

Die Attachment for -120°C to $+20^{\circ}\text{C}$ Thermal Cycling of Microelectronics for Future Mars Rovers—An Overview¹

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Active thermal control for electronics on Mars rovers imposes a serious penalty in weight, volume, power consumption, and reliability. Thus, we propose that thermal control be eliminated for future rovers. From a functional standpoint there is no reason that the electronics could not operate over the entire temperature range of the Martian environment, which can vary from a low of $\approx -90^{\circ}\text{C}$ to a high of $\approx +20^{\circ}\text{C}$ during the Martian night and day. The upper end of this range is well within that for conventional electronics. Although the lower end is considerably below that for which conventional—even high-reliability—electronics is designed or tested, it is well established that electronic devices can operate to such low temperatures. The primary concern is reliability of the overall electronic system, especially in regard to the numerous daily temperature cycles that it would experience over the duration of a mission on Mars. Accordingly, key reliability issues have been identified for elimination of thermal control on future Mars rovers. One of these is attachment of semiconductor die onto substrates and into packages. Die attachment is critical since it forms a mechanical, thermal, and electrical interface between the electronic device and the substrate or package. This paper summarizes our initial investigation of existing information related to this issue, in order to form an opinion whether die attachment techniques exist, or could be developed with reasonable effort, to withstand the Mars thermal environment for a mission duration of approximately one earth year. Our conclusion, from a review of literature and personal contacts, is that die attachment can be made sufficiently reliable to satisfy the requirements of future Mars rovers. Moreover, it appears that there are several possible techniques from which to choose and that the requirements could be met by judicious selection from existing methods using hard solders, soft solders, or organic adhesives. Thus, die attachment does not appear to be a roadblock to eliminating thermal control for rover electronics. We recommend that this be further investigated and verified for the specific hardware and thermal conditions appropriate to Mars rovers. [DOI: 10.1115/1.1347996]

Introduction and Background

Mars rovers, like most other spacecraft, use active thermal control to maintain the electronics within “traditional” temperature limits. Eliminating this thermal control could provide several major benefits: (1) reduced launch weight and volume of the payload (directly as well as indirectly from reduced power consumption and control requirements), (2) enhanced maneuverability of the rover due to weight and size reduction, (3) enhanced operating time from elimination of the power consumed by the thermal control system, (4) better overall reliability due to absence of reliability issues associated with the thermal control system, (5) reduced overall cost. Use of passive rather than active thermal control is possible, but this would still result in a weight and volume penalty; moreover, passive control might be unable to maintain the electronics within the desired temperature range. Thus the best solution seems to be adoption of electronics that can withstand the entire Mars environmental temperature range.

It has been extensively demonstrated that electronics can operate over the entire temperature range seen by a Mars rover and

beyond. There is considerable experience with many types of electronic components and subsystems for low temperatures:

- Spacecraft: The Infrared Astronomical Satellite, Infrared Space Observatory, Infrared Telescope in Space, and others used electronics operating at cryogenic temperatures ($\approx -150^{\circ}\text{C}$ and below) and additional spacecraft are planned that incorporate cryogenic electronics.
- Computers: ETA built computers with Si ICs operating in liquid nitrogen (-196°C); IBM developed packaging and interconnections for a Josephson-junction computer to operate at liquid-helium temperature ($\approx -269^{\circ}\text{C}$).
- Microwave receivers: the NASA Deep Space Network and radio astronomy receivers use semiconductor electronics operating at $\approx -260^{\circ}\text{C}$.
- Signal-processing systems: readout electronics for particle physics instrumentation operates at liquid-argon temperatures ($\approx -186^{\circ}\text{C}$) and below.
- Infrared arrays: complex readout ICs coupled to infrared detector arrays operate at a variety of cryogenic temperatures.

This experience demonstrates the ability of electronics of many types to operate at low temperatures, easily covering the Mars rover range. Regarding reliability, a General Electric group mentions that multichip modules survived 1000 cycles between -200°C and $+155^{\circ}\text{C}$ [1,2]. However, for most of the applications listed above the number of temperature cycles is much fewer. Also, formal low-temperature reliability data are scarce.

