ. If $t < \sigma$, resistance is reduced because of the presence of additional solid flow channels through the filler. For $t >> \sigma$, the bulk resistance of the filler tends to exceed the reduction in constriction resistance afforded by the filler. The assumptions made in developing this theory are identical to those of O'Callaghan et al.[6]

Antonetti and Yovanovich[8] developed a thermomechanical model for predicting the contact conductance of a nominally flat, rough surface and a metallic-coated smooth surface. A correlation for bare joints[9] was used as the basis for this coated contact theory. The resistance of a perfect joint is about two orders of magnitude smaller than the constriction resistance of a pressed contact.[10]

Their predicted contact conductance is presented in a dimensionless form that is dependent on parameters which include 1) surface roughness and asperity slope, 2) apparent pressure, 3) microhardness of the rough surface and effective microhardness of the coated smooth surface, and 4) the effective thermal conductivity of the joint (which involves the thermal conductivities of the two contacting materials and a constriction parameter correction factor for a coated joint). They stated that the effective microhardness of the coated surface must be determined experimentally for the particular coating-substrate combination in question.

Experiments were performed on silver-coated nickel specimens in contact with bare nickel specimens to verify the contact conductance theory. The applied contact pressure extended over the range of 500–3700 kPa (72–540 psi), and the mean interface temperature varied from 85 to 206°C (185 to 403°F). Their results for a pressure of 2000 kPa (290 psi) were nominally within 10% of their theoretical predictions of contact conductance. The contact conductance of the coated junction was as much as an order of magnitude greater than that of the bare junction. They also noted that for a given layer thickness, the enhancement increased for smoother surfaces.

Kang et al.[11] determined the degree to which lead, tin, and indium vapor-deposited coatings could increase the contact conductance of 6061-T6 aluminum interfaces. They used four thicknesses of each coating, ranging from a few tenths of a μm to a few μm. All tests were conducted in a vacuum and over a nominal pressure range of 200–1600 kPa (29–232 psi). Metrological information included average and rms roughness, peak-to-valley height, average and rms asperity slope, and average and maximum waviness height. They reported typical specimen surface measurements of approximately 0.7 μm (28 μin.) for rms roughness, 0.08 for rms asperity slope, and 2.5 μm (98 μin.) for average waviness height. The average interface temperature for all tests was approximately 25°C (77°F).

They performed extensive Vickers microhardness tests of coated and uncoated specimens. Five readings at seven indenter loads were taken for each specimen tested. Coated surfaces exhibited a trend of increasing microhardness with increasing load (i.e., decreasing ratio of coating thickness to indenter penetration depth), which was also noted by Antonetti and Yovanovich.[8] Kang et al.[11] developed analytical expressions for the effective microhardness of the three coating-substrate combinations that were analogous to that given by Antonetti and Yovanovich[12] for a silver-coated nickel specimen. Kang et al.[11] noted that the microhardness of the bare 6061-T6 aluminum samples increased slightly for greater indenter loads.

Kang et al.[11] concluded tht the optimal coating thicknesses were in the range of 2.0–3.0 μm (79–118 μin.) for indium, 1.5–2.5 μm (59–98 μin.) for lead, and 0.2–0.5 μm (8–20 μin.) for tin. They reported maximum coated-to-uncoated contact conductance ratios of approximately 7, 4, and 1.5 for indium, lead, and tin, respectively, and suggested that the coating hardness appears to be the most significant factor in ranking the effectiveness of a coating. They further noted that the conductance enhancement provided by a coating of a given thickness was greatest at low contact pressures, decreasing significantly with increases in contact pressure. They reasoned that as pressure was initially increased, the growth in contact area of the coated joints was much greater than for the bare joints due to the softness of the coating. They went on to state that as the pressure was steadily increased, the rapid growth in contact area was reduced by the contact between substrate asperities which had penetrated the coating material. Finally, they concluded that the reduction in the contact area growth rate resulted in a reduction in the thermal contact conductance enhancement. Kang et al.[11] also observed that the optimal coating thickness decreased as pressure was increased.

