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Initial Experiments on Thermal Interface Materials for Electronics Packaging

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14. ABSTRACT

Initial experiments on thermal interface materials (TIMs) for millimeter-wave monolithic integrated circuit (MIMIC) packaging were performed. A variety of types of TIMs were evaluated for thermal performance, ease of use, and cost, with the focus being on thermal performance. The top thermal performers were an indium (In) foil, a thermal paste, a phase change material, and graphite, respectively, with thermal pad materials all ranking significantly lower. The In foil and thermal pad (Q-Pad 3) were the easiest to apply and remove, with the most difficult being the phase change material, the thermal paste, and graphite. In terms of cost, the In foil was by far the highest followed by graphite, with the lowest being the thermal pad (Q-Pad 3) and a thermal tape (Bond Ply 100). All in all, of the TIMs tested, the In foil appears to be best suited for our applications, with the benefits of its thermal performance and ease of use outweighing its higher cost.

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Thermal interface material, TIM, electronics packaging, electronics heat dissipation

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Contents

List of Figures

List of Tables

1. Introduction

Thermal management of millimeter-wave monolithic integrated circuit (MIMIC) power amplifiers is a matter that calls for significant attention. The reason centers around an extremely high dissipation of heat in a small volume and the need to maintain a “reasonable” temperature in the active regions of the device such that it provides acceptable performance and reliability, both of which degrade with increasing temperature. One of the major bottlenecks in heat removal from a device is at the interface between the package and the heat sink. One might assume the transition from one highly conductive metal to another to be of little concern; however, due to small imperfections in the surfaces (a less than perfect surface finish), there is a significant thermal resistance or “contact resistance” at this interface. Industry has been working diligently to reduce this contact resistance by engineering a variety of thermal interface materials (TIMs) to be placed between the metals that “fill-in” the small gaps. Many of these materials are application specific in their benefits. Our interest is to evaluate several of the offerings, so that we can decide which TIMs are best for our applications. While thermal performance drives our applications, we are also very sensitive to ease of use, including ease of removal so the package can be reworked or replaced, and to a lesser, extent cost. With this in mind, a series of experiments were performed to make an initial assessment of the performance of several commercial TIM offerings.

A range of TIM types were tested; there is a variety on the market. In general, the TIMs tested here are all relatively thin sheet or film materials with the exception of Arctic Silver 5, which is paste-like. The specific materials are listed in table 1, which includes the manufacturer and a brief description. Published material properties of the TIMs are provided in table 2.

Table 1. TIMs tested.

TIM	Manufacturer	Description
Tpli 210	**Laird Technologies**	“Thermal gap filler pad” silicone and boron nitride
Tpli 220	**Laird Technologies**	“Thermal gap filler pad” silicone and boron nitride
Tflex 720	**Laird Technologies**	“Thermal gap filler pad” silicone with ceramic filler. (very high compressibility)
Q-Pad 3	Bergquist	Pad (fiberglass carrier), electrically conductive
Tpcm 585	**Laird Technologies**	Phase change material (PCM) pad. Begins to soften at 50 °C
Pyrolytic Graphite Sheet (PGS)	Panasonic USA	Electrically conductive
Indium (Heat Spring Type D)	Indium Corp	Micro-structured foil
Bond-ply 100	Bergquist	Thermal tape (fiberglass carrier)
Arctic Silver 5	Arctic Silver, Inc	Polysynthetic compound loaded with silver and other particles (thermal paste)

Table 2. Properties of TIMs tested (from the manufacturers).

TIM	Thermal Conductivity, k (W/m-K)	Thickness (mils)	Hardness	Thermal Resistance at 10 psi (C-in^2/W)	Thermal Resistance at 50 psi (C-in^2/W)
Tpli 210	6.0 ASTM D5470 (modified)	10	75 Shore 00	0.160	~0.13
Tpli 220	6.0 ASTM D5470 (modified)	20	75 Shore 00	0.210	~0.19
Tflex 720	5.0 Hot Disk (method)	20	50 Shore 00	Falls ~0.18[a]	Falls ~0.14 [a]
Q-Pad 3	0.8 ASTM D5470	5	86 Shore A	0.65	0.35
Tpcm 585	3.80	5	Very soft[c]	0.020 C-in^2/W	0.013 C/in2/W
PGS	Z: 15 X-Y: 1600	1	Kinks and tears easily[c]	0.033	unavailable
Indium	83.7	4	Brinell: 0.9 (ductile)	Increases rapidly with pressures below 50 psi.	3 mil is ~.01 (4 mil = unavailable
Bond-ply 100	0.8 ASTM D5470	5	Stiff [c]	0.56	0.52
Arctic Silver 5	8.5[b]	User controlled (1–3 typical)	0 (paste)	-	Pressure dependence can be expected to be negligible.[c]

[a] There are no thermal resistance data for Tflex 720, but data for 740, 760, and 780 were available and it appears that the thermal resistance for 720 can be extrapolated—which provided the value in the table.

