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Thermal Contact Conductance of Diamond-Like Films

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The reliability of electronic components may be improved by enhancing the thermal contact conductance at the interface of the chip and heat-spreader systems with diamond films. This investigation evaluated the effect of diamond-like films on the thermal contact conductance deposited on aluminum 6101-T6 and copper C11000-H03 in contact with bare aluminum A356-T61. A rigidizing layer of silicon nitride, 3 μm thick (120 μin.), was deposited prior to the ion beam diamond-like carbon deposition. For a diamond-like coating deposited on silicon nitride/aluminum 6101-T6 in contact with bare aluminum A356-T61, the thermal contact conductance varied from 145.7 to 1525.6 W/m²K (25 to 268.69 Btu/h ft² °F) with the highest conductance resulting from the 1-μm-(40-μin.-) thick film. For diamond-like coatings deposited on silicon nitride/copper C11000-H03 in contact with bare aluminum A356-T61, the thermal contact conductance varied from 204.0 to 2031.5 W/m²K (35 to 350 Btu/h ft² °F) for the test parameters employed. Similar to diamond-like coatings deposited on silicon nitride/aluminum 6101-T6, the highest conductance was measured for a diamond-like film thickness of 1 μm (40 μin.) with the conductance significantly decreasing with increasing film thickness.

Nomenclature

D = root mean square slope
F = flatness
H = hardness
h = thermal conductance
k = thermal conductivity
R = roughness
t = film thickness
W = waviness

Subscripts
a = average
c = coated, coating
q = root mean square
s = substrate
u = uncoated

Introduction

INCREASED emphasis on the reliability of electronic components for many applications suggests the need for techniques to predict the temperature change across the component interface, as well as chip and heat-spreader systems. As a consequence, there is a continuing search for materials suitable for thermal enhancement in microelectronic applications.

Recent advances in the development of diamond film deposition techniques have resulted in a number of potential new applications for diamond materials in the field of microelectronics, because of their extremely high thermal conductivity, corrosion and erosion resistance, and low friction. Free-standing diamond films can be used in high-power electronic packages as a thermal spreader material. Diamond films, then, may lead to a whole new generation of microelectronic components and systems, with higher performance and longer life.

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Blanchard et al.[1] conducted a comprehensive review of the literature for synthetic single crystal, polycrystalline, and type I and II natural diamond materials. Experimental data obtained by a number of different investigators were evaluated and prepared in graphical form for comparison. Based on the evaluation, it was noted that the thermal conductivity of synthetic diamond was found to depend on crystal size at lower temperatures, and on hydrogen impurity at higher temperatures. A number of other impurities were also found to affect the thermal conductivity of chemical vapor deposited (CVD) diamond film including graphite content, amorphous carbon content, and carbon hydrides. In terms of natural diamond, the thermal conductivity was found to depend primarily on either the nitrogen impurity concentration or the Umklapp processes. Further, the thermal conductivity for natural diamonds depends on crystal size and surface condition at the lower temperatures and on nitrogen content at the higher temperatures. Clearly, synthetic diamond and diamond-like films appear to be ideal for microelectronic applications.

The temperature change across a diamond film or a composite material incorporating diamond films is of significant importance to thermal designers. While the thermal conductivity of diamond materials may be high, the interfacial resistance associated with diamond films in contact with other materials appears to be of significant importance. As a consequence, this article will describe the results of an experimental investigation to determine the thermal contact conductance of diamond-like carbon coatings on aluminum 6101-T6 and copper C11000-H03 materials. A more detailed description of this investigation was reported by Marotta et al.[2]

The thermal contact conductance h_c of a junction is defined by the relationship

$$h_c = (Q/A)/(T_1 - T_2) = (Q/A)/\Delta T \tag{1}$$

The temperatures of the bounding surfaces of the contact are T_1 and T_2, and Q/A is the heat flow per unit area, as shown in Fig. 1. The temperature difference across the interface includes the effect of any interstitial materials incorporated in the joint. The thermal contact conductance between the diamond-like material and the prime surfaces may be derived from the overall thermal conductance from the following expression:

$$1/h_c = (1/h_{cc}) + (t/k) \tag{2}$$

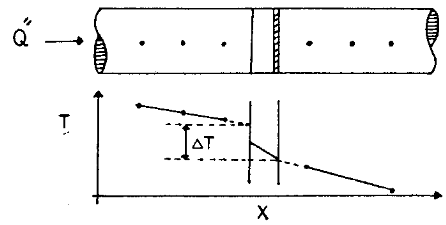

Fig. 1 Schematic of a metallic junction with an interstitial bonded film.

where h_{cc} is the contact conductance between the diamond-like film and prime surface, and t/k is the bulk resistance of the diamond material, assuming that the thermal resistance between the molecular bonded diamond film and substrate is negligible. Based on the assumption that the thermal conductivity is the same for the diamond material at the same temperature and that the overall thermal conductance varies with the thickness, it is then possible to determine derived values for the thermal contact conductance, such that

$$h_{cc} = \frac{1}{(1/h_{c1}) - (t_1/k)} = \frac{1}{(1/h_{c2}) - (t_2/k)} \tag{3}$$

The thermal contact conductance between the diamond film and prime surface may be determined using the results of several different thickness coatings.

