Ultra-Precision Metal Additive Manufacturing for Thermal Management of Microelectronics

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1. Introduction:

1.1. Thermal management of electronic and photonic devices: State-of-the-art

Thermal management of microelectronic devices is an ongoing technological challenge that directly affects device-level and system-level performance and reliability [1]. The fundamental process of electron transport in a transistor device results in dissipation of heat. This causes temperature rise, which in turn limits device performance. For most semiconductor devices, performance goes down with increasing temperature due to reduced charge carrier mobility [2]. Several reliability concerns are also encountered at high temperature. Most semiconductor technologies have a specified peak temperature that the devices are capable of withstanding.

Typically, the extent of thermal management required depends on the total power expected to be dissipated and the reliability requirements for the semiconductor device. A number of strategies are typically adopted for thermal management to ensure effective dissipation of the generated heat. These strategies may be classified in a number of ways: active vs. passive thermal management, hardware vs. software based thermal management, and design-stage vs. run-time thermal management.

Active thermal management refers to heat removal using an actively cooled thermal management strategy, such as fan blowing over a heat sink, whereas passive thermal management refers to heat removal using other approaches such as a heat spreader. Hardware strategies include the use of heat sink, heat pipe or other mechanisms to direct the flow of heat away from the device, whereas software strategies include intervention in device operation depending on the device temperature. For example, based on temperature measured through temperature sensors embedded in microprocessor cores, load reallocation is often performed to reduce the load on cores that are running too hot. In an extreme case, if the measured temperature reaches a critical threshold, the microprocessor is switched off completely to avoid physical damage. Design-stage thermal management refers to thermal-friendly design of the microprocessor architecture to ensure effective thermal dissipation, for example, by allocating sufficient physical distance between heat-generating blocks. Run-time thermal management refers to hardware and software based thermal interventions during operation to manage the device temperature.

Over the past several decades, the number of transistors on a semiconductor microprocessor has roughly doubled every two years, validating the prediction of the so-called Moore's law. As a result, the thermal management problem has also become progressively more challenging. Architectural innovations such as multicore designs have helped mitigate the heat dissipation problem somewhat, but nevertheless, performance and reliability of devices and systems continues to be gated by thermal considerations, for both low-power consumer electronics such as cell phones, as well high power devices such as power amplifiers and high-speed microprocessors used in data centers and supercomputers. Historically, the first attempts at thermal management included the provision of a metal-based heat spreader on the die backside, along with a heat sink with extended surface area to facilitate convective heat transfer. Heat pipes are ubiquitous in the electronics cooling industry and operate under the principle of evaporation and condensation of a working fluid to transport heat from the electronic component to the heat dissipating zone. Microchannel liquid cooling has also been investigated in a limited set of applications, starting from the first demonstration in the classical paper by Tuckerman and Pease [3]. Two-phase microchannel cooling, which involves the evaporation of a coolant liquid flowing in micro channels, offers much higher heat removal rates, but suffers from several technological challenges.

With the recent interest in new microprocessor architectures such as three-dimensional integrated circuits, there has been recognition for novel approaches for thermal management of such architectures. Due to the reduced availability of surface area for cooling, three-dimensional architectures necessitate a liquid-based cooling approach, in which liquid delivery to various strata of the multi-die stack, and heat removal through such a liquid network, become challenging problems. In addition, the role of the through-Silicon via (TSV) as a dual-physics element has also been investigated. A TSV facilitates both electrical and thermal transport [4].

Another key research direction of significant current interest is the design of materials with novel thermal properties. In particular, much research has been carried out to optimize the thermal and mechanical performance of thermal interface materials used to bond the die backside to the heat spreader or heat sink [5]. For example, the inclusion of novel materials such as carbon nanotubes and graphene has been widely investigated [6].

Despite the critical need for thermal management and ongoing research on novel materials and architectures, the semiconductor industry continues to be heavily cost-driven. Any new innovations in thermal management must compete with well-established approaches both in terms of technical performance as well as cost.