Chung et al.[13] studied the effects on contact conductance of ion-vapor-deposited coatings of aluminum, lead, and indium on 6061-T6 aluminum. They employed two total coating thicknesses, 25.4 and 50.8 μm (0.001 and 0.002 in.), and two surface roughnesses, 1.6 and 3.2 μm (63 and 126 μin.). Two-surface coatings (i.e., both surfaces of a contact pair were each coated to a thickness of 12.7 or 25.4 μm) were also investigated. Thermal conductance enhancement varied from 0 to 500% of the uncoated value, depending on the surface characteristics. Four nominal contact pressures from 100 to 500 kPa (14 to 72 psi) were used.

The ratios of coated-to-uncoated contact conductance for the rougher substrates showed greater improvements. This was attributed to the fact that a rougher substrate will penetrate a soft coating more deeply, thereby increasing contact area and contact conductance. For the smaller substrate roughness, 1.6 μm (63 μin.), pressure had little effect on the conductance ratio, with the exception that the thicker indium coating exhibited a peak conductance at 175 kPa (25 psi). Also, for aluminum and lead coatings, the coated-to-uncoated conductance ratios for the two coating thicknesses showed little difference, while the conductance ratios for indium increased slightly for the thicker coating.

For the larger substrate roughness, 3.2 μm (126 μin.), the conductance ratio increased with pressure for aluminum and lead coatings, and was generally slightly less for the thicker coating than for the thinner coating. Interfaces coated with indium exhibited an opposite trend of higher conductance ratios for the thicker coating, and contact pressures between 175–275 kPa (25–40 psi) provided the greatest enhancement of conductance. Also, for a given coating material and total coating thickness, two-surface coatings generally provided greater increases in contact conductance than one-surface coatings.

The enhancement of thermal contact conductance varied from 150 to 500, 0 to 250, and 0 to 100% increases for indium, aluminum, and lead, respectively. Chung et al.[11] observed that the differences between the conductance ratios of two-surface and one-surface coatings were dependent on the coating material involved. Lead coatings showed no significant differences, whereas two-surface coatings of aluminum and indium displayed significantly increased conductance over one-surface values. They noted that, in general, for a given coating thickness, the enhancement of conductance increases with surface roughness, provided the thickness of the coating is many times greater than the value of surface roughness.

Chung et al.[14] examined pure copper and copper-carbon mixtures (transitional buffering interfaces, TBI) applied to both contacting surfaces of 6061-T651 Al. They employed four aluminum surface roughnesses ranging from 0.17 to 3.55 μm (6.8 to 142 μin.). Two coating thicknesses, 0.19 and 0.24 μm (7 and 9 μin.) for the copper coatings and 0.25 and 0.45 μm (10 and 18 μin.) for the Cu/C coatings, were tested for each of the four surface roughnesses. The coating process involves plasma-enhanced deposition onto cold surfaces of either conducting (metallic) or nonconducting (nonmetallic) base material. They claimed that TBI coatings provide excellent contact conductance and long life under repeated loads.

Pure copper yielded contact conductance values 1.09–1.31 times those for copper and carbon phase mixtures over a pressure range of 125–500 kPa (18–72 psi). They stated that a pure copper coating is more thermally enhancing than a Cu/C coating because of the low thermal conductivity and high hardness of carbon.

They assumed that load cycling increased contact conductance by successively plastically deforming the surfaces. There were also hysteresis effects, i.e., the unloading conductance was greater than loading conductance for a given pressure. Blasted rough, bare surfaces had higher conductances than polished surfaces by a factor of from 1.3 to 2.6, due to the larger area of contact spots of the former. They also noted that the most significant improvement in conductance, as a result of the application of coatings, was obtained for turned surfaces (as opposed to polished or blasted surfaces) for which the rms roughness was approximately equal to the coating thickness. Coating thicknesses beyond this led to decreased conductance. Also, coatings much thinner than the surface roughness values did not improve conductance.

Selection of Metallic Coating Materials

A number of materials have been used as coatings for controlling the thermal contact conductance of pressed contacts. As previously reported,[1] of the four basic types of interstitial materials, only surface treatments and coatings are deemed suitable for microelectronic applications. Coatings may be polymeric, ceramic, composite, metallic, nonmetallic, or oxidic in nature. Although polymeric coatings are typically resistant to deterioration in a marine environment, and may improve conductance if impregnated with metal particles, they generally only provide moderate enhancement. Ceramics and oxides are almost invariably insulative. Composites generally exhibit the same performance as polymers, as they are usually comprised mainly of polymeric resins. Metallic coatings are typically the most highly thermally conductive materials and may afford the greatest improvment in thermal contact conductance.