¹This paper, in its original form, was presented at the Pacific Rim/ASME International Intersociety Electronic Packaging Conference InterPACK '99 and published in the Proceedings: *Advances in Electronic Packaging—1999*, EPP Vol. 26-2, pp. 1399–1405.

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Contributed by the Electrical and Electronic Packaging Division for publication in the JOURNAL OF ELECTRONIC PACKAGING. Manuscript received at ASME Headquarters October 20, 2000. Associate Editor: R. Schmidt.

Table 1 Guide to low-temperature/cryogenic information in references. Notes: RT=room temperature; ●=some information, ●●=more information

Materials	Temperature (°C)	Thermal cycling	Mechanical properties	Fracture/Interface analysis	Thermal/mechanical modeling	Coefficient of thermal expansion	Micro-structure	Other	References
"Soft" Solders									
Pb, Sn, PbSn	-269, -196		●●					Electrical resistivity	[16]
SnPb	-196 to RT		●●						[20]
PbSn	-269		●						[17]
PbSn	-196 to RT	●		●	●●			Joint resistance	[25-27,53]
SnPb, SnPbAg, SnAg	-200 to +150		●●						[8-11]
PbSn, PbSnAg, SnAg	-200 to +150		●●	●●					[12]
SnPb, SnPbAg, SnAg, InPb	-269		●●						[18]
Sn, SnPb, SnSb, PbSnAg	-250 to +200		●●						[6]
PbSn, SnSb, SnAgSb	-150 to +200		●						[5]
PbSn, PbAg, PbSnAg	-182, -59, -29, RT		●●						[7]
PbSnAg	-140, -100, RT		●		●			Fatigue	[24]
Sn, SnPb, PbAg, PbAgIn, PbAgSn, SnAg, SnSb, PbIn, PbAgSb, SnPbSb, SnPbNi	-130 to +150		●●						[13-15]
In	-196 to RT	●●						CTE of substrate and chips	[59,60]
In	-269, -263, -197, RT		●●				●		[34]
In	-269, -197							Creep	[35]
In	-273 to RT		(●)			●		Electrical resistivity	[36]
InSn	-269 to -196		●●	●●				Aging	[37]
InSn	-269, -196		●				●		[38]
InBiSn	-269 to RT	●		●				Joint resistance, fluxes	[54]
InBiSn	-269	●	(●)	●			●	Joint resistance	[55]
InBiSn, InSn	-196 to RT	●	●●	●●		●	●		[33,39]
In, InBi, InBiSn, InSn, PbSn	-196, RT		●●						[19,(28)]
In, InPb, InSn, SnPb	-196 to RT	●●	●●					Wetting, power cycling, joint resistance	[29,30]
In, SnPb, InSn, InPb	-196 to RT	●				●		CTE of substrate and chips	[31]
InSn, InSnAg, InSnAgZn, InSnZn, InPb	-200 to +100		●●						[32]
"Hard" Solders									
AuSn	-196 to +135/+160	●		●●					[43,44,57,58]
AuSn	-196 to +160	●	● RT only	●●	●			Low- and high-temperature storage	[41,42]
AuSn	-196 to +262		●					Data for intermetallic compounds only	[40]
AuSn, AuGe, AuSi	-80 to +180		●						[5]
Organic Adhesives									
Epoxies (conductive & insulating)	-138 to RT	●	● RT only			●			[45,56]
Epoxy (conductive)	-196				●●			Measurements on test assembly	[48-51]

Thus, eliminating thermal control for electronics on the rover, or for other spacecraft electronics, becomes a matter of establishing the required reliability for the electronics. In regard to packaging and interconnections, two critical areas have been identified [3]:

- Flexible cabling (thermal cycling plus mechanical flexing at low temperatures),
- Die attachment of semiconductor devices onto substrates and into packages (thermal cycling) [4].

This paper addresses the latter of these, die attachment, relative to low temperatures and thermal cycling to low temperatures. It summarizes an initial phase—gathering available information from literature and personal contacts, and outlining provisional conclusions and recommendations. So far, over one hundred technical papers, reports, and books have been examined, and of these approximately half (included in the references) have data relevant to low-temperature die attachment. Also, so far, approximately two dozen persons have been contacted for relevant information and experience.

