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Novel cooling strategy for electronic packages: Directly injected cooling

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ABSTRACT

This publication describes the development of a novel cooling strategy for electronic packages. During the conceptual design phase, the engineering disciplines involved are considered simultaneously. Through a case study, it is demonstrated that this integrative approach is an effective methodology leading to an innovative design. A novel, improved and highly integrated cooling strategy for electronic packages is presented. Standardized package types, as for instance ball grid array packages, are equipped with a directly injected cooling support. The developed concept is a new and very cost effective concept, as fewer productions steps and fewer procured parts are required compared to traditional cooling concepts. The new concept is also easily scalable, as multiple components on an electronic product can be cooled both uniformly across the product and simultaneously. This increases design flexibility and results in electronic products with advantages in terms of performance, compactness, weight and production efficiency.

1. Introduction

The last two decades, thermal management is becoming *the* challenge area in electronic product design. Worldwide, both consumer and industry continuously demand more functionality, better performance and increased product miniaturization. As a result, power dissipations increase on even smaller surfaces, thus intensifying local heat fluxes. To cope with these growing thermal issues, the thermal design process of electronic products plays an increasingly dominant role in the total design process.

This study focuses on developing a novel cooling strategy for electronic packages. Fig. 1(a) shows a general view of such an electronic package. The heart of the package is formed by the semiconductor die or integrated circuit (IC). Here, all active electronic processes take place, and thus all heat is also generated here. Packaging requirements make it often impossible to attach the IC directly to a printed circuit board (PCB); therefore, a rigid laminate is used in between. Electronic signals to and from the IC run through bondwires, vias in the rigid laminate and solder balls to the supporting PCB. In this case, the ball grid array (BGA) interface is used for both electronic signals and mechanical fixation. Other standardized packaging types such as land grid arrays (LGA), pin grid arrays (PGA), stud bump arrays and quad flat-no leads (QFN) are also often seen. Finally, the IC is protected from the environment by a mold compound (on a component level). In Fig. 1(b) some actual products with a BGA package are shown.

In this study, cooling strategies based on conduction and convection of air are primarily addressed. The authors acknowledge advanced cooling concepts of, for instance, two-phase or on-chip principles as interesting cooling solutions. However, as conduction and air convection are relatively straightforward to implement, we strive to extend the limits of these solutions. The cooling system to be designed should be able to keep an electronic product at a relatively uniform temperature. In addition, a scalable solution is demanded, as electronic products often comprise multiple packages.

Instead of focusing only on the thermal issues, the total design is researched in an integrative approach. In-depth and coherent knowledge of the engineering fields involved (i.e. electronics, mechanics, heat transfer and production) is required to pursue the best system performance at the lowest cost. By designing for all engineering disciplines, a level of product integration previously unseen in cooling solutions is aimed for. However, this integration should not be at the cost of flexibility. Still an overall flexible design in terms of scalability, electronic component layout and electronic product embodiment is demanded. Finally, as electronic production technology is appreciated for low cost, mass market applications, the cooling strategy to be designed should not impede this.

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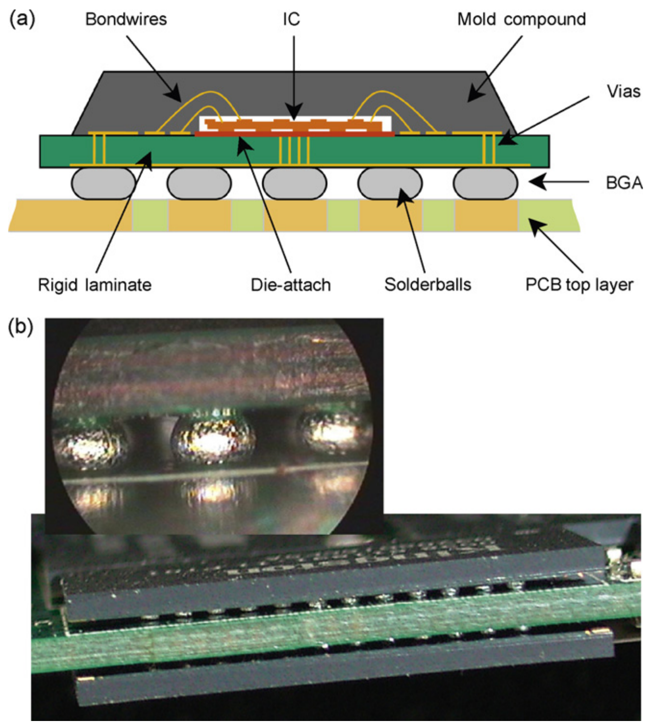

Fig. 1. Ball grid array (BGA) package: (a) schematic cross-section; (b) actual products.