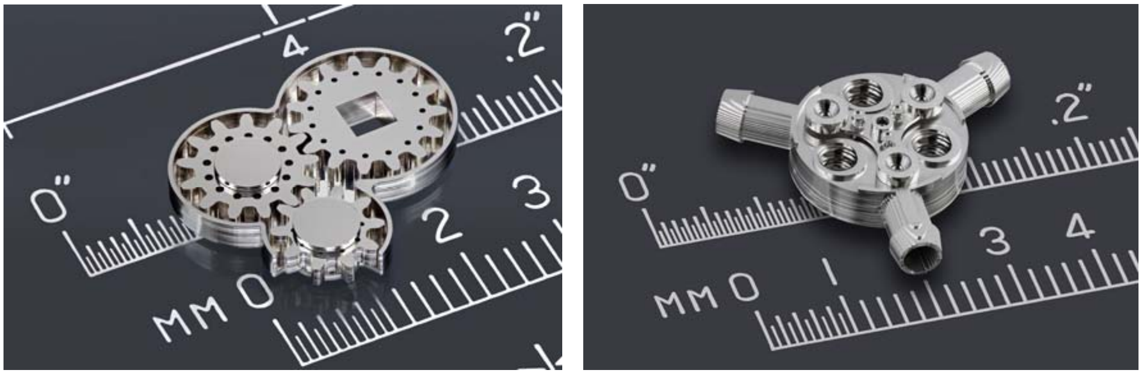
1.2. Overview of additive manufacturing and MICA Freeform

Since the late 1980's, additive manufacturing (a.k.a. 3-D printing) has grown very significantly in terms of the diversity of processes, available materials, and performance, taking it well beyond its initial uses making models, prototypes, and tooling to encompass functional end-use parts. In particular, 3-D printed metal parts have in recent years been adopted frequently for use in dentistry, and are rapidly finding aerospace applications.

While most 3-D printing processes are not easily scaled to high-volume applications, Microfabrica's MICA Freeform process—an ultra-precision additive manufacturing process for millimeter-scale parts with micron-scale features—is routinely used to produce millions of parts each year. The MICA Freeform process can also fabricate functional "printed assemblies" comprising multiple moving parts for which no assembly is required. The MICA Freeform process is used in a variety of industries including semiconductor, medical and aerospace.

As with other 3-D printing processes, parts fabricated using the MICA Freeform process are built with layers. The MICA Freeform process involves three primary steps per layer. First, a fully-dense structural metal is electrodeposited onto a substrate in selected regions corresponding to the desired cross section of the part to be fabricated. Deposition occurs through apertures in a photoresist patterned using a sub-micron resolution photomask, in a method similar to that used in semiconductor fabrication facilities. After removal of the photoresist, a sacrificial metal is blanket-electrodeposited over the structural metal. Finally, both metals are planarized to yield a layer that is flat, planar, and of precisely-controlled thickness. The three steps are then repeated for all layers required, after which a chemical etchant is used to dissolve the sacrificial metal, releasing the parts.

Figure 1 shows images of typical parts manufactured using the MICA Freeform process. The MICA Freeform process provides tolerances of approximately +/- 2 µm, and minimum features as small as 20 µm in the horizontal plane and 5 µm along the vertical plane. The process uses several fully-dense engineering grade metals which include Valloy-120, nickel-cobalt alloy comparable to stainless steel, pure palladium, and rhodium. These metals have excellent mechanical properties and corrosion resistance. Copper can also be embedded within the Valloy-120 and palladium metals for electrical and thermal applications.



(a) (b)

Figure 1. Images of parts manufactured using the MICA Freeform process.
(a) Gear train assembly, (b) Micro fluidic device

Due to its ability to combine metals and provide precise control over geometry at the microscale, yet produce parts that are millimeters in size, the MICA Freeform process has potential application in thermal management devices where precision features (i.e. microchannels and jet impingement orifices) and large surface area-to-volume ratios which can substantially improve heat transfer.

2. Opportunities for thermal management using ultra-precision additive manufacturing:

The MICA Freeform additive manufacturing process offer several unique capabilities not available with traditional manufacturing. These capabilities may extend the state-of-the-art for thermal management of semiconductor devices and systems. A few unique capabilities are discussed below:

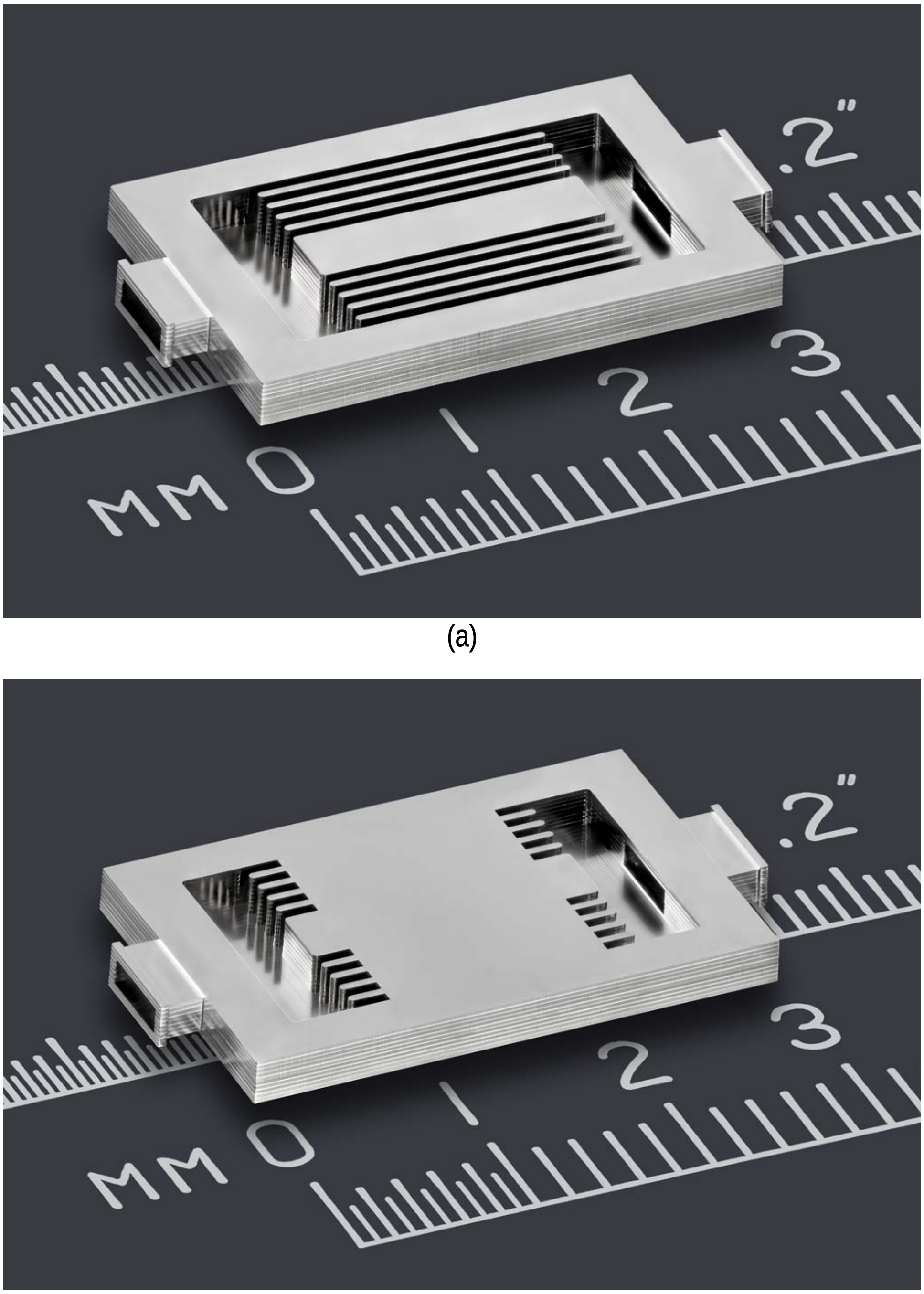
2.1. Optimized heat transfer through high precision liquid cooled micro channels and jet impingement architectures

Liquid cooling using microchannels have been shown to offer exceptional heat transfer performance with low board level form factors. This is partially due to the high heat transfer coefficients that are achievable at these small length scales [3,7]. The MICA Freeform process offers a unique proposition for manufacturing microchannels that can be much more precise and complex than what has been done in the past. Microchannels fabricated with the MICA Freeform process can have features as small as 20 μm and have tolerances of +/- 2 μm. The flexibility of the MICA Freeform process allows microchannels to be optimized for fluid transport to specific hot spots. Multi-level microchannels can be used to distribute and remove fluid efficiently, potentially reducing internal pressure drops. Figure 2(a) shows an image of a thermal device with exposed microchannels that are 225 μm tall and Figure 2(b) shows an image of a heat sink with embedded micro channels that are 200 μm tall. The channels in both of these devices are 65 μm wide and are separated by 50 μm walls. The microchannels of these devices are strategically positioned to direct the coolant over known hot spots of the IC. Inlet and outlet manifolds are positioned at the edges of the thermal device to reduce the overall profile of the system. The overall size for both devices are 2mm by 3 mm.

Jet impingement has been demonstrated to reduce thermal resistance and improve thermal cooling of IC chips [8, 9]. True 3-dimensional geometries can be fabricated using the MICA Freeform process to create unique jet impingement architectures to cool localized hotspots on ICs. The size, shape and position of the orifices can be optimized for maximum performance. The freedom of design offered by the MICA Freeform additive manufacturing process enables new design possibilities never feasible before.