Coating Materials

Criteria that are considered most important for enhancement of the thermal contact conductance of the frame-rail interface have been evaluated. Some investigators, such as O'Callaghan et al.[6] and Snaith et al.,[7] suggest that the ideal coating material possess a large ratio of thermal conductivity to hardness. They contend that coatings of low hardness deform readily under load, flow around the asperities, and thereby increase the contact area. High values of thermal conductivity tend to alleviate the constriction resistance through the reduced areas of the microcontacts, and this coating property is considered by Mikic and Carnasciali[5] to be highly important. A number of metals with high ratios of thermal conductivity-to-hardness are listed in Table 1 for comparison. Some of the hard metals listed are included because they exhibit excellent corrosion resistance.

Since metals are the type of coating material thought to be most appropriate for microelectronic applications, and, in general, for maximizing contact conductance, an assay of all metallic elements has been made to identify those metals that may be suitable for use as conductance enhancing coatings. Those considered as such are listed in Table 1. Their selection was based on loosely defined requirements of low hardness, high thermal conductivity, excellent corrosion resistance, or a combination of these properties. Properties of the metals were taken from a number of sources, including Tabor,[5] the *Metals Handbook*,[16] Touloukian and Ho,[17,18] Hutgren et al.,[19] Westbrook and Conrad,[20] Ho,[21] Weast,[22] Smith,[23] Richman,[24] Brick et al.,[25] and Flinn and Trojan.[26]

The elements in the periodic table are arranged according to their electronic configurations, which give rise to many of their properties. Therefore, it would seem logical to sort through the metals group by group (a group being those elements with similar valence or outer shell electron configurations), to determine those which best suit the requirements of a conductance-enhancing coating.

The alkali metals, with valence numbers of one or two, are typically highly reactive. All but two, beryllium and magnesium, may be summarily excluded from consideration because they are either poisonous, radioactive, available in insufficient supply, or react vigorously or even explosively when exposed to moisture or ignite spontaneously when exposed to air. Beryllium, employed where lightness and stiffness are needed, resists oxidation in air. Although beryllium has a high thermal conductivity, it is toxic and is very hard with a Brinell Hardness (BHN) of 97. Magnesium tarnishes slightly when exposed to air and ignites when heated. This combination of disadvantages makes magnesium an unlikely choice. However, since it is used in a number of applications, it is included in the group of candidate coatings.

The rare-Earth or lanthanide series of metals, includes lanthanum which oxidizes rapidly in air and exhibits low-to-moderate toxicity. Cerium, which oxidizes very readily in moist air, may ignite if scratched. Praseodymium, though somewhat more stable than lanthanium or cerium, develops a green oxide coating in air which spalls off, thereby exposing more of the metal. Neodymium quickly tarnishes in air, its oxide

Table 1 Thermophysical properties of candidate coating metals

Material[a]	Atomic symbol	BHN, kg/mm^2	Thermal conductivity (at 27 C), W/mk	Thermal expansion coefficient, μm/mK	Melting, point, C	Moleular weight	Density, g/cm^3	Comments[b]
Indium*	In	1	81.7	32.1	156.6	114.8	7.3	Inert, low toxicity
Lead*	Pb	4	35.2	28.9	327.5	207.2	11.34	Inert, cumulative toxin
Tin*	Sn	5	66.6	22.0	232	118.7	7.31	Inert
Aluminum*	Al	16	237	23.1	660.4	27.0	2.71	Oxidizes
Silver*	Ag	25	427	18.9	961.9	107.9	10.5	Oxidizes slightly
Gold*	Au	30	315	14.2	1064.4	197.0	19.3	Inert
Copper*	Cu	35	398	16.5	1083.4	63.5	8.9	Oxidizes slightly
Cadmium	Cd	23	104	30.8	320.9	112.4	8.6	Oxidizes, toxic
Zinc	Zn	30	121	30.2	419.5	65.4	7.14	Oxidizes
Magnesium*	Mg	30	156	24.8	648.8	24.3	1.74	Oxidizes
Palladium	Pd	40	75.5	11.8	1552	106.4	12.0	Inert
Platinum	Pt	40	71.4	8.8	1772	195.1	21.45	Inert
Cobalt	Co	48	99.2	13.0	1490	58.9	8.9	Inert
Bismuth	Bi	11	7.86	13.4	271.3	209.0	9.80	Inert
Rhodium	Rh	135	150	8.2	1966	102.9	12.5	Oxidizes
Chromium	Cr	100	90.3	4.9	1903	52.0	7.1	Inert
Nickel*	Ni	75	90.5	13.4	1453	58.7	8.9	Inert
Niobium	Nb	80	53.7	7.3	1950	92.9	8.4	Inert
Tantalum	Ta	60	57.5	6.3	2977	181.0	16.6	Inert
Vanadium	V	72	31.5	8.4	1730	50.9	5.96	Inert

