A Tenfold Reduction in Interface Thermal Resistance for Heat Sink Mounting

D. Van Heerden, O.M. Knio, and T.P. Weihs

Reactive NanoTechnologies
111 Lake Front Drive
Hunt Valley, MD 21030

Abstract

Reactive NanoTechnologies (RNT) has developed a new platform joining technology that can form a metallic bond between a chip package and a heat sink and thereby offer a thermal interface resistance that is ten times lower than current thermal interface materials (TIM). The joining process is based on the use of reactive multilayer foils as local heat sources. The foils are a new class of nano-engineered materials, in which self-propagating exothermic reactions can be initiated at room temperature with a hot filament or laser. By inserting a multilayer foil between two solder layers and a chip package and heat sink, heat generated by a chemical reaction in the foil heats the solder to melting and consequently bonds the components. The joining process can be completed in air, argon or vacuum in approximately one second. The resulting metallic joints exhibit thermal conductivities two orders of magnitude higher, and thermal resistivities an order of magnitude lower, than current commercial TIMs. We also demonstrate, using numerical modeling, that the thermal exposure of microelectronic packages during joining is very limited. Finally we show numerically that reactive joining can be used to solder Si dies directly to heat sinks without thermally damaging the chip.

Key Words: Heat sink mounting, thermal interface material, reactive multilayer foil

1.0 Introduction

Thermal management is an ongoing problem for chip manufacturers. As chips get smaller and more powerful, the need to cool the chips to prevent failure becomes both more essential and more difficult. The overall market for thermal management is split between active solutions (fans, refrigeration, immersion) and passive solutions (heat sinks, natural convection). The trend is toward passive solutions as active solutions cease to work on a smaller scale (such as for hand-held devices or cell phones).

In the passive solution a heat sink is mounted onto a chip or ceramic substrate and draws heat away from the chip or active device and dissipates it into the air (Figure 1). Currently, heat sinks are mounted to chip packages with adhesives, pads, or pastes. A much higher thermal conductivity would be possible if a true metallic bond was formed between the heat sink or chip package. Such a bond could be achieved by brazing or soldering. However, the temperatures required for conventional soldering or brazing would damage or destroy the chip. In addition, a heat sink can de-bond from a ceramic substrate during conventional soldering or brazing, due to mismatches in thermal contraction on cooling. Reactive NanoTechnologies (RNT) has developed a novel method for soldering heat sinks to chips, chip packages and substrates that uses a multilayer foil as a local heat source to melt the solder. No protective atmosphere are required and the soldering can be performed rapidly in air without fluxes.

Using a thin foil as a heat source instead of a furnace, enables the solder at the interface to be heated without substantial heating of the components being joined. The chips and chip package are never exposed to high temperatures and therefore are not damaged. In addition, large thermal stresses are avoided when joining metallic heat sinks to ceramic substrated because neither the heat sink nor the substrate are heated substantially, only the interfaces being bonded.

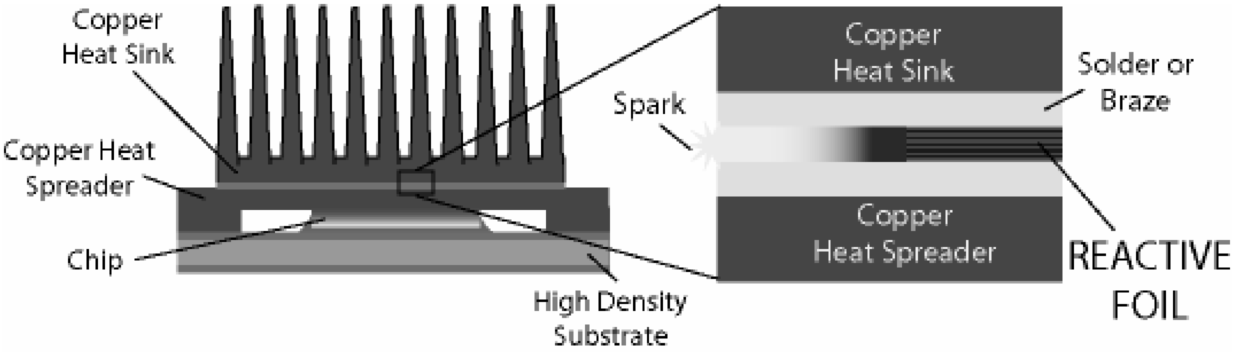

Figure 1: Schematic illustration of reactive joining of a copper heat sink to a copper heat spreader. A reactive multilayer foil is sandwiched between two solder layers and the heat spreader and heat sink. A self-propagating reaction is then initiated in the foil and to travels along the foil, from left to right. The heat of reaction melts the solder layers and results in a strong, metallic bond between the two components