[b] This value was found from a source other than the manufacturer and reliability of the value should be considered questionable. The manufacturer has chosen not to supply any thermal resistance data.

[c] These are our assessments.

2. Experimental

Thermal resistance testing was performed with each TIM. The complete test setup is shown in figure 1. Essentially, the TIM under test was sandwiched between a heated block and a coldplate. The other items in the test setup were used to dissipate the heat, and sense, monitor, and record temperatures. Using K type thermocouples, the temperature of the block as well as the ambient temperature and the temperature of the cooling fluid were monitored. The primary measurement, at this time, was to record the steady-state temperature of a specific point on the block along with the ambient temperature with both the heat on and coldplate operating—this was performed for all of the TIMs. This information is sufficient to compare the various TIMs in terms of thermal resistance. Additionally, various time-dependent measurements were made, such as temperature as a function of time for the block to reach steady state as well as time for the block to cool down to steady state with the heat turned off.

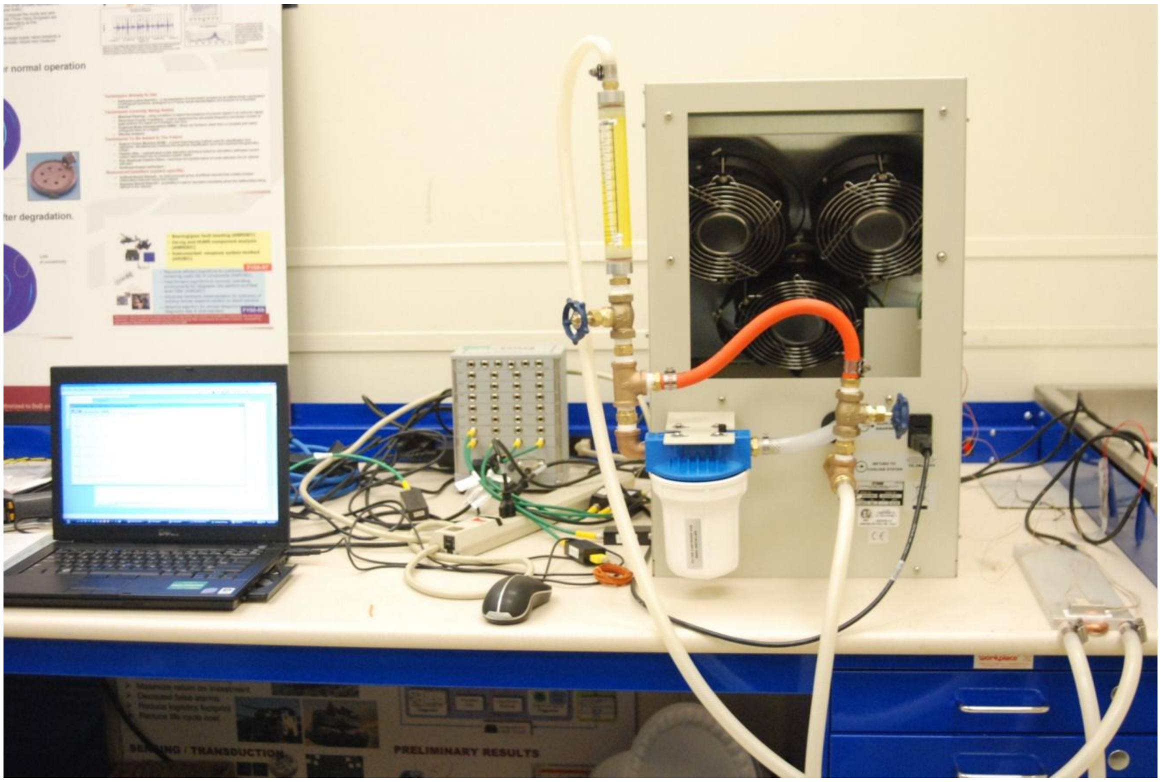

Figure 1. Test setup for the thermal resistance measurements.