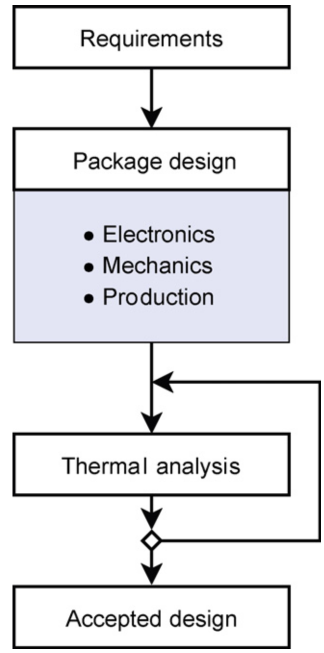

Fig. 2. Traditional design process from a thermal perspective.

2. Design methodology

2.1. Traditional design approach

Traditionally, the design process of most electronic products has been dominated by electrical and mechanical requirements. As cooling is generally not a primary function of electronic products, thermal analyses were usually addressed toward the end of the design process. This is illustrated schematically in Fig. 2 for the case of subject electronic package design.

In the struggle to keep pace with increasing semiconductor performances, add-on cooling devices are becoming grotesque in size and power consumption. Although traditional forced convection cooling may have sufficient cooling potential in theory, it is constrained by the fact that the heat-dissipating component usually cannot be directly exposed to the cooling air. In other words, the generated heat has to travel from the IC through a series of thermal resistances before it is finally dissipated to the ambient environment. These thermal resistances consist, for instance, of adhesive layers, encapsulation resins, solder connections, pockets or layers of stationary air, etc. This results in a significant and often unacceptable temperature gradient across the IC, the package and the heat sink.

Until recently, thermal management aspects scarcely impeded an optimal product design. However, the state of the art in semiconductor technology has reached a thermal limit. Current package sizes are not in accordance with their required heat sinks. To solve this, our approach focuses on a more substantial thermal engineering contribution earlier in the design phase.

In many cases, electronic packages dissipate most heat through their top surface to either a heat sink or a more sophisticated (active) cooling device. This has little impact on the PCB design itself. However, this technique has its limitations as in most cases thermal resistance from the semiconductor IC to the package top surface is relatively high. Moreover, in some applications the component's top surface is not even accessible, in particular when the electronic package is (part of) an integrated sensor. In these cases, most of the heat must be dissipated through the bottom and "footprint" of the package through the PCB. Although, in many cases, the bottom side of electronic packages has the lowest thermal resistance, this side is often not directly exposed to a coolant medium because it is facing the PCB. Generally, PCBs have a poor thermal conductivity, due to its low conductive polymeric layers. The conductivity can be moderately improved by adding more or thicker copper layers. In fact, adding additional amounts of metal and using thicker metallic layers is generally seen as a genuine method to enhance cooling capabilities through board structures. Needless to say, this is not very weight efficient.

2.2. Integrated design approach

As indicated, due to thermal management issues a new cooling strategy is required to manage heat dissipations of electronic packages. This is not just an isolated case. In fact, recent research publications indicate that a limit has been reached for cooling electronics in general [1–3]. As a result, the continuous product improvement cycle threatens to stall, if no appropriate action is taken toward thermal innovation in the design and manufacturing process. This challenge is addressed by applying a domain integrative design approach, resulting in further integration of primary and support functions [4]. Knowledge of heat transfer principles is integrated into the overall design process, as illustrated in Fig. 3.

Although the design process may seem more compact, it actually tends to become more complex due to the addition of thermal aspects. A greater number of conflicting relationships needs to be considered, to establish cause-and-effect coherence. The basic strategy is to reduce thermal resistance between the heat source and its corresponding heat exchanger, thereby bringing the coolant (thermally) closer to the heat source.

