Room Temperature Device Attach with Reactive Multilayer Foils

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Abstract

This paper describes a process investigation to rapidly solder bond semiconductor integrated chips or small components to a heat sink with minimal thermal exposure. The bonding process utilizes a foil material that, upon initiation, acts as a localized heat source to melt the solder and create a solder bond between the components. The foil is a multilayered material comprised of thousands of nanoscale layers that alternate between two elements with large negative heats of mixing. After being initiated with a small electrical or thermal stimulus, the reactive foil acts as a local heat source, melting solder on either side of the foil and bonding the components without exposing them to the high temperatures associated with typical solder reflow process. The reactive bonding process creates a true solder bond between the device and the heat sink, which provides a low thermal resistance high thermal conductivity solution, compared with traditional organic adhesive methods. In this paper we detail the optimization of these joints, using a combination of numerical modeling and experimentation, to minimize interfacial voiding while limiting thermal exposure during bonding. We show optimized bonding results for two lead-free solders, eutectic Sn-Ag and Au-Sn.

Introduction

Common methods of mounting components onto heat sinks include adhesives, mechanical fastening, and conventional solder reflow. Adhesive joints suffer from poor electrical and thermal conductivity, low strength, and can degrade over time with exposure to air. Mechanical fastening requires complex assembly processes that add to cost and design restrictions. The most commonly used alternative is conventional reflow soldering. The solder reflow process dictates that all components are exposed to temperatures higher than the melting temperature of the solder, which potentially, can damage temperature sensitive components. Reflow processes usually require the application of flux to the surfaces of the components to be joined, necessitating additional cleaning steps. Often, multiple components must be reflowed in successive process steps using solder alloys with different melting temperatures, thus creating complicated thermal hierarchies. To reduce cost, expensive components are usually attached later in the process. This decreases flexibility in the order that components can be joined and in the solders that can be used for a particular component attach process.

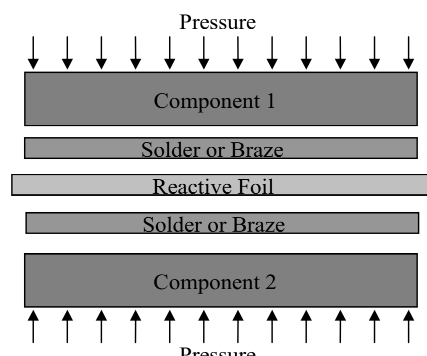

Figure 1: Schematic illustration of Nanobond® soldering process.

The use of NanoFoil® provides more process flexibility because components can be mounted in any order and with any solder,

including higher melting temperature and high strength lead-free solders (e.g. eutectic Au-Sn). In addition, the use of flux is not necessary, thus allowing the elimination of costly cleaning steps.

As shown in Figure 1, the NanoBond® joining process is based on the use of multilayer foils as localized heat sources to melt the solder. The foils are a new class of nano-engineered materials, which consist of thousands of nanometer scale layers that alternate between elements with large exothermic heats of mixing, such as Ni and Al. With a small thermal or electrical stimulus, controlled, self-propagating reactions can be initiated in these foils at room temperature. By inserting a multilayer foil between two solder layers and two components, heat generated by the reaction melts the solder and consequently bonds the components. A small applied pressure allows the solder to flow and wet all surfaces. The basis of this technology has been discussed in previous papers and presentations [1-7].

Results and Discussion

In any solder based application, both wetting and voiding are major concerns. Due to the rapid heating and cooling characteristics of the NanoFoil®, trapped gasses and surface imperfections can have a major impact on the quality of a particular bond. In order to minimize these effects, several variables can be adjusted including the type of NanoFoil® used, its thickness, as well as the type of solder employed.

In the present application, back side gold metallized 2 mm square silicon wafers were joined to gold plated aluminum heat sinks as shown in Figure 2. The joint is produced by placing a 25μm free standing Sn-Ag or Au-Sn solder perform on either side of a reactive foil preform. Eutectic Au-Sn and Sn-Ag solder were used for their high strength, wide spread use in industry and the fact that they are lead-free.