The key outcome from reviewing available information is that there appear to be die attachment materials and techniques, reasonably practical, that can be used for the required Mars rover temperature range, which includes temperatures much lower than the usual $-55/-65^{\circ}\text{C}$. There have been a number of experimental investigations on materials and techniques relevant to die attachment for low temperatures, as summarized in Table 1.

However, the available data are for assemblies that were cycled at most hundreds of times from room temperature to cryogenic temperature. The proposed requirement for the Mars rover is somewhat different—thousands of temperature cycles over a smaller temperature range. Thus, further work is needed to verify die attachment for Mars rovers.

Materials Choices for Die Attachment

Materials used for die attachment may be grouped into four categories: “soft” solders, “hard” solders, organic adhesives, and inorganic adhesives. These are considered below in regard to electronics that will be exposed to low temperatures. Most information found during this investigation relates to the soft solders.

(1) **“Soft” solders:** Examples include PbSn, InSn, and InPb alloys (M.P. $\approx 150-300^{\circ}\text{C}$). Compared to the hard solders, these solders have the advantage of lower assembly temperatures during die attachment, particularly low-melting alloys such as In52Sn48 (M.P. 118°C) or In51Bi33Sn16 (M.P. 61°C). However, they tend to relax under stress, and repeated temperature cycling can lead to failure [5]. Behavior differs greatly among the alloys; some general trends may be extracted from the experimental reports:

Soft solders typically increase in strength and decrease in ductility with decreasing temperature [6–15]. This remains generally true down to cryogenic temperatures, -196°C (77 K) and -269°C (4 K) [16–19]. Pb-rich PbSn alloys retain a fair fraction of their ductility down to cryogenic temperatures; however, as Sn content increases, particularly for ≥ 40 percent Sn, PbSn alloys become brittle below $\approx -50^{\circ}\text{C}$ to $\approx -150^{\circ}\text{C}$ [9–13,20,21]. Thus there is a serious question whether Sn-rich PbSn solders would be advisable for Mars rovers.

Several persons contacted said that their experience showed that adding a small amount of Sb to Sn-rich solders avoids the problem of low ductility at low temperatures. SnPbSb has been used extensively for cryogenic wind tunnel instrumentation. Reports of low-temperature testing, although scant, also tend to indicate that SnPbSb is usable down to cryogenic temperatures [22,23]. On the other hand, Reichenecker’s [13] measurements of Sn40Pb58Sb2 (as well as SnSb, SnAg and SnPbNi alloys with a high percentage of Sn) show a drop in ductility below $\approx -50^{\circ}\text{C}$ similar to that of Sn-rich SnPb alloys. Yoshioka et al. [24] mea-

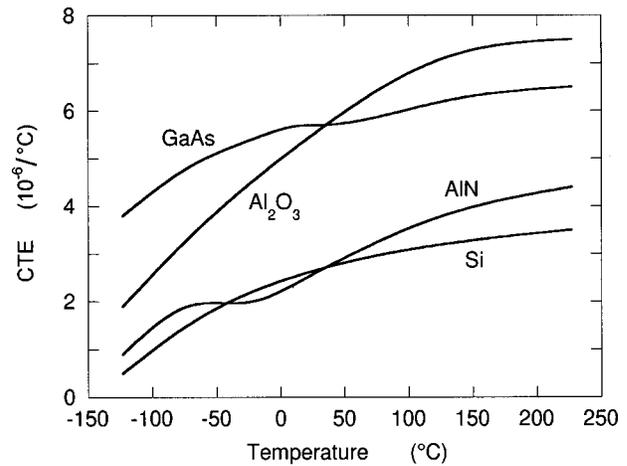


Fig. 1 Coefficient of thermal expansion (CTE) for four materials used in microelectronics: silicon (Si), gallium arsenide (GaAs), alumina (polycrystalline Al_2O_3), and polycrystalline aluminum nitride (AlN) [52]

sured a Sn-rich solder with 2 percent Ag and found that although its ductility decreased at low temperature, its fatigue life did not decrease.