[a] Asterisk following element name indicates that the metal has been experimentally evaluated for its ability to enhance thermal contact conductance.

[b] Reactivity in air, level of toxicity.

also spalls off, and it has low-to-moderate acute toxicity. Promethium is extremely rare, it does not exist naturally on Earth and must be synthesized at great expense. Samarium, though reasonably stable in air at room temperature, ignites when heated above 150°C (302°F) and is also possibly toxic. Europium is about as hard as lead, is the most reactive metal of this series, and quickly oxidizes in air. As with other rare-Earth metals, except for lanthanium, europium ignites in air at 150–180°C (302–356°F). Gadolinium is relatively stable in dry air, but in moist air it tarnishes with the formation of a loosely adhering oxide film that spalls off. Terbium is reasonably stable in air and is soft and ductile, however, it is very expensive and possibly toxic. Dysprosium is soft and relatively stable in air at room temperature, rapidly oxidizes in moist air and at elevated temperature, and possibly exhibits low toxicity. Erbium is fairly stable in air and does not oxidize as rapidly as some of the other rare-Earth metals. Thulium is reasonably stable in air, but will oxidize when exposed to moisture. It is expensive and has low-to-moderately acute toxicity. Ytterbium, while fairly stable, oxidizes in air and moisture and has low acute toxicity. The last rare-Earth, lutetium, is stable in air, but very expensive and also has low toxicity.

The first in the actinide series, actinium, is highly radioactive. Its chemical behavior is similar to the rare-Earths, particularly lanthanum. Thorium is soft and very ductile, however, it is a radiation hazard and should be stored and handled in areas with good ventilation. Protactinium is a dangerous toxin and is very expensive. Uranium and its compounds are highly toxic, both chemically and radiologically. Neptunium, found only in trace quantities in nature, is chemically reactive and very expensive. The remainder of the transuranium elements (those to the right of uranium) are radiological poisons. They are absorbed by bone marrow, and trace quantities may destroy the body's ability to generate blood corpuscles.

The transition elements are not radioactive and are generally less reactive than the alkali or rare-Earth metals. The properties of scandium and yttrium resemble those of the rare-Earth elements. Scandium is relatively soft, oxidizes slightly in air, is expensive, and may also be toxic. Yttrium is less expensive than scandium and is relatively stable in air in bulk form. Titanium, zirconium, and hafnium all have excellent resistance to seawater corrosion. Titanium, however, is too hard (BHN 200) to be useful as a coating. Vanadium, niobium, and tantalum all have desirable low reactivity. Vanadium is moderately hard and ductile, and resistant to salt water. Niobium is slightly harder, but still ductile and begins to oxidize above 200°C (392°F). Tantalum is almost completely inert below 150°C (302°F) and is relatively hard (BHN 60).

Chromium is extremely resistant to corrosion and is usually quite hard, even in the annealed state (BHN 100). It is included in consideration because it is widely used as a protective plating. Molybdenum and tungsten are too hard and brittle for microelectronic applications. Manganese is extremely hard (BHN 300) and brittle, so it is not considered. Technetium does not naturally exist, is very expensive, and is radioactive. Rhenium, is corrosion and wear-resistant, but too hard to be useful.

Iron is moderately hard (BHN 70) and oxidizes rapidly in moist air. Ruthenium and osmium, are extremely hard (BHN 220 and 400, respectively) and are stable in air at room temperature. The oxides of the latter two are highly toxic and unsuitable for microelectronic interfaces. Cobalt, rhodium, and iridium all are extremely oxidation resistant. Cobalt is moderately hard (BHN 48) in the annealed state, and may be worth consideration. Rhodium is very hard (BHN 135), but, since it is sometimes employed as a plating, it is listed as a candidate material. Iridium is even harder (BHN 170) than rhodium, so it is unlikely to improve conductance.