Experimental Program

The experimental investigation was conducted in a manner similar to previously reported investigations.[2–5] The facility, diamond material deposition, and experimental procedure are described in this section.

Experimental Facility

The experimental test facility used in this investigation was similar to those used by previous investigators[3–6]: a vertical cylindrical column under axial load located within a high-vacuum system (approximately 10^{-5} torr). The fixtures that hold the specimens were each equipped with a 1000-W Watlow thin-band heater and integral cooling passages through which refrigerated ethylene glycol from a constant temperature bath was circulated. This facility allows the heat flux to be directed in either direction through the column, depending upon which heater and cooling passages were activated. The apparent interfacial pressure was controlled by pressurizing a gas bellows attached to the lower support plate of the frame. To ensure uniform loading of the test interfaces, loading was transmitted to the specimen fixtures through two stainless steel ball bearings. The cooling passages were supplied by flexible hoses so as to eliminate any torque to the test column that would create a bending moment and result in uneven interfacial loading. The load was measured by a 453.6-kg (1000-lb) capacity interface load cell that has been dead-weight calibrated over the load range of interest, 0–45.4 kg (0–100 lb).

The vacuum was maintained by an Alcatel 2300 roughing pump in series with a Varian VHS-6 oil diffusion pump. The vacuum level was measured with a Monitor 2000 ion gauge controller. The test specimens were surrounded by a cylindrical passive radiation shield lined with highly reflective aluminum foil. The shield contains ring-shaped inserts located adjacent to the specimen interfaces to reduce radiation exchange between specimens.

Material

The base materials and surface finishes specified for this research investigation were as follows:

Aluminum

Aluminum alloy 6101-T6, extrusion base material: the surface finish was maintained at 0.60 μm (24 μin.) and a surface flatness of 50 μm (2000 μin.). The surface treatments were 0.25-μm (10-μin.) sputtered Ni, 3-μm (120-μin.) Si_3N_4, and 1–5 μm (40–200 μin.) of diamond-like carbon.

Copper

Copper alloy C11000-H03 temper: the surface roughness was 0.6 μm (24 μin.) with surface flatness of 250 μm (10,000 μin.). The surface treatments were similar to those maintained for aluminum alloy 6101-T6.

Aluminum Fluxmeters

Aluminum alloy A356-T61 solution heat treated and aged: the surface roughness and flatness were maintained at 0.60 μm (24 μin.) and 50 μm (2000 μin.) respectively, to be consistent with the specified surfaces. The surfaces were bare since this research investigation focused on the contact conductance between diamond-like carbon (DLC) and the other two alloys.

Once the materials had been heat treated to required conditions, the various cylindrical test samples were then machined for further evaluation and testing.

Sample Preparation

All test specimens were 2.54 cm (1.0 in.) in diameter. The specimens that were inserted into both the upper and lower fixtures were fabricated from A356-T61 aluminum. Both were 10.16 cm (4 in.) in length, as this was calculated to be a length sufficient to ensure one-dimensional heat flux. Both ends of the A356-T61 specimens were left bare. Inserted between the two bare specimens was a 3.76-cm- (1.5-in.-) long sample of aluminum 6101-T6 or copper C11000-H03 that was coated on one end with sputtered silicon nitride and then with diamond-like carbon. The ends of the 6101-T6 or C11000-H03 specimen were either bare or coated with approximately 1–5 μm (40–200 μin.) of ion beam deposited diamond-like carbon. The diamond-like film was deposited directly on a 3-μm- (120-μin.-) thick coating of silicon nitride that acted as a rigidizing layer to prevent cracking of the film.

All specimens were instrumented with five chromel-alumel (type K) Teflon®-coated American wire gauge 30 thermocouples. These thermocouples were special limit of error ($\pm$1.1°C, one-half normal) grade. The thermocouples were inserted into holes in the specimens drilled to their axes with a no. 56 drill at 0.635-cm (0.25-in.) intervals along the specimen axes. Metallic (aluminum or copper) powder is tamped into each hole to ensure that the thermocouple bead provides a truly representative reading of the temperature in the material surrounding the hole. The thermocouples were connected to a Hewlett–Packard 3497A data acquisition control unit and an IBM compatible computer.

The thermal conductivity for each of the three base materials (A356-T61, 6101-T6, and C11000-H03) was previously measured and reported by Lambert and Fletcher,[5] and was not replicated for this study since the specimen material was from the same stock.

Surface Measurements

The surfaces of the aluminum and copper samples were characterized prior to deposition of the silicon nitride and the diamond film. In addition, the surface characteristics of the aluminum A356-T61 flux meters were also determined. These surface profiles were measured using a Surfanalyzer 5000/400 manufactured by Federal Products Corporation. A complete surface characterization was conducted, including rms surface roughness, average and rms waviness, and the overall flatness deviation. A summary of the measurements is provided in Table 1.