The primary elements of the test are the components shown in figure 2. They include a block with heater cartridge, the TIM under test, the coldplate, thermocouples, and attachment screws. The heated block was 6061-T6 aluminum with a specified surface finish of 32 µin and a measured surface finish of 28.8 µin (average). One of two heater cartridges was inserted into the block; either a 100- or 30-W heater cartridge was used. The TIM to be evaluated was cut to size, slightly larger than the contact area, and holes were punched in it for passage of the screws. The TIM and heater block were then aligned on the cold plate, and the four #4-40 screws were inserted and tightened. Most of the TIMs tested were thin, pliable, and in some cases “sticky,” which made the above two operations weigh heavily into ease of use considerations. As a note, for this initial testing, the screws were hand tightened—a specific torque was not applied.

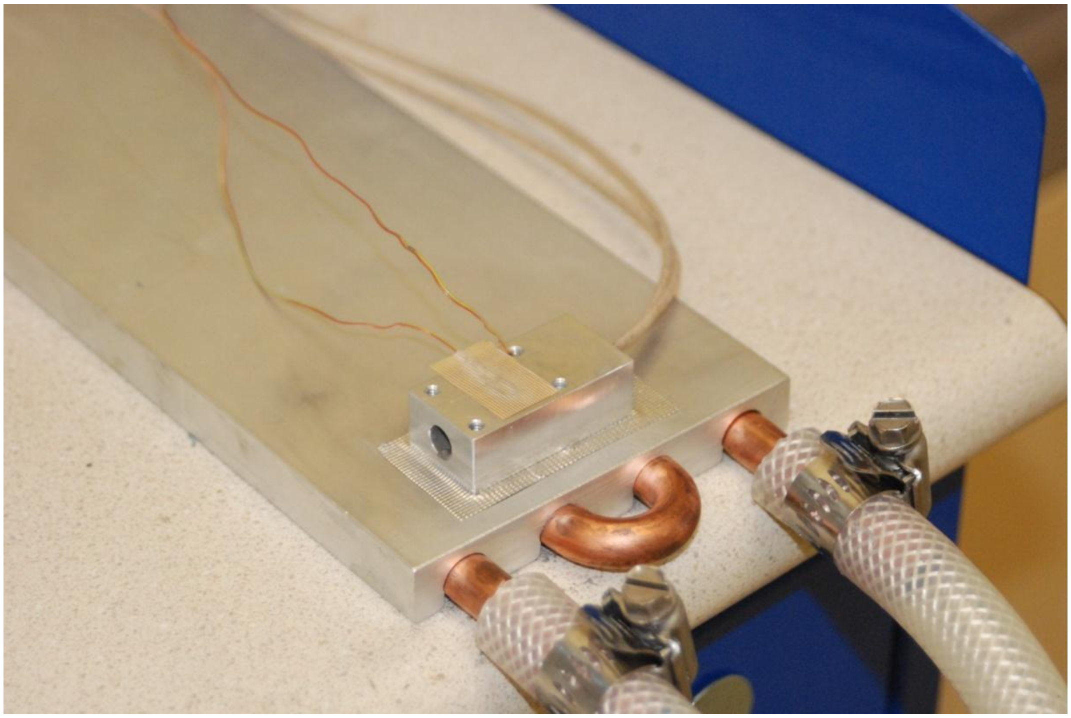

Figure 2. Test components of primary interest.

3. Results

For a simple view of the relative performance of the TIMs, normalized results for each category of consideration are presented in figure 3. Each category was normalized such that its highest value was one. Noting that a low value for each of the categories is desirable, one can quickly see that no single TIM is best in all three considerations and that a trade-off is necessary. For our purposes, thermal performance is the primary driver, followed closely by ease of use, with cost being a lesser consideration. The rankings in each of these categories is discussed in sections 3.1 through 3.3.