Nickel, palladium, and platinum all are noble metals and are used to differing extents as platings. Thus, all are evaluated in terms of their applicability to this project. Nickel is fairly hard (BHN 75). Palladium and platinum are markedly softer, but expensive. Copper, silver, and gold are the most highly conductive metals and are relatively soft, making them attractive possibilities. Copper and silver tarnish slightly in air. Gold has the unique property among the metals that its oxide is unstable. Therefore, gold surfaces will remain bright indefinitely. Zinc, cadmium, and mercury are also transition metals. Cadmium is soft and also toxic, but used extensively in electroplating. Mercury is, of course, highly poisonous and liquid at room temperature, making it unsuitable. Zinc is fairly soft, highly reactive, and frequently used as a plating material.

Other elements become increasingly more like metalloids and nonmetals with increasing proximity to the noble gases. Aluminum, which is quite soft and highly conductive, is worthy of attention. However, aluminum does form an oxide scale in air. Gallium has an insufficiently high melting point, 30°C (86°F). Indium is extremely soft and more resistant to atmospheric corrosion than silver. There is evidence that it has a low level of toxicity, but this is considered minor and is effectively dealt with by exercising normal hygiene. Its poor shear strength makes indium susceptible to being worn from surfaces subjected to repeated or sliding surfaces. Thallium is very soft and also forms a heavy oxide if left in air. It is poisonous, even when only in contact with the skin.

Germanium is crystalline and brittle, therefore unsuitable. Tin is very soft and resistant to seawater. Lead is also very soft and resistant to corrosion. A lead carbonate-hydroxide forms on lead in the presence of moisture and carbon dioxide, resulting in a white deposit on the surface. Care must be exercised in handling lead as it is a cumulative poison. Arsenic is very hard (BHN 147) and brittle, tarnishes in air, and is poisonous. Underneath arsenic is antimony, which is an extremely brittle metal with a flaky, crystalline texture. It does not react with air at room temperature, but burns when heated. Antimony is also toxic. Bismuth is quite soft, though poorly conductive and burns when heated sufficiently in air. Since it is so soft (BHN 11), it is evaluated as a coating, despite its disadvantages. Selenium is a nonmetal which resembles sulfur in its various forms and compounds and has a very low thermal conductivity. Although elemental selenium is considered almost nontoxic, hydrogen selenide is extremely poisonous. Tellurium is a semiconductor and is brittle and probably toxic. Polonium is dangerously radioactive.

In all, 20 metallic elements were chosen as possible coating materials for use in enhancing the contact conductance of microelectronic components. Nine of these, as indicated in Table 1, have been experimentally evaluated for their ability to enhance thermal contact conductance. Their selection was based on loosely defined requirements of low hardness, high thermal conductivity, excellent corrosion resistance, or a combination of these properties.

Coating Thicknesses

Coating thicknesses which are of the same order as the combined rms surface roughness have been demonstrated to be optimal by O'Callaghan.[6] Existing data on the various coating materials was utilized in selecting the precise thickness of each coating to be used in calculations of contact conductance. Kang[11] demonstrated that the optimal coating thicknesses for indium, lead, and tin on substrates of 6061-T6 aluminum were 2.5, 2.0, and 0.5 μm (98, 79, and 20 μin.), respectively. The surface roughness of the nominally flat specimens investigated by Kang[11] was typically 0.7 μm (28 μin.). It seems odd that the optimal tin coating thickness should be greatly different from the optimal lead coating thickness, since they have essentially the same hardness.

Antonetti and Yovanovich[12] reported the ideal thickness of a silver coating on an aluminum substrate to be approximately 20 μm (0.0008 in.) for a combined rms roughness for both surfaces of 4 μm (157 μin.), yielding a ratio of coating thickness-to-roughness of five.

The specific coating thickness will be dependent upon the coating material chosen, the substrate material, and the surface characteristics of the substrate material. There are no techniques available at this time to estimate the required coating thickness for particular applications. As a consequence, the evaluation of each coating/material pair must be performed experimentally.

Results and Discussion

This section is devoted to describing how the various theories for predicting contact conductance compare to the available data. The prediction (or predictions) that best models the existing data could be useful for determining the level of contact conductance enhancement afforded by potential coating materials. First, the adequacy of the prediction techniques must be ascertained.