The exothermic chemical reactions that occur within the foils have been studied for many years [1-14] and are now being developed for commercial applications. This paper describes their application to the soldering of common chip package, heat sink and substrate materials, namely Cu, Al and AlN. The thermal interface resistance is measured for Al-Cu, Cu-Cu and Cu-AlN joints and is shown to be very low and consistent with a true metallic bond. For comparison Cu-Cu joints are also formed using common commercial interface materials and the resulting thermal interface resistances are measured.

2.0 Foil Fabrication and Joint Formation

Nanostructured, Ni/Al reactive multilayer foils [2-17] were fabricated using a large-area, magnetron sputter system. The foils were deposited onto substrates and then were peeled from their substrates for use as free-standing samples. The reactive foils incorporate thousands of alternating layers of Ni and Al that are approximately 25nm thick. Total foil thicknesses can range from 40 to 200μm and are varied by simply changing the total number of Ni and Al layers.

Three different material systems in the form of rectangular blocks were considered for testing. These consisted of multilayer joints of: (1) Al bonded to Cu, (2) Cu bonded to Cu, and (3) Cu bonded to AlN. The specific configurations used are shown in Figure 2. The metallic blocks were machined from commercial alloys, that are commonly used in the microelectronics industry (Al alloy 6061 T6 and OFHC Cu). These materials have well characterized thermal properties that simplify the characterization of interface thermal conductivity and resistance.

When choosing a solder for the reactive bonding process, several criteria were considered including a desire to: (1) minimize solder cost; (2) maximize the thermal conductivity of the solder, (3) ensure compatibility with reactive foil and component surfaces, (4) maintain a moderate solder melting temperature so as to minimize thermal exposure of the components, and (5) avoid lead-based solders. The candidate solders included ones which had already been used successfully in reactive joining applications. In the interests of thermal compatibility Ag-Sn-based solders (based on a composition 3.5%Ag 96.5%Sn) were deemed most suitable. Thus all of the Cu samples were pre-wet with Ag-Sn solder. The Al and AlN samples in Configurations 1 and 4 in Figure 2 were pre-wet with a proprietary solder named S-Bond 220 (a Sn-Ag-Ti based). This solder was selected due to its ability to pre wet both Al and AlN while maintaining the same melting point as 3.5%Ag 96.5%Sn (solidus 221°C). In Configuration 3 the AlN samples were pre-wet with an Incusil adhesion layer before depositing the Ag-Sn solder.

Reactive multilayer joints were formed in air and at room temperature using the four configurations illustrated in Figure 2. During the reactive joining process, pressure was applied using a uniaxial press. As further discussed below, the reactive mounting process is quite rapid and is completed in several seconds.