Suppose the PCB can be thermally bypassed and components can be cooled adequately, then they would be less sensitive to nearby components on the board. Hence, denser boards can be designed, which leads to more compact boards as well. In the case of subject electronic packages this strategy and the adapted design

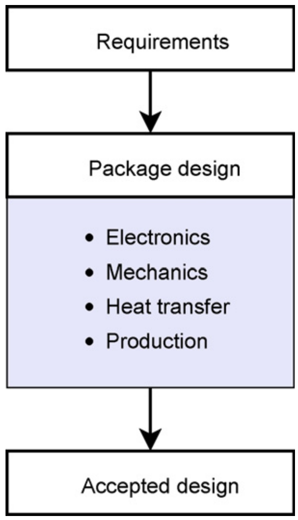

Fig. 3. Integrated design process.

process have lead to several cooling concepts, which will be presented in the next section.

3. Concept generation

Using a schematic model of the electronic package shown in Fig. 1, the concepts will be evaluated theoretically. The models show the IC (in red) on a rigid laminate. This laminate is connected to the PCB by the solder balls of the BGA.

Suppose no space is available for a cooling device on the top of the package, as for instance is the case for an integrated sensor, visual indicator or a packed board with many components. Then an available concept is to provide a cooling solution on the opposite side of the board. This is illustrated in Fig. 4, where thermal vias are placed in the PCB between the package and the cooling device to transport the heat efficiently through the board. This type of cooling can be applied by mounting an external cooler, such as a heat sink, to the board.

Although the thermal vias provide a better conducting path to the heat exchanger, the losses are still significant. Bottlenecks are the BGA interface and the vias; they contribute to up to 90% of all thermal losses, as computed by Brok [5]. Increasing the number of vias is also quite expensive.

An improved concept is shown in Fig. 5. Here, heat travels through a single conducting element, instead of through the BGA and the thermal vias. From a thermal point-of-view this concept is acceptable, however in practice it is hard to manufacture. The conducting element has to be positioned against the package with enough preload to obtain a proper thermal connection.

There are many drawbacks to both presented approaches. For instance, by mounting a cooling device on the opposite side, the ability to use this side for mounting electronics is lost. Also, in light of this study, this approach does not result in a more compact electronic product, as in fact only the location of the cooler shifts from the top to the bottom. In an effort to diminish the thermal effects of the PCB, the heat exchange location is brought closer to its corresponding heat source.

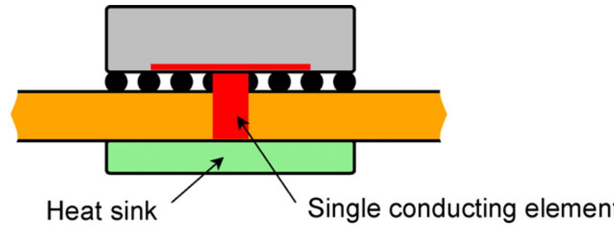

Fig. 5. Cooling through a conduction element.

The concept of in-board cooling places the heat exchanger inside the board directly below the electronic package, as shown in Fig. 6. The heat exchange area is fabricated by machining a cavity in one of the layers prior to laminating the PCB. From the opposite side two holes must be drilled to connect inlet and outlet ports to the cavity inside. For efficient heat transfer, thermal vias can be placed in the board layers separating the top and the cavity inside.

Conditioned air can be pumped through the cavity to transport the heat away from the component. As no external heat sink is required, this saves assembly steps and weight for the final product. However, additional assembly steps are necessary to supply each cavity with air. One cooling line per BGA package suffices, as the hot air from the outlet port can be bled directly into the environment.

As both the inlet and outlet ports of the presented in-board cooling concept are on the same side, this implies the use of cooling lines to supply coolant to the heat sources. These cooling lines are the main drawback of this concept, as, especially for a PCB with many heat sources, many are required. This issue is resolved in the next concept, where the heat exchange area is moved further up toward the heat source.

Upon closer inspection, the BGA interface bears quite some resemblance to a traditional heat sink heat exchanger. Both have a flat base and extensions to enlarge surface area. In a BGA interface the extensions are formed by the solder balls. The concept of directly injected cooling is illustrated in Fig. 7. Cooling air flows through the BGA, extracting heat from the electronic package through the bottom side. Hence, the BGA not only has an electrical and mechanical function, but also acts as a heat exchanger; possibly reaching total functional integration in light of this research.

The only dedicated feature of this concept is a through hole in the PCB, which can be produced using standard PCB production techniques. Conditioned air is pumped from the backside to the front through the hole in the PCB. Instead of connecting a cooling line to each individual heat exchanger, the entire PCB with numerous BGA packages can also be placed on a pressure chamber to supply coolant to all heat exchangers simultaneously.

