

Impact of convection on thermographic analysis of silver based thermal joints

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Abstract

Purpose – This paper aims to develop thermal analysis method of thermal joints characterization. The impact on convection on thermal resistance analysis with use thermography for silver-based thermal joints were investigated for non-metallized and metallized semiconductor surfaces. Heat transfer efficiency depends on thermal conductivity; radiation was used to perform thermographic analysis; the convection is energy loss, so its removing might improve measurements accuracy.

Design/methodology/approach – Investigation of thermal joints analysis method was focused on determination of convection impact on thermal resistance thermographic analysis method. Measuring samples placed in vacuum chamber with lowered pressure requires transparent window for infrared radiation that is used for thermographic analysis. Impact of infrared window and convection on temperature measurements and thermal resistance were referred.

Findings – The results showed that the silicon window allowed to perform thermal analysis through, and the convection was heat transfer mode which create 15% energy loss.

Originality/value – It is possible to measure thermal resistance for silver-based thermal joints with convection eliminated to improve measurements accuracy.

Keywords Thermography, Convection, Silver nanoparticles

Paper type Research paper

1. Introduction

Modern trends in electronic industry, mainly miniaturization with simultaneous faster operation speed of electronic devices are causing larger amount of heat generation than in the past. Heat dissipation becomes crucial, where both technology and used material will ensure high conductivity thermal joints with simultaneous acceptable mechanical strength. Typical joining materials, solders and thermally conductive adhesives are no longer sufficient, because of their limited thermal conductivity (Xiao, 2013; Göbl and Faltenbacher, 2010). The mechanism of heat removal is made by using high thermal conductive layer as a filler between surfaces of heat generating element (heat source) and a proper substrate (might be a heat spreader). Their role is to fill micro-sized gaps which leads to thermal resistance decrease of such joint and heat transfer efficiency improvement. Silver becomes interesting material for heat removing applications, thanks to its relatively high thermal conductivity. Compared with the solder reflow interconnection, pressure-assisted silver sintering, besides better electrical and thermal performance, has also the advantages, such as more uniform interconnecting layers, and

higher reliability. That is why sintering process of nano- and micro-sized silver particles is increasingly used for thermal joint manufacturing in electronics (Siow, 2019). Parameters of joints depend on many technological and material factors, among which joined surfaces, temperature and time of sintering, external pressure and sintered material seem to be the most important (Felba, 2018). For this research, important technological parameters were selected experimentally (Stojek *et al.*, 2017a, 2017b) including main sintering parameters – allowing to determine that the process is low temperature at low external pressure (below 250°C and less than 0.5 MPa). As mentioned before, there are given two main requirements for thermal joints: highest heat transfer efficiency as possible with simultaneous acceptable mechanical strength. The mechanical strength of the joints was not tested in this work, as previous studies have shown that this type of joints have sufficiently good mechanical

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parameters for applications in electronics (Stojek *et al.*, 2017a, 2017b). Of course, there is no doubt that bulk silver is a highly conductive material ($\sim 429 \text{ W/mK}$); however, sintered layer cannot be treated as bulk silver and its thermal conductivity has to be measured. Usually, this value is estimated on the base of Wiedemann–Franz law (Welker *et al.*, 2015; Lu *et al.*, 2007; Kähler *et al.*, 2011), calculated by density, specific heat and thermal diffusivity measurement (Bai, 2005; Wang *et al.*, 2013; Zhang and Lu, 2002) or estimated by porosity evaluation (Fu *et al.*, 2014). We propose the direct measurement by using the thermography method. Their main features, such as contactless, repeatable, accurate, relatively fast and cheap determined the need of use this method. By measuring the source and heat receiver temperatures, it is possible to calculate the thermal resistance of the joint. Unfortunately, the measured heat balance is disturbed by radiation and convection phenomena. While at relatively low operating temperatures of electronic systems, it is justified to omit the phenomenon of radiation in ambient atmosphere when convection occurs. The purpose of this work is to assess the impact of this phenomenon on the accuracy of the measurement method used.