2.2. Enhanced convection due to increased surface area

When compared to traditionally manufactured parts, additive manufacturing offers the possibility of dramatically increased surface area for the same overall part size. The capability to readily fabricate 3-dimensional parts, compared for example, to extrusion, enables large surface-area-tom volume ratio parts to be produced. This is obviously a significant advantage

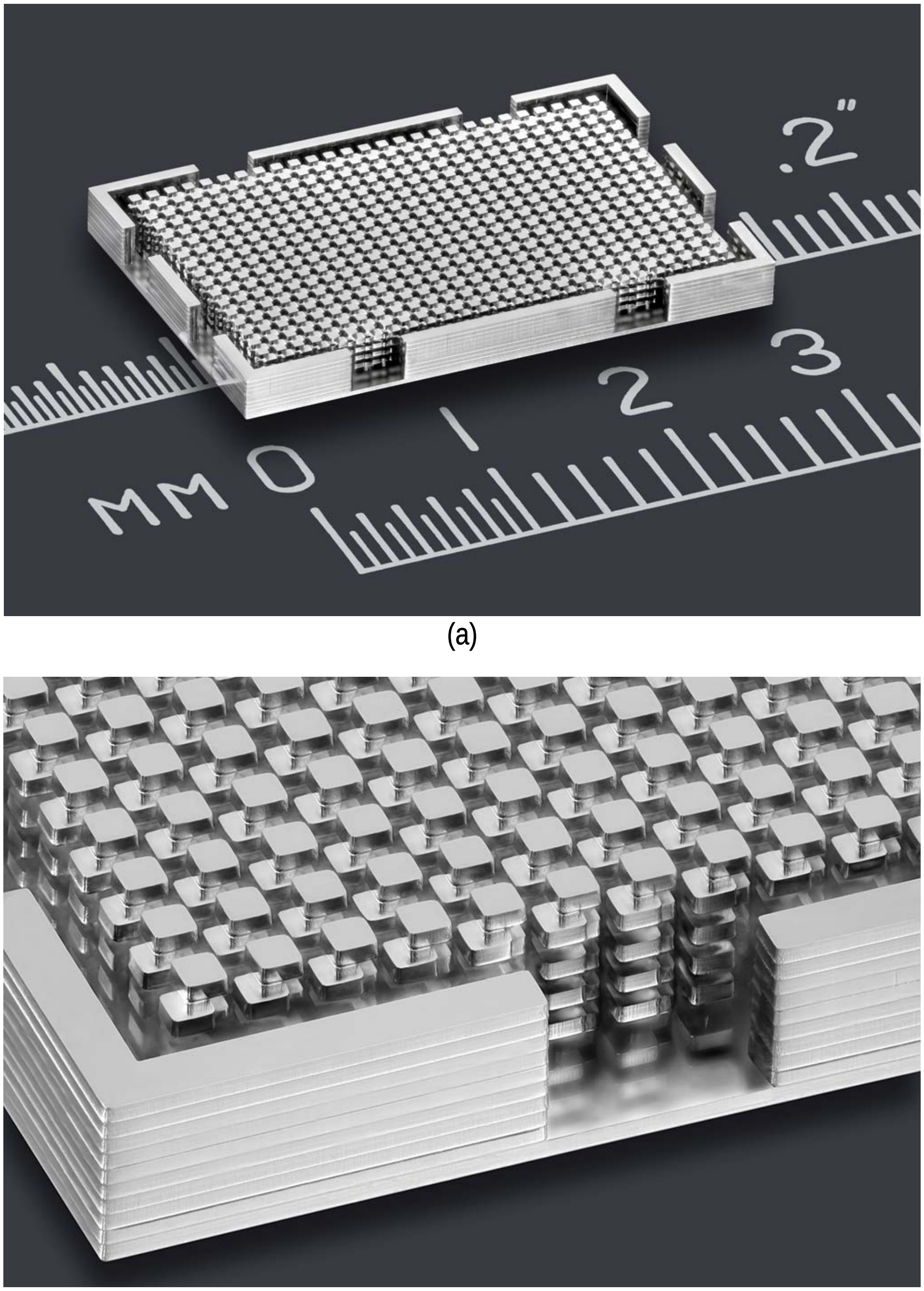


(a)

(b)

Figure 2. Images of devices manufactured using the MICA Freeform process.
(a) With exposed micro channels, (b) With embedded micro channels

for convective heat transfer, where the effective thermal conductance of the heat sink is directly proportional to available surface area. Traditional heat sinks employ surface area extensions such as pins and fins for increasing surface area, and this effect could be dramatically enhanced by employing an additive manufacturing approach, in which the part could be sculpted in three dimensions with precise control. In addition to enhanced surface