Table 1 Thermal conductivity, Vickers microhardness, and surface metrological data

Specimens	Coating	K_s/K_u[a]	H_u/H_c[b]	t, μm	t, μin.	R_a, μm	D_q, rad	W_a, μm	W_q, rad	F, μm
A356-F1	Bare	150/——	128/——	0	0	0.64	0.155	0.311	0.004	7.15
A356-F2	Bare	150/——	128/——	0	0	0.65	0.161	0.43	0.004	8.15
6101-S7	Bare	201/——	42/——	0	0	0.62	0.142	1.04	0.004	9.35
6101-11B	Si_3N_4	201/——	42/185	3	120	0.49	0.159	1.89	0.005	15.61
6101-11B	DLC[c]	201/——	42/——	1	40	0.51	0.147	1.83	0.005	13.21
6101-9B	DLC	201/——	42/1429	3	120	0.45	0.144	1.72	0.004	12.21
6101-3B	DLC	201/——	42/——	5	200	0.42	0.123	1.31	0.004	11.85
C1100-9A	Bare	389/——	56/——	0	0	0.36	0.114	0.25	0.003	3.88
C1100-1A	Si_3N_4	389/——	56/185	3	120	0.38	0.125	2.18	0.005	13.01
C1100-9A	DLC	389/——	56/——	1	40	0.26	0.106	0.73	0.003	5.95
C1100-5A	DLC	389/——	56/1476	3	120	0.32	0.116	1.26	0.003	8.15
C1100-7A	DLC	389/——	56/——	5	200	0.31	0.097	0.961	0.003	7.61

[a]K_s/K_u units are W/m K @ 25°C. [b]H_u/H_c units are kg/mm². [c]Values for DLC are @ 50 gmf.

Surface Coating

Once the surfaces were prepared, each test surface was coated with a 3-μm (120-μin.) layer of silicon nitride. The sputtered coating was necessary to assure that the surface was sufficiently stable for deposition of a diamond film.

The diamond-like films were prepared by a direct ion beam deposition from which carbon-containing ions of controlled composition, energy, and flux were directed onto the substrate. Since the substrate was isolated from the plasma in the ion beam deposition, the metallic substrates were not subjected to bombardment by high-energy electrons, and interaction with radiation from the plasma was reduced. The net result was a reduced substrate temperature, which subsequently lowers the occurrence of annealing the base metal.

The deposition was conducted in a cryopumped CHA Mark 50 stainless steel vacuum chamber. The chamber pressure was reduced to 5×10^{-6} torr prior to deposition and the vacuum pressure increased to the range of 1×10^{-4} torr during deposition. A single 11-cm (4.33-in.) ion beam source was used for Ar^+ ion precleaning of the substrates and deposition of diamond-like carbon. The ion beam energy used can coat several substrates to a thickness uniformity to $\pm 1.5\%$.

Microhardness Measurement

Base Materials

The Vickers microhardness of the two base materials coated with the diamond-like film was measured for two specimens, each with a nominal surface roughness of 0.5 μm (24 μin.). These specimens were tested over a range of indentor loads from 10- to 1000-*g* force.

DLC- and Si_3N_4-Coated Materials

The Vickers microhardness was measured for silicon nitride-coated aluminum, diamond-like coated aluminum, and diamond-like coated copper surfaces over a range of indentor loads from 10- to 1000-*g* force. The microhardness measurements as a function of indentor load are presented in Figs. 2–4.

The Vickers hardness number (VHN) for the silicon nitride-coated aluminum 6101-T6 measurement is for a coating thickness of 3 μm (120 μin.). The microhardness generally decreases with increasing indentor load and equals that of the base material at the higher load.

Experimental Procedure

Successive tests were conducted with varying thicknesses of diamond-like carbon. The coated samples were inserted in the test facility and carefully aligned. A slight axial force was then applied to the heat fluxmeters to ensure that the surfaces remained in contact during the evacuation of the chamber. The temperature was set by adjusting the heat meter to the required power and data were recorded when the fluxmeter temperatures did not vary more than 0.3°C over a 1-h period. Thermal equilibrium occurred in a period of 6–8 h.

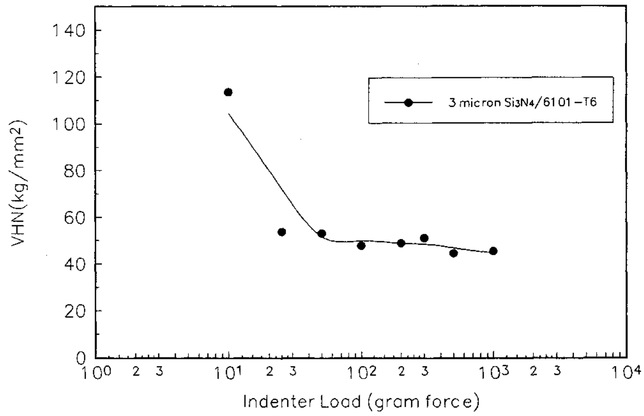

Fig. 2 Vickers microhardness of silicon nitride-coated aluminum alloy 6101-T6 as a function of indentor load.