The descriptions and comparisons of the various theories and data given below refer to Fig. 1. This figure illustrates two prediction techniques and data from a number of investigations on the thermal contact conductance of metallic junctions with metallic coatings. All data and prediction techniques included in Fig. 1 have been reduced to the same dimensionless groupings as those employed by Antonetti and Yovanovich,[8] since this prediction technique proved to be most useful for reducing all of the information to an equivalent form. Their analysis[12] also contains a table of constriction factors that are listed in terms of topographical (i.e., metrological), thermophysical, and loading information on the contact that is readily, though tediously, calculable. This later work illustrates the application of their previous investigation to different coatings and substrates. The predictions of Antonetti and Yovanovich[8] and O'Callaghan et al.[6] explicitly apply to metallic coatings.

The predictive technique in Antonetti and Yovanovich[8] utilizes the mean asperity slope m, a surface parameter not found in all of the investigations on contact conductance from which data has been extracted. However, Antonetti and Yovanovich,[8,12] Kang et al.,[11] and O'Callaghan et al.[6] did provide measurements of mean asperity slope. Analysis of the metrological information revealed a relationship betwen rms asperity slope and rms roughness, which is described by the expression

$$m \approx \sqrt{\sigma}/100$$

This relationshp was used in reducing data from those investigations lacking asperity slope measurements to the nondimensional form given by Antonetti and Yovanovich.[8] This expression is accurate to within approximately ±50% for all but the data of O'Callaghan et al.[6] The measured asperity slopes of O'Callaghan et al.[6] are considerably smaller than those predicted by the slope equation.

Translation of the prediction technique of O'Callaghan et al.[6] to the nondimensional form found in Antonetti and Yovanovich,[8] resulted in a family or group of parallel lines for the theory in Ref. 6. Since the prediction lines for these data were not widely separated, their average trace is shown in Fig. 1.

The two theories of O'Callaghan et al.[6] and Antonetti and Yovanovich,[8] are almost precisely colinear, however, their associated data extend over the high- and low-pressure regimes, respectively. Although the two theories for metallic coatings are accurate for their corresponding data, they both perform rather poorly for the majority of the data on such contacts extracted from other investigations; Chung et al.,[13] Fried and Kelly,[3] Kang,[11] and Mal'kov and Dobashin.[4] The two predictions overestimate the contact conductance by as much as a factor of 100. These discrepancies may be due in part to the fact that both of the theories implicitly assume that the contacting surfaces are perfectly flat, so they cannot account for the significant flatness deviations and waviness reported in some of the other studies. As the waviness or flatness deviations of a surface increase, its contact area decreases, thereby reducing the contact conductance. For example, specimens used by Mal'kov and Dobashin[4] exhibited variances from flatness of 5 to as great as 40 μm (0.0002–0.0016 in.). This last value is approximately 20 times larger than its associated roughness. This wide range of flatness may be the cause of the considerable scatter of the results from their experiments seen in Fig. 1. Fried and Kelly[3] listed the maximum flatness deviation as 3.8 μm (150 μin.). Although