(a)

(b)

Figure 3. (a) High surface area part manufactured using the MICA Freeform process, (b) High surface area micro pillar structure

area, geometrical features on the part could be designed and manufactured to specifically enhance flow mixing which will result in further enhancement in heat removal [11]. Figure 3(a) shows an image of a cooling structure, manufactured using the MICA Freeform process, with an overall footprint of 2 mm x 3 mm and is 0.25 mm tall. This heat sink has achieved large surface area by tightly nesting 459 (17 x 27 array) micro pillars made of alternating 60 μm square features that are attached at one corner. A close up image of these pillars is shown in Figure 3(b). The total surface area of the micro pillars is 43.6 mm^2, which is over 3x the surface area compared to a heat sink with 100 μm wide fins and channels that fit in the same footprint and have the same overall height.

2.3. Integrated composite structure with optimized material pallet

Traditional heat sinks and cold plates are composed of a single material (i.e. copper, aluminum). These materials are usually chosen because of their high thermal conductivity. Other considerations for liquid based thermal management systems include corrosion resistance, ease of integration with the chip and erosion due to particles in the fluid or high flow rates. There is not a single metal that can be optimized for all of these requirements. Metal alloys are sometimes used but suffer from compromised performance for each requirement.

The MICA Freeform process has the unique ability to fabricate a composite structure using multiple metals. For example, the top and bottom surfaces of the heat sink can be made of palladium, which has several inherent advantages. Palladium is a platinum group metal and corrosion resistant to most chemicals, making it the ideal material to be in contact with the liquid coolant. The palladium oxidation temperature of 800ºC is significantly higher than copper, which oxidizes at room temperature. Therefore, palladium is typically free from oxides and easily wettable by solder, allowing it to be directly attached onto the surface of a chip, reducing the thermal resistance at the interface of the heat sink or cold plate. Copper oxidizes easily, making direct solder integration to an IC problematic. A thermal grease or adhesive is typically used with copper heat sinks, which adds thermal resistance to the overall system. Some micro fluidic systems suffer from long term erosion due to high flow rates or particles in the fluid. The hardness of palladium (400 MPa HV) is higher than aluminum (160-350 MPa HV) and copper (343-369 MPa HV), and will therefore have higher wear resistance against erosion. For improved wear resistance, the MICA Freeform process can also incorporate rhodium in targeted regions. Rhodium is also corrosion resistant and has a hardness of 1100 MPa HV making it extremely resistant to wear. Copper, which has a

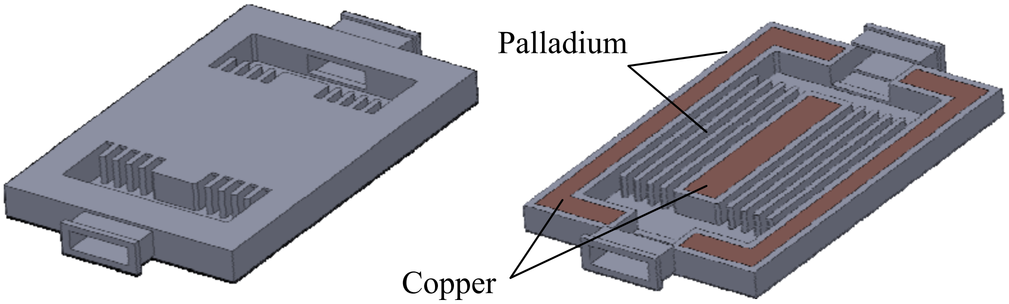


Figure 4. Cross-Sectional view of a thermal management device showing locations of embedded copper

thermal conductivity of around 40 $W \cdot m^{-1} \cdot K^{-1}$, can be embedded within the heat sink or cold plate to enhance the thermal conductivity of the device. Figure 4 illustrates a cross-section of a thermal management device indicating the locations of embedded copper. The copper is fully encapsulated by palladium, isolating it from the coolant. The MICA Freeform process offers a truly unique solution for thermal management with a multi-metal composite structure optimized for thermal conductivity, corrosion resistance, solder wettability and wear resistance to erosion.

3. Conclusion

Thermal management of microelectronic devices continues to remain a critical technological challenge. Effective mechanisms to remove heat from microelectronic devices not only improves device performance, but also results in improved reliability. The MICA Freeform process may facilitate drastically new approaches for thermal management by enabling high precision, microchannels and jet impingement architectures, increasing surface area of heat sinks with complex geometries, and integrating multiple metals in a composite material structure to enhance performance of a thermal management device.

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