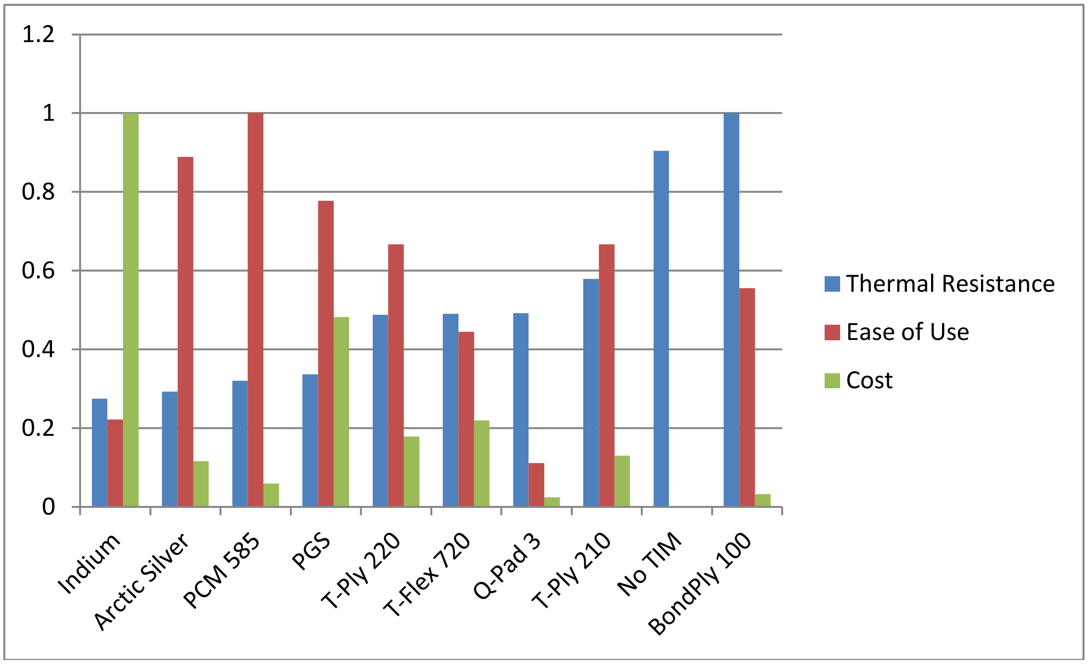

Figure 3. Overview of results.

3.1 Thermal Performance

The calculated thermal resistance for each TIM, in order of lowest to highest, is provided in table 3. The thermal resistance, R, presented here is given as the temperature difference between a specific (and consistent) point on the heated block and the ambient divided by the heat input, Q, as shown in equation 1. Note that the thermal resistance values presented here are for the entire heat path, not for the TIMs themselves; however, since the other elements of the system are the same for each TIM experiment, the total thermal resistance is a suitable indicator of the relative thermal resistance of the TIMs. The indium (In) TIM is seen to be the best performer, but is followed fairly closely by Arctic Silver 5 (the paste), PCM 585 (the phase change material) and PGS (graphite), respectively. The pad type materials all rank significantly poorer, and the thermal tape ranks even poorer than no TIM at all. Due to the design of the test there is some ambiguity in the results, which is not expected to affect the rankings; this is discussed in section 4 of this report.

$$R = (T_{block} - T_{ambient}) / Q \tag{1}$$

Table 3. TIM thermal performance (thermal resistance).

TIM	Thermal Resistance (°C/W)
Indium	0.152
Arctic Silver 5	0.162
Tpcm 585	0.177
PGS	0.186
T-Ply 220	0.27
T-Flex 720	0.271
Q-Pad 3	0.272
T-Ply 210	0.32
None	0.5
BondPly 100	0.553

Thermal resistance or impedance provided by manufacturers often incorporates the contact area, such that the value could be used by designers for different package sizes. This, however, is unnecessary here, since, at this time, we are simply interested in a ranking of the prospective TIMs. Incorporating the contact area in our case would provide the same ranking and would not provide any additional benefit.

3.2 Ease of Use

Ease of application and removal are important to us both for component testing and in the limited run productions for which we design. If the material is very difficult to apply, then it is more likely to be applied incorrectly thus diminishing its performance. Additionally, if the material is very difficult to remove, this creates a significant disadvantage, since we want to be able to remove components for rework or replacement. The ranking of the materials with regard to ease of use is presented in table 4. We include additional comments significant to the evaluation. The ranking is based on a scale of 0 to 10 with 1 being very easy and 9 being extremely difficult to use. Note that a ranking of 0 is reserved for no TIM applied and 10 is reserved for a TIM that we would consider impossible to use. Ease of use for us can be expected to be different from that of a large production facility where dedicated machinery may be employed. For component testing and the production levels we would normally anticipate for our applications, the TIM is expected to be cut and/or applied and removed by hand; this dramatically affects our view. Other than "no TIM," the Q-Pad 3 material ranks highest on our list of ease of use because it is easy to physically handle, cut, place, and remove. It is closely followed by the In foil, which is easy to cut, place, and remove; however, the foil is thin and malleable and is prone to deforming during handling. Tpcm 585 ranked the worst due to its high elasticity and gummy nature; handling and application were very difficult.