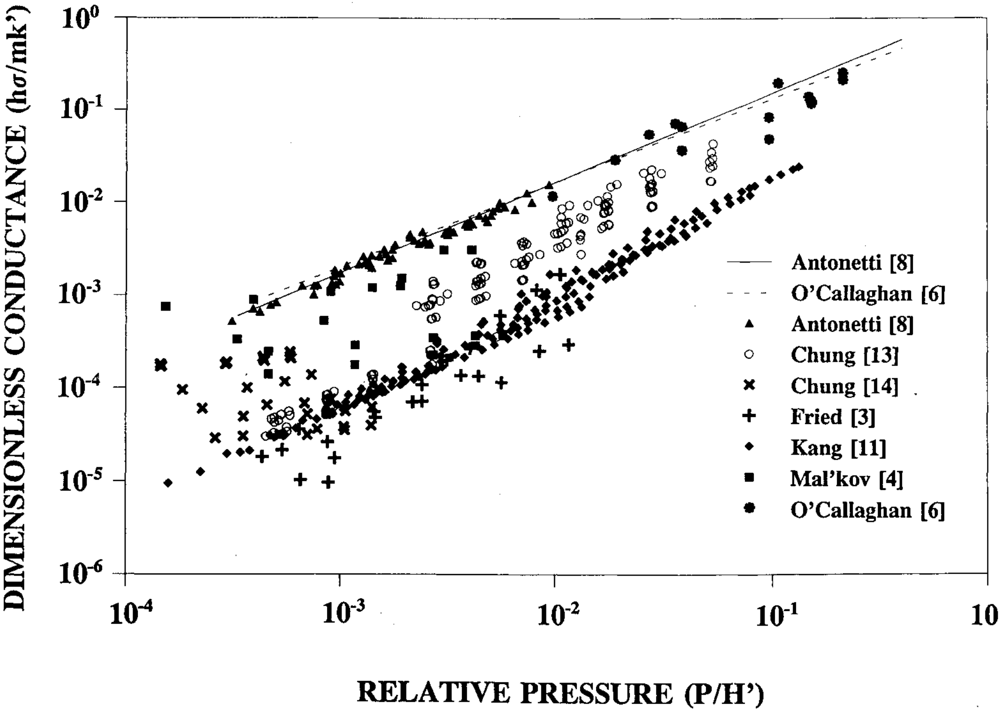

Fig. 1 Dimensionless thermal contact conductance vs relative pressure for metals with metallic coatings.

this value is approximately four times the associated rms surface roughness, it is unlikely that this alone could have caused the very low dimensionless conductances (nearly two orders of magnitude less than the theories) calculated for this set of experiments. Chung et al.[14] did not provide explicit values of flatness or waviness. However, some of the specimens they studied had turned surfaces, which usually exhibit significant deviations from flatness and waviness. Kang[11] listed waviness heights typically equal to 2.5 μm (98 μin.) for the turned aluminum surfaces examined.

The theories in O'Callaghan et al.[6] and Antonetti and Yovanovich[8] describe the upper bound of contact conductance, since they were developed for flat surfaces. The estimated contact conductances of coated contacts determined using these predictions will not be representative of real machined or ground surfaces (which may exhibit considerable flatness deviations and waviness) unless corrected by some appropriate factor to account for this waviness. No theory has been proven adequate for quantitatively evaluating the effect of surface flatness and waviness.

In order to assess the potential of the various coating materials for thermal enhancement applications, a contact conductance value of 3334 W/m^2K (587.2 $Btu/h\text{-}ft^2\text{-}°F$) has been selected. This value is reported to be typical for "standard electronic modules" installed in aluminum card rails, and is considered to be independent of the associated contact pressure and temperature.

The three very soft coatings (indium, tin, and lead) provide the greatest estimated increases in thermal contact conductance, however, lead is susceptible to galvanic corrosion in a marine environment when in contact with nickel-plated copper. Aluminum, magnesium, zinc, and cadmium coatings should improve the contact conductance, but these metals are also incompatible with nickel plating. Bismuth is not listed in the galvanic series, but is probably also incompatible.

Silver, gold, copper, palladium, platinum, rhodium, chromium, cobalt, tantalum, and, of course, nickel are all compatible with nickel-plated copper module cards. Vanadium and niobium are both probably compatible with nickel plating because they are almost completely surrounded in the periodic chart by metals that are compatible with nickel (i.e., chromium, molybdenum, tungsten, tantalum, and titanium). These harder metals (e.g., silver, gold, etc.) do not afford such large estimated improvements in contact conductance as do indium and tin.

It is likely that dissimilarities in electric potential of the proposed coatings with anodized aluminum are less severe than with the nickel-coated copper, because the low electrical conductivity of the anodized coating should greatly impede galvanic corrosion of the coating.

Conclusions and Recommendations

Although estimates indicate that indium is expected to provide the greatest enhancement of thermal contact conductance, its poor shear strength makes it susceptible to being worn with repeated removal and insertion. Tin is expected to be second in terms of increasing contact conductance. However, tin platings, when mechanically or thermally stressed, have been found to form "whiskers" in electronic components. Also, at temperatures below −18°C (0°F) tin platings deteriorate into a powder.

Of the remaining metals that are compatible with the nickel-plated copper, silver, gold, and copper are expected to provide far greater increases in contact conductance than the other materials. Since copper forms a light oxide and its thermal conductance is calculated to be slightly less than that of gold or silver, copper would likely be supplanted by one of the other two. Silver also tarnishes slightly, but its cost is a small fraction of that of gold. Both silver and gold are readily plated or deposited onto surfaces, and they are excellent choices for thermal enhancement coatings.

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