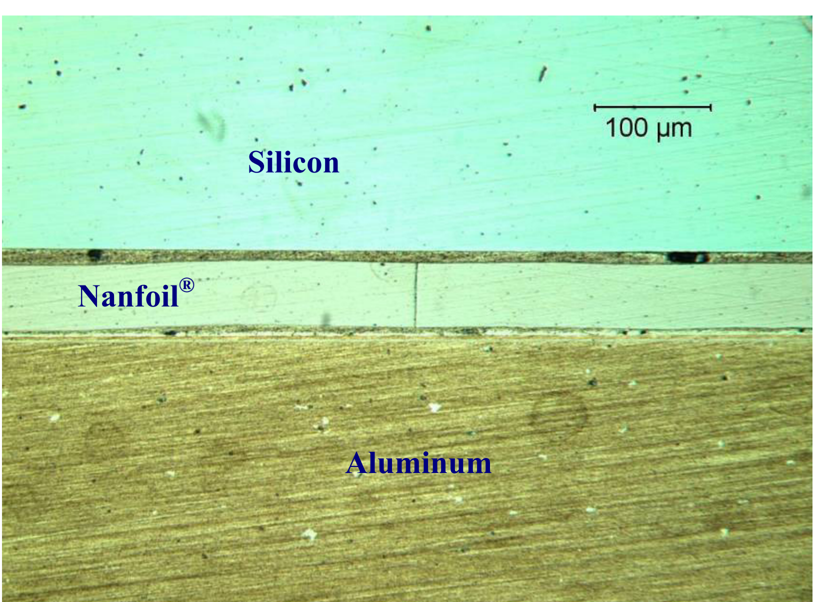

Figure 2: Optical micrograph of a Si to Al NanoBond® fabricated using a 60 micron thick Ni/Al foil and Sn-Ag solder.

Two different types of NanoFoil® material were used for this investigation. The Al/Ni foil produces a peak reaction temperature of 1450º C and a heat of reaction of -59 kJ/mol-atom, while the Al/Pd-based foil has a peak reaction temperature of 1800º C and produces -92 kJ/mol-atom. These parameters were used to numerically model the thermal exposure of the components during joining. In parallel, the void content and degree of wetting for fabricated joints were determined using acoustic microscopy.

Numerical Modeling

The thermal exposure of the various components during and immediately after the reaction of a NanoFoil® can be predicted computationally. The numerical model is based on a simplified description of the one dimensional motion of self propagating reactions that relates the nanoscale transport and kinetic phenomena within the foil, which govern the self propagation, with the thermal transport and phase evolution, which occur in the solder layers and components. The model simulates heat flow into the solder layers, phase-changes within these layers, and temperature evolution within the bonded components. The temperature evolution is obtained by integrating the energy conservation equation, which is independently solved within each layer of the assembly. The thickness and properties of the foil solder and components, such as thermal conductivity, heat capacity, heat and velocity of reaction, are incorporated into this model, along with an approximate thermal resistance for the unbounded interfaces [8-10].

Simulations were done for 60µm and 80µm thick Al/Ni foils and 40µm and 60µm thick Al/Pd foils – these foil thicknesses were selected based on previous experience. Examples of simulations for an 80 micron Al/Ni foil and a 40 micron Al/Pd foil, both using Sn-Ag solder, are shown in Figure 3. Comparing the two simulations, it is apparent that the peak temperature in the Al/Pd foil is indeed higher than that in the Al/Ni foil. Nevertheless, in both simulations the temperature of the bond drops to less than 130º C in 10 ms. In addition, the front of the silicon die does not sustain a peak temperature of more than 145º C in either of the simulations. The simulations are also helpful in terms of predicting the degree of wetting that occurs during bonding [11]. Previous experiments have shown that all other factors being equivalent (i.e. with the component surfaces having the same gold metallizations), the interface which experiences the lowest peak temperature during bonding is typically the critical interface, that is the interface least likely to be wet. Examination of the simulations in Figure 3 indicates that this interface is the aluminum/solder interface. This is to be expected based on the higher thermal conductivity of Al (237 $W \cdot m^{-1} \cdot K^{-1}$) compared with Si (148 $W \cdot m^{-1} \cdot K^{-1}$). The peak temperature experienced by this interface, as well as the duration of melting of the solder during bonding for each of the bond configurations is included in Tables 1 and 2.