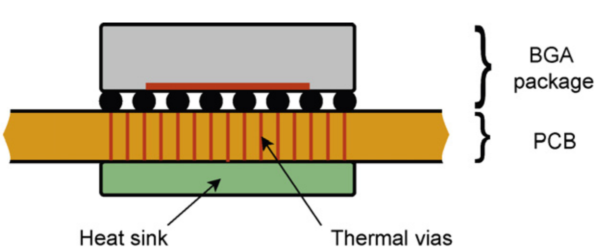

Fig. 4. Cooling through thermal vias.

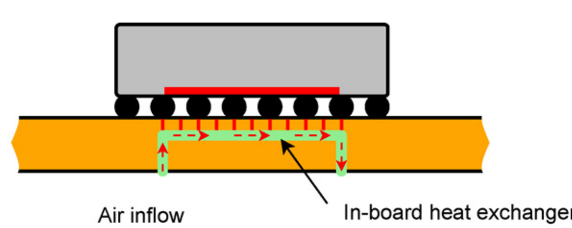

Fig. 6. Concept of in-board cooling.

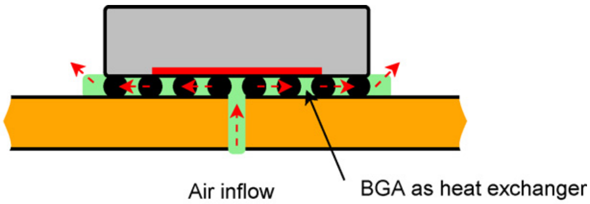

Fig. 7. Concept of directly injected cooling.

This concept, for which a patent is granted [6], is expected to work well for all sorts of commercial electronic packages; however, it is especially promising for high-density cooling, where many components need to be cooled simultaneously. A technology demonstrator and measurement results in a controlled environment are presented in Sections 5 and 6, respectively.

4. Detailed conceptual design

4.1. Principle cooling strategy

In the concept of directly injected cooling, an air jet is positioned to impinge on the bottom surface of the electronic component. After impinging on the bottom surface, the air spreads radially underneath the component. Here, the solder balls of the BGA are not only used for the transmission of electronic signals and mechanical fixation, but also act as an integrated heat exchanger. As the heated air reaches the edge of the component, it is bled into the environment. The jet nozzle is formed by drilling a through hole in the PCB. The number of through holes – and thus number of jets – should be determined by the thermal criteria of the mounted component. However, it is obviously limited to the footprint area of the package.

The standoff distance of a BGA component is usually determined by the size of the solder balls and the amount of solder required to make a reliable electrical and mechanical connection. However, in this concept, adequate height must also be realized for the coolant medium to pass through, absorbing as much power as required; for instance, by selecting smaller or larger solder balls.

By injecting air directly into the BGA, the air is brought very close to the hot underside of the rigid laminate, thus bypassing several thermal resistances. In addition, as the cooling air approaches the hot surface from a perpendicular direction, the jet impingement effect will also occur. This increases the heat transfer rate compared to tangent flow by locally breaking through the thermal boundary layer. Finally, as a BGA typically has a large number of solder connections, the heat exchange area is relatively large. As the air spreads underneath the package, the solder balls act as a static mixer, which improves forced convection heat transfer even further. In an advanced set-up, the balls could even be placed in such a way that cooling potential is maximized. Both forms of heat transfer (i.e. jet impingement and forced convection) are illustrated in Fig. 8.

4.2. Jet impingement theory

Important parameters for confined jet impingement, according to Glynn et al. [7], and Colucci and Viskanta [8], are the Reynolds number of the air flow and the ratio of jet-to-target spacing and jet diameter. For optimal heat transfer, this ratio should be low, close to unity:

$$\frac{h}{d} \approx 1 \quad (1)$$

The jet-to-target spacing (h) is determined by the standoff distance of the rigid laminate. For BGA packages this is typically 0.5–1 mm. The jet diameter (d) is determined by the size of the hole(s) in the PCB. Both properties are also illustrated in Fig. 8. According to Eq. (1), the diameter should approximately equal the standoff distance. Also, to optimize heat transfer a high Reynolds number, and thus high air flow velocity should be used. However, in practice this is limited by both the maximum pressure the system can endure and pumping capacity.