Tong et al. [25–27] found that a polymer coating doubled the life for cycling PbSn bump bonds to -196°C .

The advantage of using indium and indium alloys for cryogenic joining has been appreciated for many years. Their greater ductility [19,28] and longer lifetime [29–31] have been demonstrated, especially for pure In, compared to standard PbSn solders at cryogenic temperatures. Hashimoto et al. [29,30] suggest the elongation-to-strength ratio as an indicator of fatigue life. Adding other elements can further improve low-temperature ductility [32] or fatigue life [33]. Several other papers furnish additional information on properties of In [34–36], InSn [37–39], and InBiSn [39] at cryogenic temperatures.

(2) **“Hard” solders:** Examples include AuSn, AuGe and AuSi alloys (usually eutectic). These have higher melting temperatures (M.P. $\approx 300-400^{\circ}\text{C}$), and are often called *brazes* in the microelectronics community. These materials do not undergo stress relaxation at ordinary electronics temperatures, but as a consequence may transmit more stress to semiconductor die provoking cracks in the die [5]. The high temperatures required for die attachment would also aggravate stress when assemblies are cooled to low temperatures.

We have not located any low-temperature mechanical data for these alloys, except that of McNeil [40], who found that the hardness of the AuSn intermetallic compounds increases with decreasing temperature, and that of Olsen and Berg to -80°C [5].

In regard to low-temperature electronics, a University of California Irvine group reports success in using AuSn to attach both Si and GaAs die to alumina. During cycling between -196°C and $+160^{\circ}\text{C}$ for up to 40 cycles for Si die [41,42] and up to 100 cycles for GaAs die [43,44], they saw no degradation, so conceivably the die attachment could withstand many more cycles.

(3) **Organic adhesives:** These include epoxies and polyimide adhesives, usually filled with metal (such as silver) or dielectric (such as alumina) powder. Low-temperature physical properties and cycling data are scarce, but there are a few reports of epoxies used successfully for low-temperatures with standard die attachment [45–47]. Also, Ulrich and Rajan have performed thermal modeling and measurements on epoxy-mounted Si die on Si and MgO substrates in a -196°C environment [48–51]. We have found no data on polyimides at low temperatures as yet. There are also newer thermoplastic adhesives, but likewise no low-temperature data have been found for these.

(4) **Inorganic adhesives:** The primary example is silver-glass. We have found no low-temperature data for this category of materials as yet.

Temperature Cycling

Temperature Range and Number of Cycles. For the purposes of this task, we have adopted a temperature range of -120°C to $+20^{\circ}\text{C}$, to provide a safety margin on the low end. The baseline rover operation life is a minimum of one earth year. A Martian day is about the same length as an earth day, and thus the rover electronics would experience about 360 temperature cycles minimum. The proposal is to qualify the electronics for an order-of-magnitude greater number of temperature cycles—several thousand cycles. As mentioned, this is considerably greater than existing experience for low-temperature electronics. The electronics would also need to withstand exposure to temperatures up to $+50^{\circ}\text{C}$ several times for qualification thermal-vac or bake-out treatments.

Stress and strain in die bonds from temperature effects (such as cycling) are related to three factors:

- Size, specifically the greatest length over which materials are joined, ΔL ,
- Differences in coefficient of thermal expansion (CTE), ΔCTE , between joined materials,
- Temperature extremes or temperature differences, ΔT .

It is preferable to minimize each of these factors. The first, size, is subject to the same considerations as for conventional electronics, and will not be discussed here. The second and third are discussed below in relation to the temperature range of the Mars rover.

CTE Differences. For illustration, CTE data for four materials used in microelectronics are plotted over the temperature range of interest in Fig. 1 [52]. Since the die will likely be silicon or possibly gallium arsenide, the substrate CTE should be considered relative to the CTEs of these two die materials.