Table 4. Ease of use ranking.

TIM	Ease of Use	Comments
No TIM	0	No effort is required in application or removal
Q-Pad 3	1	Semi-rigid, rubber-like. No difficulty in handling and removal. Very little difficulty in preparation
Indium	2	Metal foil. Minor difficulty in handling. No difficulty in preparation and removal
Tflex 720	4	Soft, rubber-like. Some difficulty in preparation and handling due to its flimsiness.
Bond-ply 100	5	Stiff tape (with adhesive). Must be placed very carefully due to the strong adhesive.
Tpli 210	6	Paper-like, but flaky. Structurally weak and susceptible to damage when protective film removed.
Tpli 220	6	Paper-like, but flaky. Structurally weak and susceptible to damage when protective film removed.
PGS	7	Thin, stiff, and brittle. Susceptible to fracture during handling and preparation.
Arctic Silver 5	8	Paste. Messy. Very difficult to achieve a consistent thickness during application. Extremely difficult to remove.
Tpcm 585	9	Extremely soft/pliable and gummy. Extremely difficult to place (in original cut shape and in the precise location)

3.3 Cost

The cost of the TIMs examined are listed in table 5 in order of lowest to highest. Although cost is not a primary driver in our applications, it is always a factor. One can see that the least expensive by far are Q-Pad 3 and Bond Ply 100, respectively. The In TIM is by far the most expensive with PGS following at roughly half the cost. Of course, not using a TIM would be the lowest cost.

Table 5. TIM cost ranking.

TIM	Cost ($\$/in^2$)
No TIM	0.00
Q-Pad 3	0.09
Bond-ply 100	0.12
Tpcm 585	0.22
Arctic Silver 5	0.43
Tpli 210	0.48
Tpli 220	0.66
Tflex 720	0.81
PGS	1.78
Indium	3.69

4. Discussion and Conclusions

Data on thermal interface materials were gathered experimentally and through a literature review. Rankings were presented on thermal performance, ease of use, and cost. Due to our higher weight on thermal performance and ease of use, respectively, the In Heat Spring TIM appears to be most suitable for our purposes, having the lowest thermal resistance and ranking very well in ease of use. Although its cost is much higher than the other TIMs, its cost is considered to be acceptable, based on our limited production. Three of the other TIMs ranked very close to the In material in thermal performance (Arctic Silver 5, Tpcm 585 and PGS); however, each of them performed very poorly with regard to ease of use. Under certain conditions, these other materials may be considered for use. For example, the phase change material (Tpcm 585) can absorb heat very well and may prove especially advantageous when thermal transients are involved.

This study should be considered preliminary, particularly since certain experimental procedures were not optimal. The most significant of which was that the same heater block and location on the cold plate were used to test all of the TIMs. It is possible that some residue from the previously tested TIMs could have affected the results of the following TIMs under test. Two protocols were followed to reduce this risk, including a thorough cleaning of the surfaces and the testing order of the TIMs, with those most likely to leave a residue tested later—for example, the paste, Arctic Silver 5, was tested last. If residue from a previously tested TIM were to impact the results of a following TIM, one would expect the results of the TIM under test to be “damped” by the previous TIM(s) results. In other words, if the TIM under test tested better than the previous TIM, then the actual result should be expected to be better still, and likewise, if the TIM under test tested worse than the previous TIM, then the actual result should be expected to be even worse. With this in mind, the ranking is still expected to be relevant. Even so, further testing of the TIMs is in preparation. In the planned set of tests, a separate heated block and heat sink will be used for each TIM. Additionally, in the planned set of experiments, thermocouples will be placed directly on each side of the TIM, thus allowing for the thermal resistance of the TIM itself to be determined, thereby eliminating the thermal resistances of the heated block and the heat sink.

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