2. Samples

Heat sources (controllable silicon resistor) and heat receivers in research were made by $3000 \mu\text{m}$ thick bare-die silicon with

Figure 1 Structures for thermal analysis of sintered silver layer

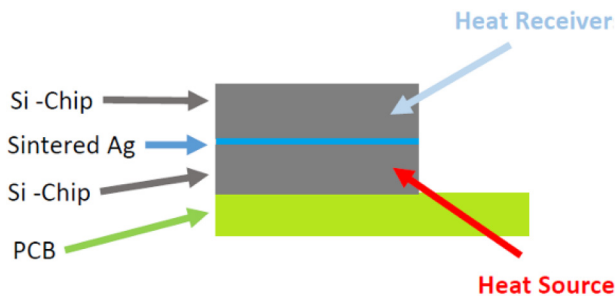
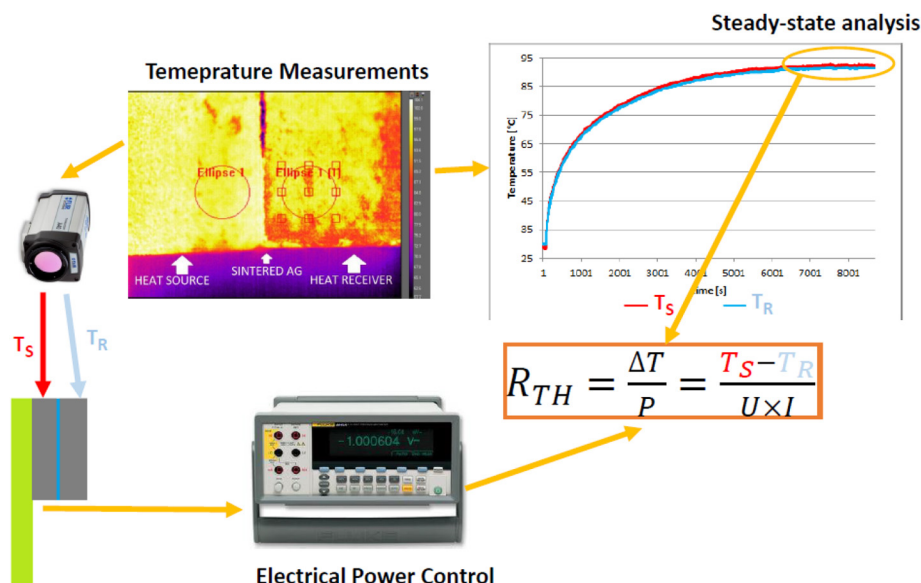


Figure 2 Thermal resistance measurements schematic setup



dimensions of $5 \times 5 \text{ mm}$. Both silicon parts are joined (Figure 1). The paste for sintering had 95 Wt.% of silver particles (60:40 nano- to micro-sized flakes silver particles ratio) and 5 Wt.% of epoxy resin. Silver nanoparticles had average size 70 nm and micro-sized flakes about $15 \mu\text{m}$. Addition of epoxy resin was allowed to manufacture thermal joints for non-metallized surfaces. The sintering process was done in 60 min in 230°C (+ 54 min of heating with ratio 4°C/min). The pressure assistance was present at level of 0.5 MPa .