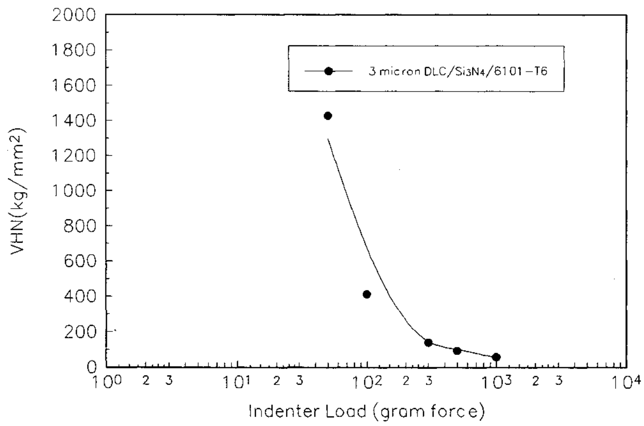

Fig. 3 Vickers microhardness of diamond-like carbon deposited on silicon nitride/6101-T6 as a function of indentor load.

Experimental data were obtained utilizing a Hewlett–Packard datalogger system and the gradients and thermal conductivity of the heat fluxmeters were used to determine the heat fluxes in both the upper and lower fluxmeters.

A 6101-T6 or C11000-H03 specimen was placed between two A356 specimens and an alignment fixture was then clamped around all three specimens. An adjustment nut on the top plate was turned to bring all specimens into contact and a preload of 862 kPa (125 psi) was applied. The alignment fixture was then removed. The radiation shield was placed around the test specimens and positioned so as not to come in contact with the specimens, which would then behave as a heat sink.

The test chamber was evacuated to a vacuum of 1×10^{-5} torr or lower. Upon reaching the desired vacuum level, the power to the heater was turned on and the heat sink tem-

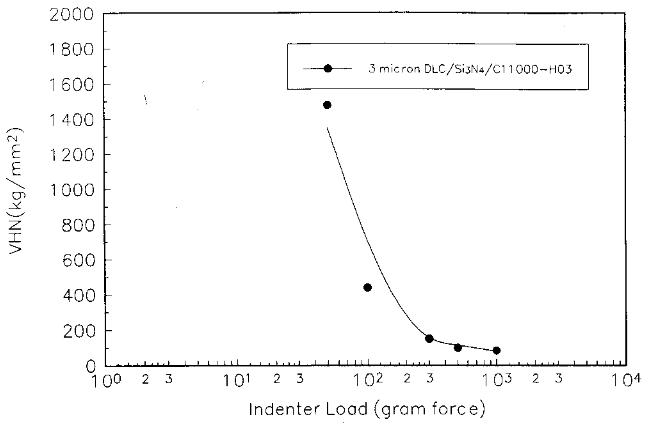

Fig. 4 Vickers microhardness of diamond-like carbon deposited on silicon nitride/C11000-H03 as a function of indentor load.

perature was set. The samples were allowed to out-gas for approximately 6–8 h.

Data Analysis

Once the test column reached a steady-state temperature profile, as defined in the experimental procedure section, a data retrieval and analysis program was executed. The program gathers temperature data, load data, and voltage input, and computes the heat flux through both test samples. The heat flux was computed using the temperature gradients obtained by a linear least-squares-fit of the temperature, and the thermal conductivities are calculated using the thermal conductivity correlation and interpolation program, as developed by Lambert and Fletcher.[5] The heat flux across each junction was computed as the average of the heat flux through the specimens on either side of the interface. The temperature drop across the interface was obtained by extrapolating the temperatures within the specimens on either side of the interface. The contact conductance was computed to be the average heat flux across the interface divided by the change in temperature across the junction.

Uncertainty Analysis

The uncertainties in the various quantities that are used in calculating contact conductance can be combined to determine the overall relative uncertainty in the reported conductance data. A detailed analysis of the uncertainty of the thermal conductivity of the base materials, temperature gradient, and temperature discontinuity at the interface are discussed by Lambert and Fletcher.[7]

The relative uncertainty in the contact conductance consists of the uncertainty in the thermal conductivities of the base materials, the temperature gradients, and the temperatures across the junctions. For each type of contact pair the average uncertainties in the conductivity and gradient of both members of the contacting pair are used in error calculations.

The overall relative uncertainty of the contact conductance of silicon nitride to bare A356 junction is 4.8%, while that for diamond-like carbon/6101-T6 to bare A356 contact is 4.8%. The average uncertainty for diamond-like carbon/C11000-H03 to bare A356 contact is 13.6%. The technique used to calculate the uncertainties has been described by Kline and McClintock.[8]

Results and Discussion

This article presents unpublished thermal contact conductance results for diamond-like carbon coatings. Experimental tests of these materials ranged from 0.172 to 0.862 MPa (25 to 125 psi) and interface temperatures from 25 to 100°C (77 to 212°F) to encompass the range of pressures and temperatures generally experienced in electronic components.