Si. The most common substrate material, alumina, does not match particularly well to Si; even so, several groups have reported success for Si die attachment to alumina over the required temperature range. Hashimoto et al. [29,30] used soft solders and flip-chip mounting; presumably the solders released stress during thermal cycling, in accord with the longer lifetime of the more ductile solders. Tong et al. [25,27,53] were also successful in flip-chip mounting using a soft solder. On the other hand, Matijasevic et al. [41,42] were successful using a hard solder and standard (not flipped) die attachment. Aluminum nitride (AlN) has a better CTE match to Si than does alumina; however, we have found no data on die attachment to AlN for low temperatures. The best CTE match for Si is Si itself and several groups have used Si substrates, demonstrating successful die attachment over the required temperature range using soft solders [54,55] or epoxy [45–47,56].

GaAs. Two groups report successful die attachment for GaAs to alumina: for flip-chip with soft solders [29,30], and for standard attachment with a hard solder [43,44,57,58]. The CTE match for GaAs to alumina is better than that for Si to alumina, consistent with the longer life of GaAs soft-solder flip-chip bonds reported by the first group [29,30]. Aoki et al. [59,60] developed a special ceramic (alumina-treated zirconia plus borosilicate glass composite) for an improved CTE match to GaAs die and thereby obtained superior lifetimes compared to alumina substrates for soft-solder (In) flip-chip attachment cycled to -196°C .

These results suggest that certain materials and techniques can be used successfully for die attachment for the required rover temperature range. Both soft and hard solders are candidates. However, these results are for only several hundred or fewer temperature cycles and further work would be needed to confirm suitability.

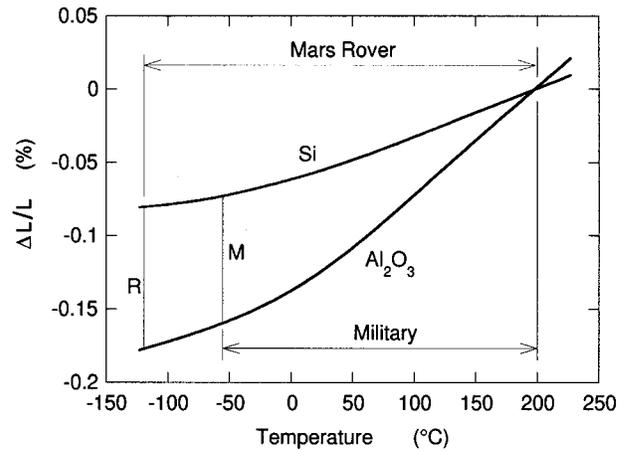


Fig. 2 Relative linear thermal expansion ($\Delta L/L$) for silicon and alumina, normalized to 200°C [52]

It should be borne in mind that even with perfect CTE matching there are unavoidable thermal expansion stresses due to temperature gradients. These arise from heat flow and differences in heating and cooling during the environmental temperature changes and due to power dissipation and power cycling. Such gradients can be reduced through good thermal conduction. In addition, insulation and heat “sinking” (thermal inertia) might be used to reduce temperature excursions and rate of change.

Temperature Extremes. For most materials CTE decreases as temperature decreases, as illustrated in Fig. 1 for the four materials used in microelectronics assemblies. This is fortuitous for the rover. Such data can provide a basis for comparing the stress from thermal cycling of the rover electronics with that for “standard” electronics.

There are two temperature ranges of relevance for rover die attachment:

- (1) Between the die attachment temperature and the lowest exposure temperature. This temperature cycle will typically occur only once. There may be a few similar cycles (going above $+20^{\circ}\text{C}$) from other assembly operations, bake-out, sterilization, etc., of the electronics.
- (2) Between the high and low extremes of the Mars range (here taken to be -120°C to $+20^{\circ}\text{C}$). This cycle will occur many times (hundreds) during the mission, and consequently is likely to be the more important of these two.

Consider the first temperature range. The upper extreme will be the temperature during die attachment, specifically the solidification temperature of the alloy or adhesive. Since the zero-stress point is “frozen in” at this temperature, there is some “built-in” stress even at room temperature when the assembly cools. To see

Table 2 Comparison of differences in thermal expansion $\Delta(\Delta L/L)$ between silicon and alumina for an upper temperature of $+200^{\circ}\text{C}$ (numerical data corresponding to Fig. 2).