Based on the literature used, a local heat transfer coefficient of at least 1500 W/m^{2}K should be feasible. By combining this value with the thermal conduction properties of a typical BGA package, with an IC of 1 cm^2, an overall thermal resistance from junction to ambient environment as low as 8 K/W can be obtained. Here, thermal resistance is defined as

$$R_{th} = \frac{\Delta T_{junction \rightarrow ambient}}{Q_{dissipated}} \rightarrow R_{th} \approx 8\,\text{K/W} \quad (2)$$

This value includes the heat conduction from the junction to the bottom of the package (≈1 K/W) and heat convection caused by the cooling jet air (≈7 K/W).

The maximum allowed junction temperature of ICs is specified by many manufacturers at 150 °C. Hence, with air conditioned at 25 °C, an electronic package dissipating as much as 15.6 W can be cooled effectively, according to the value of Eq. (2). It must be noted that this is a rough, preliminary estimate.

4.3. Production techniques

Fewer production steps are required during assembly, as no external heat sink is required. The only dedicated feature is a (non-plated through) hole in the PCB, which can be produced using standard PCB production techniques. This is especially advantageous when multiple components on a board must be cooled. As each heat source has an individual cooling support, the heat from multiple sources can be transported simultaneously without

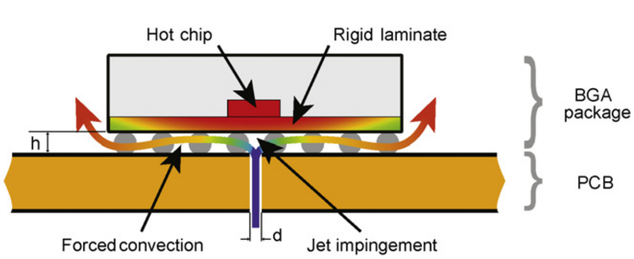

Fig. 8. Cooling principle of directly injected cooling.

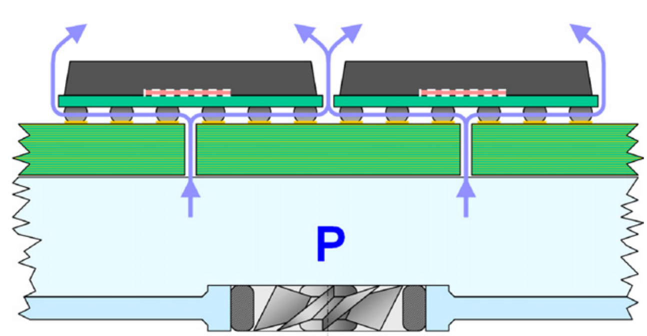

Fig. 9. Concept design for the cooling of multiple packages simultaneously.

Table 1
Tested jet arrangements for the directly injected cooling concept.

Jet layout	Number of holes	Diameter (mm)
1 × 2	1	2
3 × 2	3	2
5 × 2	5	2
1 × 3	1	3

introducing unacceptable temperature gradients across the PCB. A concept design for high density cooling is illustrated in Fig. 9.

From a thermal perspective, there is no coupling between the individual components. The thermal properties of the PCB, which normally affects overall thermal behavior dramatically, is now circumvented by the directly injected cooling. This is valid for any number of components, as long as they fit on the PCB and sufficient jet power can be maintained. As illustrated, this cooling concept is also easily scalable to the number of components that require cooling support.

5. Technology demonstrator

In order to validate the concept of this new cooling technique, a technology demonstrator was developed. A test board with seven electronic components was manufactured. The components consisted of a copper laminate (15 mm × 15 mm) with a diode, acting as a power source, mounted onto its surface. The standoff distance of the laminate was 0.9 mm. The test board had a thickness of 1.6 mm. Each component was equipped with an individual cooling support, by drilling through holes directly underneath the diode. The jet diameter and number of holes were tested for four different arrangements, as listed in Table 1.

During the measurements, the entire board was placed on a pressure chamber. Power, and thus heat, was dissipated through the diode, while air was fed to the pressure chamber. Both air pressure and velocity, as well as temperature were measured continuously. The electrical resistance of the diodes varies proportionally with its temperature. Therefore, by alternating a power current (to heat-up the diode) and a measuring current, the diodes were also used to measure the junction temperature. By opening and closing the air inlet holes for each component separately, the performance of each arrangement was determined individually.

6. Measurement results

6.1. Thermal benefit

To determine the thermal benefit of the developed prototype, it was measured both unpressurized and pressurized. The former is equivalent to the case of natural convection, whereas the latter introduces both forced convection through the confined channel and the impinging jet effect. By subtracting both measurements from each other, the thermal benefit can be determined.