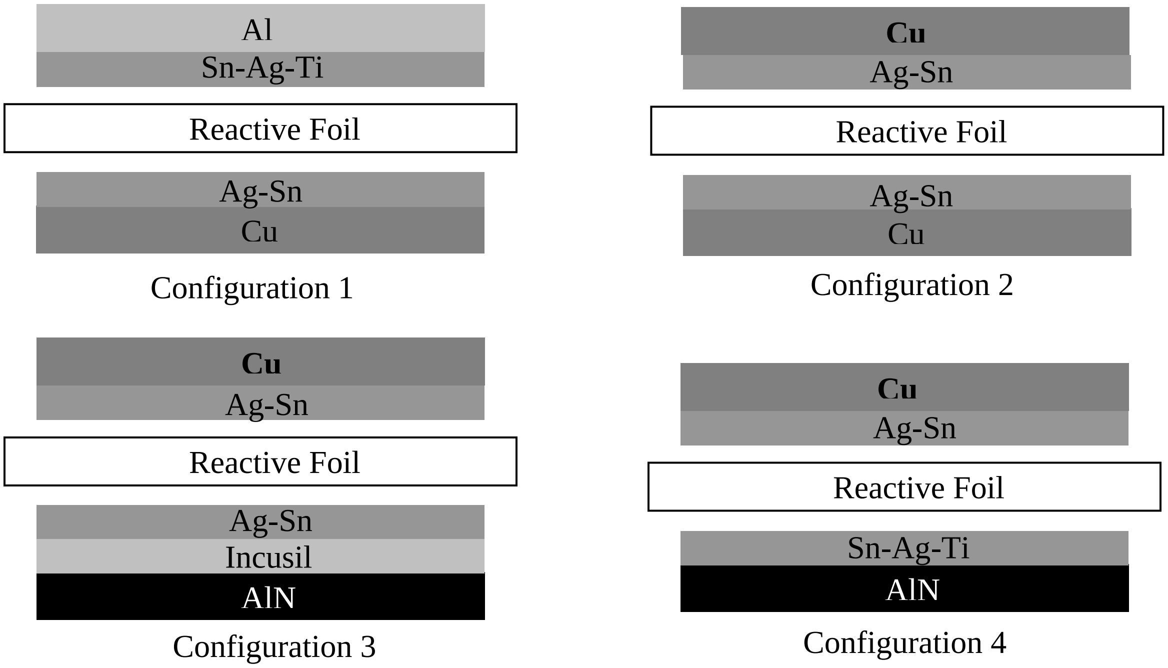

Figure 2: Joint configurations studied. The joining surfaces of the Cu, Al and AlN components were pre-wet with an Ag-Sn based solder and joined using reactive foils.

Measurement of Mechanical Strength: The shear strength of reactively bonded interfaces was tested using compressive shear lap tests performed at room temperature. In all cases the measured shear strengths ranged between 14MPa and 22MPa, similar to 20MPa measured for conventional Ag-Sn solder joints on the same test configuration. Fracture of the joints occurred within the solder layers, and revealed no significant bulk interfacial porosity or discontinuities. The observed fracture strength and fracture surfaces indicated that we had indeed fabricated a true metallic solder bond using reactive joining.

Measurement of Thermal Conductivity and Interface Resistance: The thermal conductivity of the joints was quantified using infrared thermometry. As illustrated in Figure 3, the reactively bonded assembly was heated from above using a heating plate, while the bottom surface was cooled. The front face of the joints was machined flat, polished, and coated with a high-emissivity paint to maintain a constant emissivity across each component. The heating flux was maintained until steady conditions were reached, at which point data collection started.

Thermal profiles were measured across the side of the samples using an IR camera, with a 100µm spatial resolution. Using measured temperature profiles and the known thermal conductivities of the components, a heat balance across the interface was performed in order to determine the thermal conductivity of the reactively formed interface and the corresponding interface resistance. This analysis was performed for all configurations shown in Figure 2.

To measure thermal conductivity and interface resistance accurately a pressure was applied normal to the interface during the IR characterizations. This ensures lateral uniformity in heat conduction between the multiple components, and it mimics most applications. In current package designs the heat sink is pressed onto the chip package with clips and/or clamps that exert a pressure of approximately 10psi (69kPa). Thus, the thermal measurements were performed at different pressures, close to 10psi. Figure 4 illustrates the effect of applied pressure on a Cu-Cu reactive foil/solder joint, and includes, for comparison, results obtained for competing interface materials (mounting technologies). Figure 4 shows that, unlike common interface materials, the thermal conductivity of the reactively formed interfaces is essentially independent of the pressure applied during the thermal measurements. This result is expected as reactive joining leads to strong metallic joints.