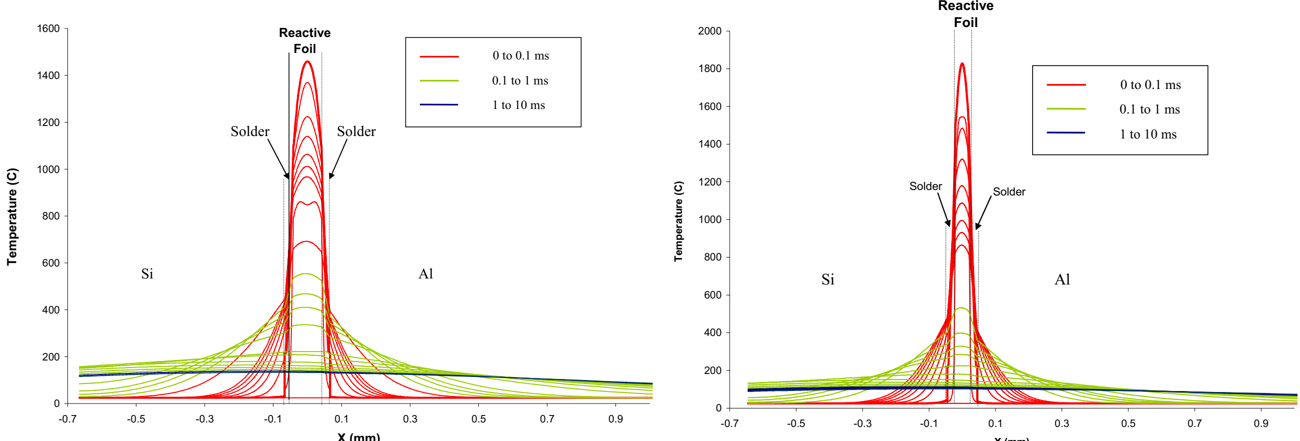

Figure 3: Thermal profile simulations for 80 micron Al/Ni foil (left) and 40 micron Pd/Al foil (right) with Sn-Ag solder.

Scanning Acoustic Microscopy

For the purpose of designing and optimizing the joint configurations, the joints were evaluated for wetting and voiding characteristics through the use of Scanning Acoustic Microscopy (SAM). SAM is

an imaging technique that utilizes changes in material properties across interface boundaries to detect the presence of internal flaws and anomalies. Differences in acoustic impedance (Z = density · acoustic velocity) at a material interface result in a change in the response to an incident sound wave. A portion of the ultrasound is reflected back to the transducer from the material boundary, while the remainder propagates through the boundary. The reflectance R, which is the fraction of ultrasound reflected back to the transducer at a single interface, is defined by the following relation:

$$R = (Z2 - Z1)/(Z2 + Z1) \qquad (1)$$

where, Z1 and Z2 are the acoustic impedances of the first and second media respectively.

As the difference in acoustic impedance increases, so does the reflectance at the material boundary. If both materials have similar acoustic impedances, then most of the ultrasonic signal is transmitted through the material boundary. When air is present at an interface, the reflectance is 100%, since air has an acoustic impedance of zero and all of the ultrasound is reflected back to the transducer.

Ultrasound at high frequencies does not travel through air due to attenuation. Therefore, water is used as a coupling medium. Two modes of operation can be used to produce SAM images: pulse echo, in which the ultrasound reflected back to the transducer is digitized to produce the image and through-transmission mode, in which a second receiving transducer examines the ultrasound transmitted through the sample to produce the image (Figure 4). The pulse echo mode was used to produce the C-scan images for this study. A peak amplitude C-scan is produced by raster scanning over a sample and recording the peak amplitude from a certain depth within the sample at each (x,y) location. Based on the strength of the reflected echo, each pixel is mapped to a gray scale color. A pixel with high signal strength is assigned a lighter shade of gray compared to one with lower signal strength. Since air is a strong reflector, the presence of air is identified on a C-scan image by bright areas. An A-scan is the RF data at a single (x,y) location. Since every material boundary reflects a portion of the ultrasound, the peaks in the A-scan of Figure 4 correspond to the different interfaces in the joint construction.