In all cases, heat transfer improved as the air pressure – and thus air velocity – was increased. Hence, more power could be dissipated at a lower junction temperature. Fig. 10 shows the temperature profile of the 1 × 2 jet arrangement for increasing amounts of dissipated power. After increasing the power input, sufficient time was taken to record a steady junction temperature. As the maximum allowable temperature was reached, the measurement was stopped and the apparatus was allowed to cool down. Subsequently, the air pressure was increased and a similar measurement was started. For some of the measurements, the Reynolds number of the impinging jet is also given in the figure. The ambient jet air temperature was 21 °C.

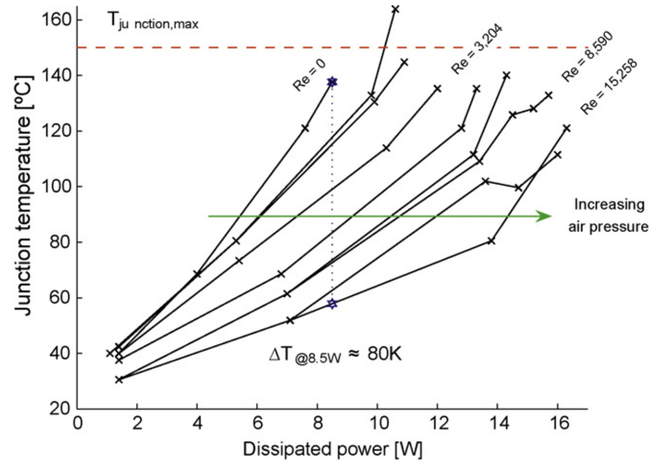

Fig. 10. Junction temperature for increasing power dissipations for the 1 × 2 jet layout.

The top black measurement line in Fig. 10 indicates no air flow, hence the Reynolds number equals zero. As the air pressure is increased, according to the green arrow, more power could be dissipated. At the final measurement, indicated by the bottom black line, the pressure was increased to 8500 Pa. The jet velocity and corresponding Reynolds number at this pressure are approximately 115 m/s and 15,258, respectively. Also, the maximum allowed junction temperature of 150 °C specified for many electronic components is indicated in the figure by the dashed red line.

The thermal benefit – determined by the difference between the natural convection measurement and a pressurized measurement – is indicated by the dotted blue line in Fig. 10. It shows that a temperature decrease of about 80 K can be realized at 8.5 W of power dissipation. At higher dissipated values, directly injected cooling also clearly demonstrates its merit, as the apparatus can operate safely, without reaching crucial thermal criteria. Measurements at higher ratings converge toward values close to the 15.6 W calculated in Section 4.2. The difference is less than 5%.

Fig. 11 shows a thermal image of a component of a similar study dissipating 13.6 W. This figure does not depict the small electronic

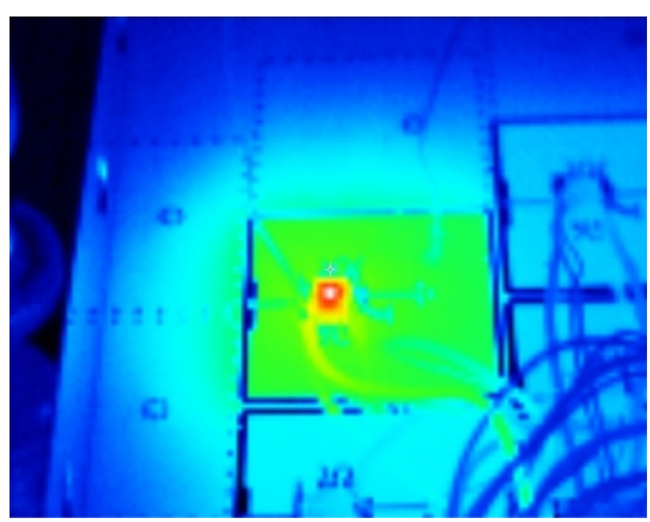

Fig. 11. Infrared image taken during a dissipation of 13.6 W and a pressure of 500 Pa.