To improve the thermal performance of interfaces that exist in microelectronic packages, an experimental study was undertaken to determine the merits of using diamond-like carbon films for the enhancement of contact conductance. This investigation involves the experimental determination of the contact conductance for diamond-like coatings on aluminum 6101-T6 and copper C11000-H03 to aluminum alloy 356-T61 (bare) material. This data can then be compared to results obtained for anodized surfaces of aluminum 6101-T6 and electroless nickel-plated copper C11000-H03 as reported by Lambert and Fletcher.[4]

Microhardness of Aluminum, Copper, Silicon Nitride, and Diamond-Like Carbon

The Vickers microhardness of the two base materials was measured for two specimens from each material and each had a nominal surface roughness of 0.62 and 0.26 μm, respectively, for aluminum 6101-T6 and copper C11000-H03. The microhardness for each material remained well below published data. The lower than expected values can be attributed to an annealing process that may have occurred during the sputtering process for both nickel and silicon nitride. Higher temperatures from each respective process will cause internal strain relief within the metals themselves and thus cause lower microhardness, as shown in Table 1.

The effect of the silicon nitride layer deposited prior to the diamond-like carbon deposition was to help reduce eventual cracking of the hard diamond-like layer under possibly large bending strains. This layer is deposited in a separate system by a sputtering method from a silicon nitride source. A plot of mean microhardness as a function of increasing indentor load is shown in Fig. 2 for a 3-μm (120-μin.) layer of silicon nitride deposited on aluminum 6101-T6. A sharp increase in the microhardness is observed as the indentor load is decreased, which reflects the material properties of the silicon nitride layer. The bulk hardness of the aluminum substrate is observed at the higher indentor loads, which correlate well with measured values, as shown in Table 1.

The effective microhardness of the film has a direct influence to the contact conductance, thus, Vickers microhardness measurements were taken for diamond-like carbon [3 μm (120 μin.)] deposited on silicon nitride/6101-T6 and diamond-like carbon [3 μm (120 μin.)] deposited on silicon nitride/C11000-H03 substrates. Figures 3 and 4 show Vickers microhardness as a function of increasing indentor loads [50–1000 grams force (gmf)] for the diamond-like carbon film for each base material. The curves show an exponential increase in the microhardness with decreasing indentor load up to a maximum observable value of 1429.0 and 1476.0 kg/mm^2, respectively, for diamond-like carbon on aluminum and copper C11000-H03. These values correlate well with hardness values obtained by Savvides and Bell[9] for diamond-like films grown by low energy ion-assisted deposition. The authors increased the ion energy from 29 to 67 eV per carbon atom,[6] corresponding to a hardness increase from 1220 to 3060 kg/mm^2.

Baseline Contact Conductance for Silicon Nitride

The effect of the silicon nitride layer on the contact conductance must be known prior to the deposition of the diamond-like coating, thus, the contact conductance for two samples with varying thicknesses [1 and 3 μm (40 and 120 μin.)] was measured. This effect must then be subtracted from the overall contact conductance for the film structure to determine the true effect of the addition of the diamond-like coating.

The thermal contact conductance data for silicon nitride on aluminum 6101-T6 to bare aluminum A356-T6 varies from 200 to 2800 W/m^{2}K (35 to 492.8 Btu/h ft^2 °F) over the range of parameters tested (Figs. 5 and 6). The magnitude of these conductance values is surprising, considering the low thermal conductivity of bulk silicon nitride [9–30 W/m-K at 400 K

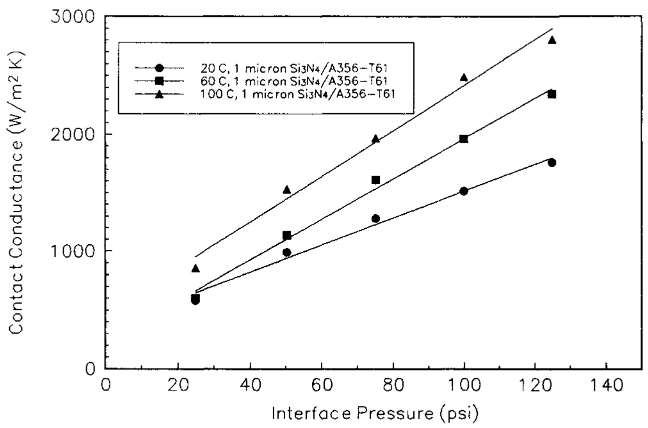

Fig. 5 Thermal contact conductance as a function of pressure and temperature for a 1-μm silicon nitride film thickness deposited onto aluminum 6101-T6 to uncoated aluminum alloy A356-T61.

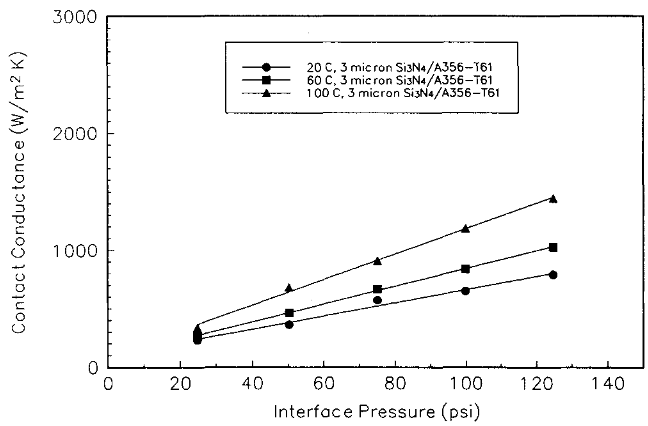

Fig. 6 Thermal contact conductance as a function of pressure and temperature for a 3-μm silicon nitride film thickness deposited onto aluminum 6101-T6 to uncoated aluminum alloy A356-T61.