The thermal conductivities and thermal resistances measured for Cu-Cu, Al-Cu and Cu-AlN joints that were soldered using multilayer foils are summarized in Table 1 below. For all three material

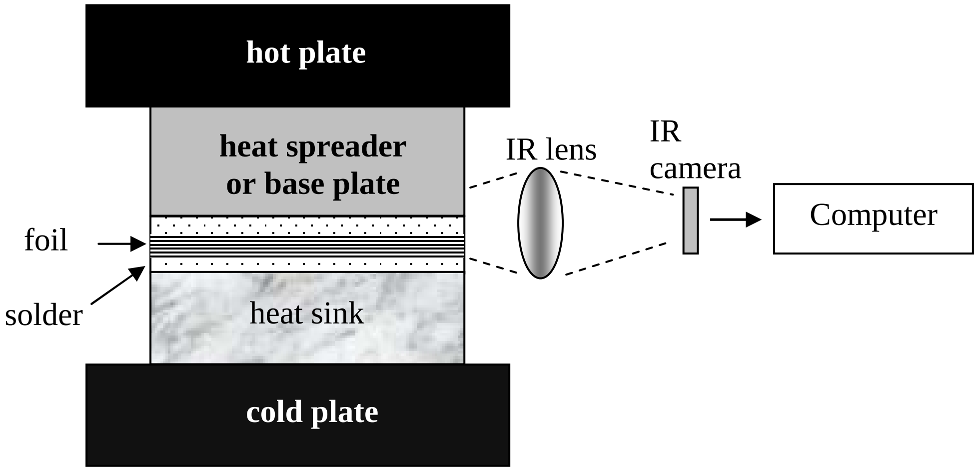

Figure 3: Schematic illustration of IR thermometry system used to measure temperature profiles across the side of joints. When steady conditions were reached, the temperature profiles were scanned across the baseplate, interface, and heat sink.

systems, the Table shows that joint thermal conductivities can exceed 65W/mK, roughly a factor of 100 higher than the best competing alternatives.

In order to quantify the last claim, Table 2 compares the measured conductivity and thermal resistance of the reactive Cu-Cu joints with results from similar measurements that were performed on Cu-Cu joints fabricated with the best commercial alternatives, including permanent adhesives and thermal pastes. In all cases, a pressure of 10psi (69kPa) was applied during the thermal measurements. The results demonstrate that the thermal conductivity of the reactive joints is approximately two orders of magnitude larger, and consequently the thermal resistance is more than an order of magnitude lower, than the values for any of the competing alternatives.

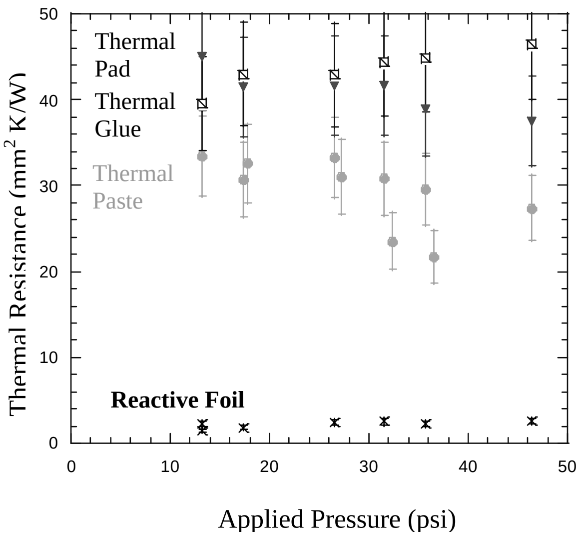

Figure 4: Dependence of the interfacial thermal resistance on applied pressure for reactively formed interface (configuration 2 in Fig. 2), commercially-available thermal pad, thermal glue, and thermal paste.

Table 1: Thermal conductivities and thermal resistance of reactive multilayer joints for different configurations (Fig. 2). Thermal measurements were done under a pressure of 10psi (69kPa).

Config.	**Description**	**Thermal Conductivity (W/mK)**	**Thermal Resistance (K mm^2/W)**
1	Al/Cu	65±9	2.3±0.3
2	Cu/Cu	77±11	1.8±0.3
3	Cu/AlN	97±14	7.4±1.0
4	Cu/AlN	34±5	9.4±1.3

Analysis of Thermal Exposure During Joining: Simulations were performed in order to determine the thermal exposure of the components during the reactive joining process. The simulations rely on a previously developed computational model, in which the reaction is described in terms of a self-propagating front with known velocity and heat release rate [12, 14]. The experimentally determined heat of reaction and propagation velocity (not shown) are used for this purpose. Based on this description, the melting of solder or braze layers and the temperature evolution within the bonded components are determined by integrating the energy conservation equation:

Table 2: Comparison of thermal properties of reactively joined interfaces to those of current competing technologies. In all cases, "best" measured values are reported.