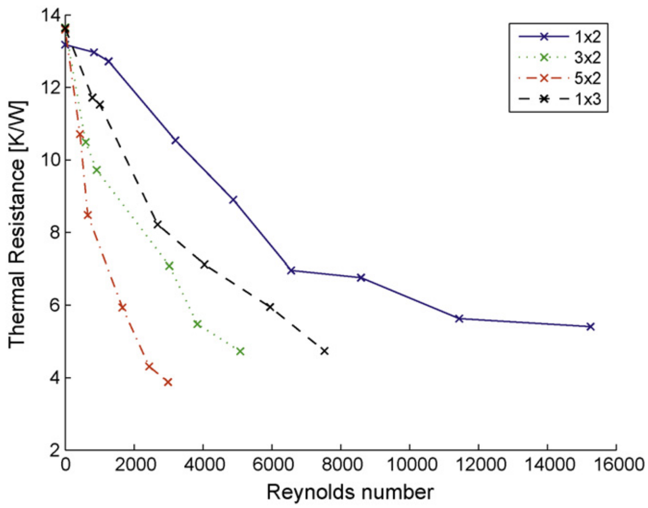

Fig. 12. Thermal resistance versus Reynolds number.

components subject of this study, but a larger component (45 mm × 45 mm). As such, the difference in temperature is more clearly visible. The diode shown in red, conducts its heat evenly across the rigid laminate (green). On the bottom side, the heat is dissipated by the cool air that passes through the BGA. In this case, the air was injected at 500 Pa. The light blue color indicates that the board and adjacent components also heat-up. This might be caused by the passing hot air; however, also heat transfer by conduction occurs. In addition, some power is lost through the electric wiring.

As the amount of heat conducted away is not known, the real jet heat transfer coefficient cannot be quantified from the measurement data. Qualitatively however, the measurements make it clear that direct injected cooling has a positive effect on the cooling potential of the mounted packages.

6.2. Thermal resistance

For each distinct jet configuration (i.e. fixed pressure and jet layout), temperature measurements were recorded for increasing power inputs. For each measurement the thermal resistance from junction to ambient jet air can be determined as

$$R_{\text{junction}\rightarrow\text{jet air}} = \frac{T_{\text{junction}} - T_{\text{jet air}}}{Q_{\text{dissipated}}} \quad (3)$$

In theory, for increasing amounts of dissipated power the thermal resistance should be constant for each of the configurations as jet conditions (i.e. h/d, Re, number of jets) do not change. Therefore, the thermal resistance for each configuration can be computed as the average of the measured values. In practice, the average standard deviation of all measurements was about 1 K/W; hence thermal resistance was relative constant. The average resistances are shown in Fig. 12 as a function of the Reynolds number.

According to Fig. 12, for higher Reynolds numbers (i.e. increased air flow) the resistance values drop, as expected. In the case of natural convection (Re = 0) the resistance values converge to about 13–14 K/W. The lowest thermal resistance value is reached for a relative open jet configuration (5 × 2), as its thermally affected area is larger. The fact that the 1 × 2 jet reaches higher Reynolds numbers does not result in the lowest resistance value. For the 5 × 2 jet a lower resistance value is reached at a much lower pressure. This is an advantage with respect to the structural integrity of the board structure and electronic components, and also for the pump requirements.

The overall resistance value of the 5 × 2 jet arrangement (≈4 K/W) equals half the value of the theoretically calculated value in Section 4.2. This discrepancy can be attributed to the fact that the calculated value was based on an h/d ratio of one and a local heat transfer coefficient. It must be noted that due to the unknown amount of heat conducted away, quantitatively these values should be used with caution. Qualitatively, the results reflect that the performance increases depending on the jet layout. As such, the results can be applied for any jet configuration to be designed.

7. Conclusions

Full integration of thermal management functions and electronic circuitry in electronic products pushes the boundary further toward more functionality and performance in a smaller form factor. In addition, products can be realized at a lower cost. Altogether, this will lead to smaller, lighter and more affordable products.

Through a case study, new thermal management strategies for electronic products have been presented. By incorporating thermal engineering aspects at an early stage in the design process, more integrated solutions are realized. It was demonstrated that without additional heat sinks and by adding just one (non-plated through) hole in the PCB, an electronic package can be cooled efficiently. The new concept design is also easily scalable, allowing electronic products with multiple components to be cooled both uniformly and simultaneously. This increases design freedom and enables a more multifunctional product design.

Future work will include a more extended experimental investigation, where the cooling of larger packages is also considered. The amount of heat conducted away should be recorded as well in order to get more comprehensive measurements.

Acknowledgments

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