(5.2–17.3 Btu/h ft °F)], which may limit the heat transfer, however, the relatively thin coating thicknesses may negate this factor.

The thermal contact conductance increases linearly with decreasing silicon nitride thickness, with the 1-μm (40-μin.) coating exhibiting the highest values. The decrease in contact conductance must be attributed to increases in bulk mass of silicon nitride and its corresponding influence in material properties (hardness and thermal conductivity), which occurs when the coating thickness is increased from 1 μm (40 μin.) to 3 μm (120 μin.). No comparison can be made to other investigations since experimental contact conductance data cannot be found.

Diamond-Like Contact Conductance on Aluminum

The thermal contact conductance data for the DLC coating on silicon nitride/aluminum 6101-T6 in contact with bare aluminum A356 are shown in Figs. 7–9. Three different thicknesses of ion beam deposited DLC were tested for the purpose of determining the optimum thickness.

In the case of the DLC deposited on silicon nitride/aluminum 6101-T6 to bare aluminum A356-T6, the thermal contact conductance varied from 145.70 to 1525.60 W/m^{2}K (25 to 268.69 Btu/h ft^2 °F) over the range of parameters tested. The thermal contact conductance is significantly decreased by increasing the coating thickness to 5 μm. The surface characteristics were similar for all three diamond-like coatings on aluminum 6101 surfaces in contact with bare aluminum A356, thus, surface parameter differences had no influence on the decrease in thermal contact conductance with increasing thickness.

The thermal contact conductance data for the 1-μm coating of diamond-like carbon in junction with bare aluminum A356 exhibits a slight increase when compared to silicon nitride/aluminum 6101-T6 in junction with bare aluminum A356, but exhibits a significant decrease in thermal contact conductance with the 3- and 5-μm coating thicknesses. The decrease in thermal contact conductance with increasing thicknesses can

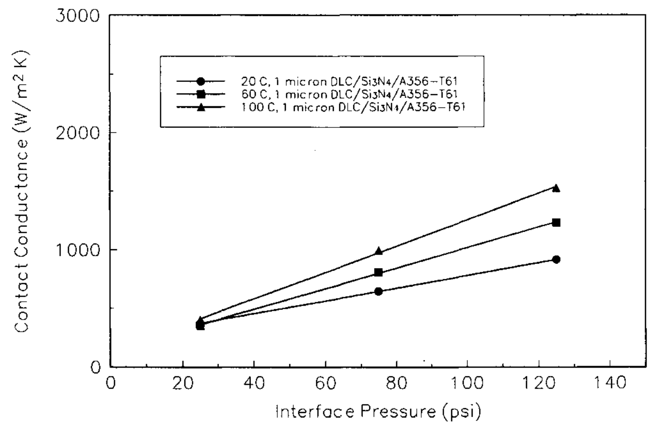

Fig. 7 Thermal contact conductance as a function of pressure and temperature for 1-μm diamond-like carbon deposited onto silicon nitride/6101-T6 to uncoated aluminum alloy A356-T61.

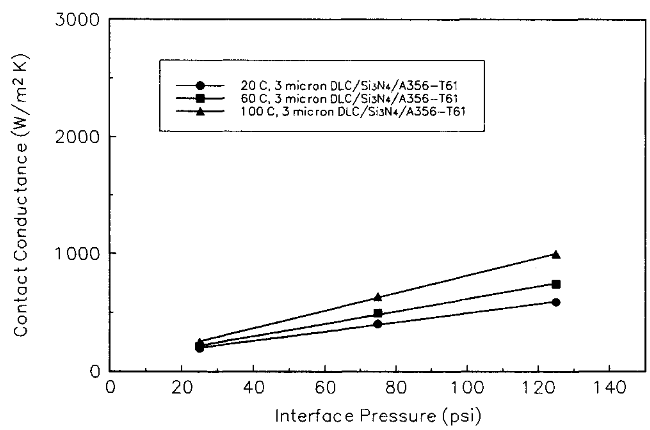

Fig. 8 Thermal contact conductance as a function of pressure and temperature for 3-μm diamond-like carbon deposited onto silicon nitride/6101-T6 to uncoated aluminum alloy A356-T61.

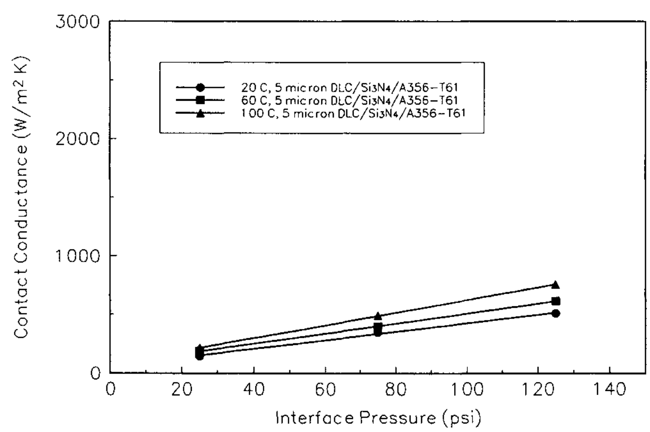

Fig. 9 Thermal contact conductance as a function of pressure and temperature for 5-μm diamond-like carbon deposited onto silicon nitride/6101-T6 to uncoated aluminum alloy A356-T61.