Mars Rover Range -120°C to $+200^{\circ}\text{C}$ ($\Delta T=320^{\circ}\text{C}$)	
$\Delta L/L$ at -120°C for silicon	-0.080%
$\Delta L/L$ at -120°C for alumina	-0.177%
$\Delta(\Delta L/L)$ -120 to $+200^{\circ}\text{C}$ “R”	0.097%
Military Range -55°C to $+200^{\circ}\text{C}$ ($\Delta T=255^{\circ}\text{C}$)	
$\Delta L/L$ at -55°C for silicon	-0.073%
$\Delta L/L$ at -55°C for alumina	-0.159%
$\Delta(\Delta L/L)$ -55 to $+200^{\circ}\text{C}$ “M”	0.086%

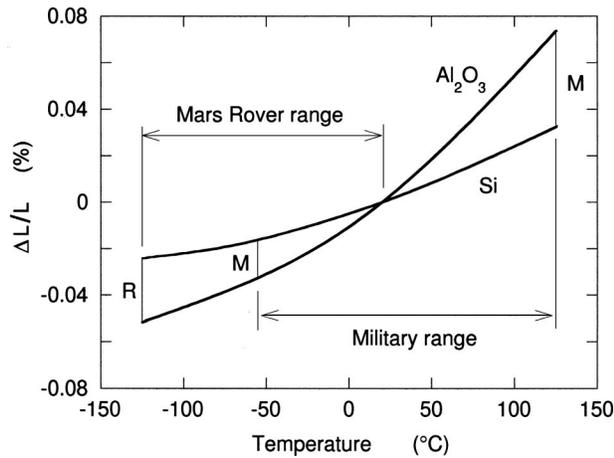


Fig. 3 Relative linear thermal expansion ($\Delta L/L$) for silicon and alumina, normalized to room temperature ($+20^\circ\text{C}$) [52]

what this means for thermal expansion mismatch, assume a silicon die attached to an alumina substrate at an assembly (zero-stress) temperature of $+200^\circ\text{C}$. Figure 2 compares the thermal expansion ($\Delta L/L$) for silicon and alumina over the relevant temperature range [52]. For convenience, the expansion has been set to zero at $+200^\circ\text{C}$. The maximum *difference* in expansion between the silicon and alumina is given by the vertical line “M” for the military case and by “R” for the Mars rover case at their respective lowest temperatures. Numerical values are given in Table 2 and show that the difference in expansion for the Mars rover range, which extends an additional 65°C lower, is only 13 percent greater than that for the military range. Even so, this example illustrates that it would be advantageous to use the lowest possible assembly temperatures for the rover to reduce stress. Materials that produce a bond at a low temperature but that retain their integrity to a higher temperature might be used, for example a two-part room-temperature-curing epoxy or certain metal systems used in soldering.

Now consider the second temperature range, for the same combination of materials. Figure 3 again compares the thermal expansion for silicon and alumina over the relevant temperature range [52]. Here the expansion is set to zero at $+20^\circ\text{C}$. (Note, however, that we do *not* assume zero stress at $+20^\circ\text{C}$.) The vertical line at -120°C labeled “R” is the difference in expansion over the proposed Mars rover range of -120°C to $+20^\circ\text{C}$, and the sum of the two vertical lines at -55°C and at $+125^\circ\text{C}$ gives the difference in expansion over the military range of -55°C to $+125^\circ\text{C}$. Numerical values are given in Table 3 and show that the difference in expansion between silicon and alumina over the Mars rover range is about half that over the military range. This is partly due to the

Table 3 Comparison of differences in thermal expansion for alumina and silicon (numerical data corresponding to Fig. 3, with some arithmetic omitted).

Mars Rover Range -120°C to $+20^\circ\text{C}$ ($\Delta T=140^\circ\text{C}$)	
$\Delta(\Delta L/L)$ at -120°C	0.027%
$\Delta(\Delta L/L)$ at $+20^\circ\text{C}$	0%
$\Delta(\Delta L/L)$ -120 to $+20^\circ\text{C}$	0.027%
Military Range -55°C to $+125^\circ\text{C}$ ($\Delta T=180^\circ\text{C}$)	
$\Delta(\Delta L/L)$ at -55°C	0.017%
$\Delta(\Delta L/L)$ at $+125^\circ\text{C}$	0.038%
$\Delta(\Delta L/L)$ -55 to $+125^\circ\text{C}$	0.055%

slightly smaller temperature range for the rover ($\Delta T=140^\circ\text{C}$ versus 180°C) but primarily due to the lower CTEs over the lower temperature range for the rover.