Description	**Thermal Conductivity (W/mK)**	**Thermal Resistance (Kmm^2/W)**	**Literature Thermal Resistance Values (Kmm^2/W)**
Thermal Grease (Arctic Silver 3)	0.89±0.12	33±5	10-109 [21]
Thermal Pad (Akasa ShinEtsu Thermal Interface Pad)	0.67±0.10	45±6	13-168 [22,23]
Thermal Adhesive (Arctic Alumina Thermal Adhesive)	2.6±0.37	40±6	71-181 [22]
Reactively joined: Cu- Cu	77±11	1.8±0.3	3.7 [24]

$$\rho \frac{\partial h}{\partial t} = \nabla \bullet \mathbf{q} + \dot{Q} \qquad (1)$$

where h is the enthalpy, ρ is the density, t is time, $\mathbf{q}$ is the heat flux vector, and $\dot{Q}$ is the heat release rate. The temperature, T, is related to the enthalpy, h, through a complex relationship that involves the latent heats [12]. The model also accounts for the effects of thermal contact resistance, and provides for variation of the thermal contact resistance as melting occurs along various interfaces. Simulations are performed using a numerical scheme that is based on a finite-difference discretization of Eq. (1). For brevity, details regarding the scheme are omitted.

The model was first validated with the transient temperature measurements and, following validation, the computations were applied to all three material systems illustrated in Figure 2. A sample of the computations is shown in Figure 5, which depicts instantaneous temperature profiles during reactive joining of Cu-Al (configuration 1) and Cu-AlN (configuration 3). The results indicate that, while the temperature along the foil centerline can exceed 1400K, the thermal exposure of the components is very limited. Specifically, for all three configurations, the solder layers only partially melt, indicating that the exposure of the components is generally below the solder melting temperature. Closer examination of the results in fact shows that the peak temperatures experienced by the components occur at the component-solder interface and generally remain below 450K. Coupled with the fast propagation time scale and the rapid decay of the temperature, these exposure profiles are well within

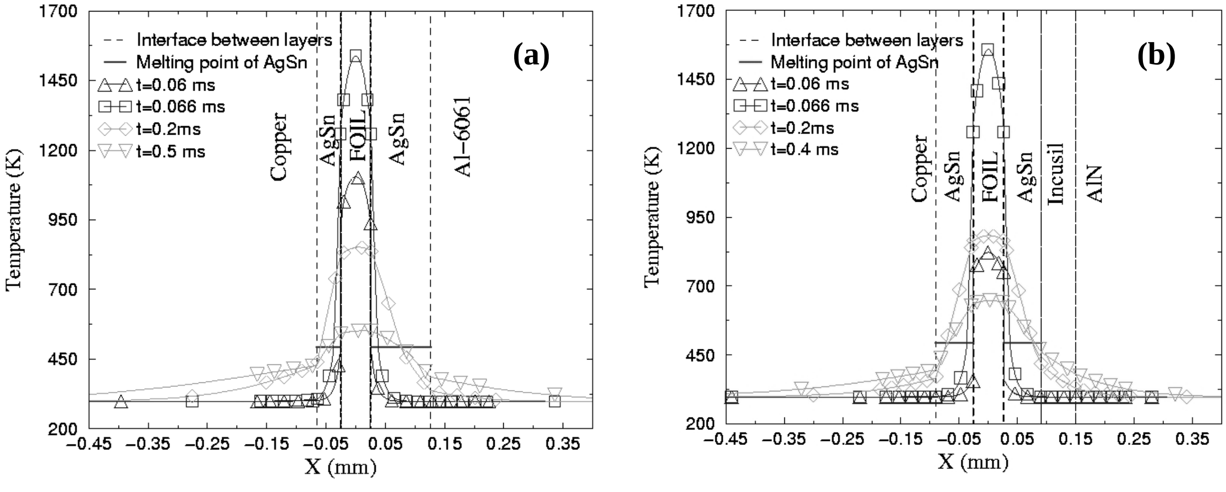

Figure 5: (a) Computed instantaneous temperature profiles for reactive joining of Cu to Al. (b) Computed instantaneous temperature profiles for reactive joining of Cu and AlN. Times at which the profiles are generated are selected so as to illustrate the temperature rise during the passage of the front and the subsequent decay.

the limits of heat sink mounting applications.