be attributed to the greater influence of the diamond-like properties exhibited by the coating. One such property is the higher surface microhardness (1429 kg/mm^2 for a 3-μm coating), which would allow less plastic deformation, which results in less surface contact area. The conductance of the 1-μm junction increases significantly as the junction temperature is increased from 60 to 100°C and the interface pressure is increased from 0.516 to 0.862 MPa (75 to 125 psi), whereas the same influence is not seen for the 5-μm coating.

Diamond-Like Contact Conductance on Copper

The thermal contact conductance data for the diamond-like carbon coating to silicon nitride/C11000-H3 in junction with bare aluminum A356 are presented in Figs. 10–12. Similar to the aluminum 6101-T6 investigation three different thicknesses of ion beam-deposited DLC were tested for the purpose of determining the optimum thickness.

For DLC deposited on silicon nitride/copper C11000-H3 to bare aluminum A356, the thermal contact conductance varied from 204.0 to 2031.5 W/m^{2}K (35 to 350 Btu/h ft^2 °F) for the test parameters employed. The effect on thermal contact conductance for DLC deposited on silicon nitride/copper C11000-H3 for increasing film thickness was similar to that of DLC deposited on silicon nitride/aluminum 6101-T6, where the higher thickness caused a decrease of the measured values. However, the thermal contact conductance values measured for DLC deposited on silicon nitride/copper C11000-H3 were 24–40% higher than DLC deposited on silicon nitride/aluminum 6101-T6 samples, but this may be due to the higher heat fluxes through the stack caused by the higher thermal conductivity

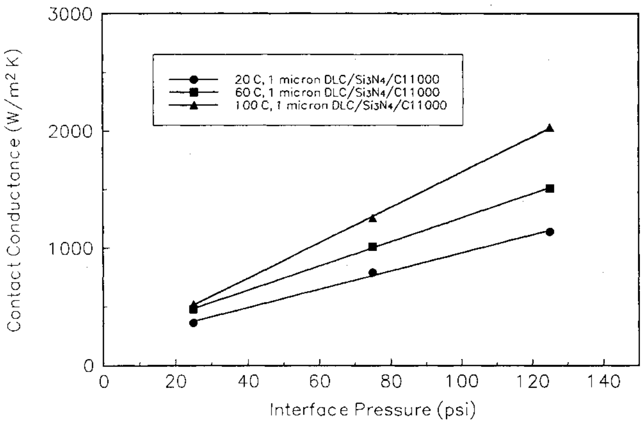

Fig. 10 Thermal contact conductance as a function of pressure and temperature for 1-μm diamond-like carbon deposited onto silicon nitride/C11000-H03 to uncoated aluminum alloy A356-T61.

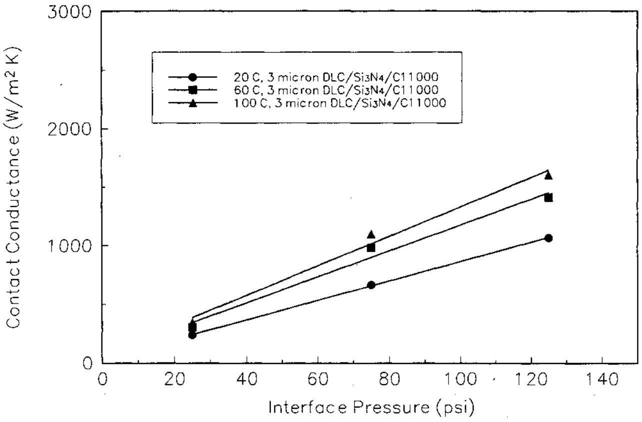

Fig. 11 Thermal contact conductance as a function of pressure and temperature for 3-μm diamond-like carbon deposited onto silicon nitride/C11000-H03 to uncoated aluminum alloy A356-T61.

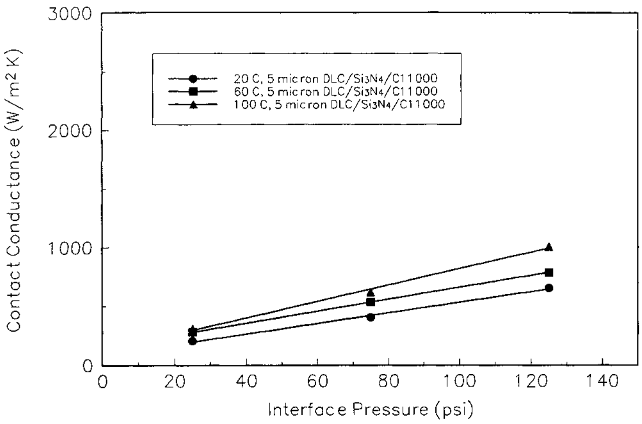

Fig. 12 Thermal contact conductance as a function of pressure and temperature for 5-μm diamond-like carbon deposited onto silicon nitride/C11000-H03 to uncoated aluminum alloy A356-T61.

of the copper substrate. The same trend in surface measurements was observed for the copper samples as well as for the aluminum samples, thus, surface characteristics had no influence on conductance. The thermal contact conductance data for the DLC coating to silicon nitride/aluminum 6101-T6 in contact with bare aluminum A356 are shown in Figs. 10–12.