Thus, on this basis, the Mars rover temperature range would result in only slightly higher stress from the assembly processes and *less* long-term cyclic stress during its mission than what would be experienced for the often-used military range. The existence of high-reliability electronics for the military range implies that the same can be achieved for the Mars rover range.

The preceding was a simple analysis, but it gives us reason to believe—from the thermal expansion standpoint—that operating electronics that must cycle repeatedly to low temperatures is feasible, an idea supported by the ongoing use of electronics in the field down to cryogenic temperatures. An actual analysis would require a detailed design for the electronics and the expected thermal scenario during fabrication and operation. This is beyond the scope of this paper, which is only intended to provide an idea of the extent of the challenge and compare it to the situation for “standard” electronics. Moreover, there remains the question of how the die-attachment materials might act under the influence of these thermally generated stresses, specifically how the materials might act differently for the lower temperature range and numerous cycles in regard to microstructural behavior.

Conclusions and Recommendations

From this initial phase of investigation, it appears that die attachment can be made sufficiently reliable to satisfy the requirements of future Mars rovers. Existing experience indicates that there are several candidate materials systems and techniques, including hard solders, soft solders, and organic adhesives. Thus, from the standpoint of die attachment, it appears feasible to eliminate thermal control for Mars rover electronics.

However, the proposed rover qualification represents a situation outside existing experience: neither guidelines nor technology have been established for the proposed thousands of cycles over the Mars temperature range. Thus, the selected die attachment technology would need verification under the appropriate conditions. The situation is not straightforward because many factors affect the results, and the conditions in previous investigations are different from those for the Mars rovers. This underscores the need for appropriate qualification.

Hard solders appear to be a primary die-attach candidate for investigation because of their resistance to microstructural evolution. In particular, eutectic AuSn (Au80Sn20) is the lowest-melting of the common hard solders and has been shown to produce bonds that remain good after cycling to low temperatures [41–44,57]. Furthermore, eutectic AuSn is a standard die attachment material compatible with normal microelectronic assembly.

Indium-alloy solders might also be a good choice for the large number of temperature cycles for the rover; however, they may not be necessary for -120°C (not quite into the cryogenic range of $\leq -150^\circ\text{C}$). “Traditional” PbSn alloys, or slight modifications thereof, could be adequate, although Sn-rich alloys warrant caution.

Investigation of alternative substrate materials for better CTE matching to Si also appears worthwhile (AlN for example, which also has high thermal conductivity) as well as evaluation of epoxy and polyimide adhesives with regard to temperature cycling life.

In addition to mechanical testing (die-shear), electrical resistance and thermal conductivity tests should be a part of any evaluation to determine die attachment quality. Acoustic and X-ray evaluations for bond integrity should be used. In particular, die attachment materials meant to be electrically conductive, such as silver-filled epoxy or silver-glass can potentially become non-conductive or less conductive at low temperatures or after temperature cycling. This possibility needs to be evaluated experimentally. Similar concerns apply to thermal conduction of die attachment materials, which may be degraded by temperature cycling.

Finally, development of reliable electronics for future Mars rovers will require a comprehensive approach including many factors in addition to those addressed here. The entire die-attachment system must be considered—the die, die attachment materials, substrate, and any metallizations, coatings, encapsulations, etc. The characteristics and influence of all of these must be taken into account. Also, the interrelation of die attachment materials with thermal conduction, power dissipation, heat distribution and overall thermal design of the rover must be considered.

Additional information resulting from this phase of our investigations is available in a Jet Propulsion Laboratory report.

Acknowledgments

We thank Richard Ulrich of the University of Arkansas for reviewing this paper and providing valuable comments.

The overview described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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