In addition simulations were also applied to explore the possibility of mounting heat sinks directly onto dies or chips, i.e. in situations where a heat spreader (typically a Cu layer) is not present. Several idealized representations of such applications have been analyzed, based on reactive joining of Cu blocks onto Si components. Briefly, the results (not shown) indicate that the thermal exposure of the chip is very limited (~400K for less than 1s) and thus provide clear support for the concept of reactive soldering Si dies directly onto Cu heat sinks without damaging the dies.

6. Conclusions

(1) Multilayer foils can be used as local heat sources to solder heat sinks to chip packages and thereby form strong, conductive, metallic interfaces between the components.
(2) The thermal conductive of the reactive joints is approximately 100 times higher than that of the best competing interface materials while the thermal interface resistances are more than 10 times smaller.
(3) The thermal exposure of microelectronic packages during joining remains limited.

7. References:

1. J.A. Floro, “Propagation of Explosive Crystallization in Thin Rh-Si Multilayer Films,” Journal of Vacuum Science and Technolgy, *A*, **4**, 631 (1986).

2. U. Anselmi-Tamburni and Z.A. Munir, “The Propagation of a Solid-State Combustion Wave in Ni-Al Foils,” Journal of Applied Physics, **66** (1989) 5039.

3. E. Ma, C.V. Thompson, L.A. Clevenger, and K.N. Tu, “Self-propagating Explosive Reactions in Al/Ni Multilayer Thin Films,” Applied Physics Letters, **57** (1990) 1262.

4. F. Bordeaux and A.R. Yavari, “Ultra Rapid Heating by Spontaneous Mixing Reactions in Metal-Metal Multilayer Composites,” Journal of Materials Research., **5**, 1656 (1990).

5. T.S. Dyer, Z.A. Munir, and V. Ruth, “The Combustion Synthesis of Multilayer NiAl Systems,” Scripta Metallurgica, **30**, 1281 (1994).

6. D. M. Makowiecki and R.M. Bionta, “Low Temperature Reactive Bonding,” US Patent 05381944, 1995.

7. T.W. Barbee, Jr. and T.P. Weihs, “Ignitable, Heterogeneous, Stratified Structures for the Propagation of an Internal Exothermic, Chemical reaction along an Expanding Wavefront,” U.S. Patent 5,538,795, 1996.

8. T.W. Barbee, Jr. and T.P. Weihs, “Method for Fabricating an Ignitable, Heterogeneous, Stratified Structure,” U.S. Patent 5,547,715, 1996.

9. T. P. Weihs, “Self-Propagating Reactions in Multilayer Materials,” chapter in “Handbook of Thin Film Process Technology,” edited by D.A. Glocker and S.I. Shah, IOP Publishing, 1998.

10. A.J. Gavens, D.Van Heerden, A.B. Mann, M.E. Reiss, and T.P. Weihs, “Effect of Intermixing on Self-Propagating Exothermic Reactions in Al/Ni Nanolaminate Foils,” Journal of Applied Physics, **87**, 1255-1263 (2000).

11. T.P. Weihs, M.E. Reiss, O.M. Knio, D.Van Heerden, T.C. Hufnagel, and H.S. Feldmesser, “Free-standing Reactive Multilayer Foils,” U.S. and PCT Patent Application filed on May 2, 2001.

12. A.B. Mann, A.J. Gavens, M. Reiss, D. van Heerden, G. Bao, and T.P. Weihs, “Predicting the Characteristics of Self-Propagating Exothermic Reactions in Multilayer Foils,” Journal of Applied Physics, **82**, 1178-1188 (1997).

13. S. Jayaraman, A.B. Mann, M. E. Reiss, T.P. Weihs, and O.M. Knio, “Numerical Study of the Effect of Heat Losses on Self-Propagating Reactions in Multilayer Foils,” Combustion and Flame, **124**,178-194 (2000).

14. E. Besnoin, S. Cerutti, O.M. Knio, and T.P. Weihs, “Effect of Reactant and Product Melting on Self-Propagating Reactions in Multilayer Foils”, J. Appl. Phys. **92**, 5474-5481 (2002).