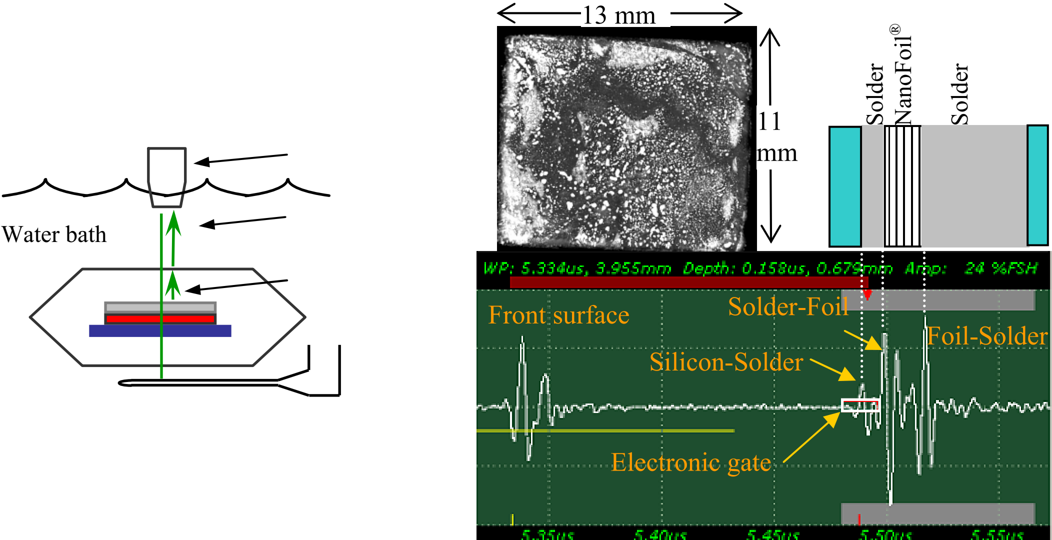

Figure 4: (Left) Schematic demonstrating the propagation of ultrasound through a sample. (Right) A-scan identifying the separate interfaces in the bonded sample. Top left shows the C-scan of the electronic gate.

Representative C-scans for all of the bonds fabricated using Sn-Ag solder, along with their estimated void content, are shown in Table 1. As can be seen in the C-scan for the 60µm Al/Ni foil, the joining process produced considerable voiding and resulted in a poorly bonded joint. The table also includes the duration of melting for the solder and the peak temperature of the critical interface, both values obtained by numerical modeling. By comparing the C-scans of joints fabricated with 60µm Al/Ni foil and 40µm Al/Pd foil, it can be seen that although they displayed similar solder melt durations, the Al/Pd foil produced a much higher peak temperature, suggesting that it is the combination of these two values that determines whether wetting occurs or not.

Table 1: Acoustic scans and numerical simulations for Si dies bonded to Al with Sn-Ag solder

Nanofoil® Type	60 µm Al-Ni	80 µm Al-Ni	40 µm Al-Pd	60 µm Al-Pd
C-Scan of the bond interface				
Voids (%)	35	10	9	11
Melt Duration (ms)	0.483	.991	.487	1.303
Peak Temp (ºC)	296	343	360	448

Acoustic microscopy scans, as well as melt duration and peak temperature simulations for bonds fabricated with Au-Sn solder are shown in Table 2. It is clear from the C-scans that only the bonds fabricated with 60µm thick Al/Pd foils produced low void content joints with good wetting. Comparing the peak temperatures at the critical interface with those for the Sn-Ag samples in Table 1, it is clear that a much higher temperature is required to get the Au-Sn to wet and bond than for the Sn-Ag solder. This would be expected based on the difference in melting point between Sn-Ag (221º C) and Au-Sn (280º C) solder alloy.

Table 2: Acoustic scans and numerical simulations for Si dies bonded to Al with Au-Sn solder

Nanofoil® Type	60 µm Al-Ni	80 µm Al-Ni	40 µm Al-Pd	60 µm Al-Pd
C-Scan of the interface				
Voids (%)	70	50	43	9
Melt Duration (ms)	.251	.548	.286	.736
Peak Temp (ºC)	346	395	419	514

Interestingly enough, the lowest void content achieved for both the Sn-Ag and Au-Sn joints was approximately 10%. It is also noteworthy that for the Al/Ni samples the void content, once wetting was achieved, did not appear to be strongly dependent on the melt duration or peak temperature at the critical interface. This suggests that additional optimization of other parameters, such as the pressure applied to the components during joining, surface finish of the components, or cleanliness of the interfaces being bonded, is required to reduce the void content further.

Conclusions

Small area die bonds with less than 10% voiding were fabricated using the reactive joining process for both Ag-Sn and Au-Sn solders. Simulations indicated that during bonding process, the face of the die experienced less than a 145º C peak temperature and cooled to below 130º C in less than 10 ms. The threshold for achieving wetting (and low void content) is dependent upon the peak temperature at the critical interface, but once wetting is achieved, the void content is not sensitive to either peak temperature or solder melt duration for the range of reactive foils studied.

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