Conclusions and Recommendations

The reliability of electronic components may be improved by decreasing overall component temperatures. This may be accomplished by enhancing the thermal contact conductance at the interface of the chip and heat-spreader systems. Advances in diamond-like film deposition techniques have resulted in a number of potential new applications in the field of microelectronics. This investigation evaluated the effect of diamond-like films on the thermal contact conductance deposited on aluminum 6101-T6 and copper C11000-H03 in junction with bare aluminum A356-T61. To reduce cracking of the hard diamond-like layer under possibly large bending strains, a rigidizing layer of silicon nitride, 3 μm thick (120 μin.), was deposited by a sputtering method prior to ion beam diamond-like carbon deposition. The effect of the silicon nitride layer on the contact conductance for aluminum 6101-T6 in junction with bare aluminum A356-T6 varied from 200 to 2800 W/m^{2}K (35 to 492.8 Btu/h ft^2 °F) over the range of parameters tested. In the case of the diamond-like coating deposited on silicon nitride/aluminum 6101-T6 to bare aluminum A356-T61, the thermal contact conductance varied from 145.7 to 1525.6 W/m^{2}K (25 to 268.69 Btu/h ft^2 °F), with the highest thermal contact conductance resulting from the 1-μm- (40-μin.-) thick film. For diamond-like coatings deposited on silicon nitride/copper C11000-H03 to bare aluminum A356-T61, the thermal contact conductance varied from 204.0 to 2031.5 W/m^{2}K (35 to 350 Btu/h ft^2 °F) for the test parameters employed. The highest thermal contact conductance values were measured for a diamond-like film thickness of 1 μm (40 μin.).

The influence of the diamond-like carbon properties, such as surface microhardness, can be inferred from the decrease in thermal contact conductance with increase in thickness. The thermal contact conductance data decreased for the higher thicknesses of DLC coating when compared to the sample with only 3 μm (120 μin.) of silicon nitride deposited on aluminum 6101-T6. However, the thermal contact conductance data showed an increase for the DLC coating of 1 μm (40 μin.), which must also infer a lower surface microhardness in comparison to the silicon nitride layer or the bare aluminum A356 surface. Thus, the optimum thickness for the thermal contact conductance was a coating thickness of 1 μm (40 μin.) of DLC when deposited on 3 μm (120 μin.) of silicon nitride.

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References

[1]Blanchard, D. G., Marotta, E. E., and Fletcher, L. S., "A Survey of the Thermal Conductivity of Synthetic and Natural Diamond Materials," AIAA Paper 92-0708, Jan. 1992.

[2]Marotta, E. E., Blanchard, D. G., and Fletcher, L. S., "A Review of Thermal Contact Conductance of Silicon Nitride and Diamond-Like Films," Conductance Heat Transfer Lab., Dept. of Mechanical Engineering, Texas A&M Univ., Rept. CHTL-6770-12, College Station, TX, Jan. 1993.

[3]Stevenson, P. F., Peterson, G. P., and Fletcher, L. S., "Thermal Rectification in Similar and Dissimilar Metal Contact," *Journal of Heat Transfer*, Vol. 113, No. 1, 1991, pp. 30–36.

[4]Fletcher, L. S., and Sparks, T. H., "Thermal Contact Conductance of Porous Ceramic Materials," *Proceedings of the NSF/DITAC Workshop on Thermal Conduction Enhancement in Microelectronics*, edited by A. Williams, Monash Univ., Melbourne, Australia, 1992, pp. 71–77.

[5]Lambert, M. A., and Fletcher, L. S., "Metallic Coatings for Enhancing the Thermal Contact Conductance of Electronic Modules," *Journal of Thermophysics and Heat Transfer*, Vol. 8, No. 2, 1994, pp. 341–348.

[6]Fletcher, L. S., Blanchard, D. G., and Kinnear, K. P., "Thermal Conductance of Multilayered Metallic Sheets," *Journal of Thermophysics and Heat Transfer*, Vol. 7, No. 1, 1993, pp. 120–126.

[7]Lambert, M. A., and Fletcher, L. S., "Thermal Enhancement Techniques for SEM Guide Ribs and Card Rails," Conduction Heat Transfer Lab., Dept. of Mechanical Engineering, Texas A&M University, Rept. CHTL-6770-6, College Station, TX, Jan. 1992.

[8]Kline, S. J., and McClintock, F. A., "Describing Uncertainties in Single-Sample Experiments," *Mechanical Engineering*, Vol. 75, No. 1, 1953, pp. 3–8.

[9]Savvides, N., and Bell, T. J., "Microhardness and Young's Modulus of Diamond and Diamond-Like Carbon Films," *Journal of Applied Physics*, Vol. 72, No. 7, 1992, pp. 2791–2796.