3. Basic temperature measurement setup

Electrical power was supplied via printed circuit board, where interconnection was done by electrically conductive adhesive. Supplied power was transformed to heat in heat source and was transferred to heat receiver and the temperatures on source (T_S) and receiver (T_R) surfaces were measured simultaneously by the infrared (IR) camera (Figure 2) and presented configuration minimizes measurement errors (Stojek *et al.*, 2017a, 2017b). Thermographic software tool “area” was used in analysis, where temperatures on source (T_S) and receiver (T_R) were average values for selected area. To ensure accurate temperature measurements, surfaces were covered by layer with known emissivity (0.98). Temperature measurements were performed in steady-state condition which needs to be considered as stabilized conditions, where conduction, radiation and convection got stable. Voltage (U) and current (I) measurements as an electrical power were done by Fluke 8,848 A multimeters. Obtaining the temperatures T_S and T_R and electrical power (U -voltage and I -current) allows us to calculate thermal resistance R_{TH} with the formula:

$$R_{TH} = \frac{\Delta T}{P} = \frac{T_S - T_R}{U \cdot I} \quad (1)$$

which corresponds to source and receiver temperature difference in relation to supplied electrical power – Figure 2.

Temperature measurements values with using thermographic Flir A40m camera are performed with $\pm 2^\circ\text{C}$ or $\pm 2\%$ accuracy,

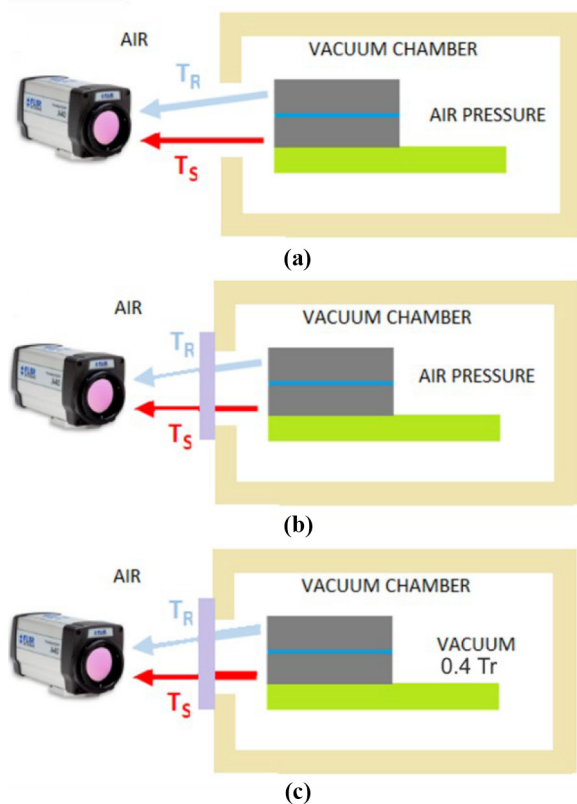
but thermal sensitivity at level 0.08°C at 30°C . It means that temperature value measurements had an error, but lowest distinguishable difference are at level lower than 0.1°C , so the temperature difference values are measured with high accuracy. External optic was used within measurements, where its impact was calibrated automatically by system.

4. Principle for convection impact on thermal analysis estimation

Basic measurements treated as a reference were made in atmospheric conditions – Figure 3(a) – AIR. In such measurements, configuration conduction corresponds to heat transfer through thermal joints, radiation corresponds to IR camera measurements, but convection causes an energy loss consumed by heating of surrounding air. In such manner, putting samples to vacuum chamber to remove the air was proposed. Nevertheless, putting IR camera to vacuum chamber was not possible, because its operation was not adjusted for lowered pressure condition. The vacuum chamber needs to be hermetic, and measurements are possible only through IR window, which is transparent for infrared radiation characteristic of the camera used (from 7.5 to $13\ \mu\text{m}$).

The configuration necessary to assess the transparency of the silicone window for measured temperatures (with atmospheric pressure inside the chamber) is shown in the Figure 3(b) – AIR,

Figure 3 Three configuration of thermal analysis measurements



Notes: (a) – via air atmosphere; (b) – via silicon IR window in air, (c) – via silicon IR window in vacuum

IR WINDOW. Figure 3(c) – VACUUM, IR WINDOW – is a target configuration, which allows to assess of convection impact on thermal resistance analysis. Thermal measurements were also calibrated for ambient temperature, relative humidity and distance between object and camera. Using external optics allows to measure radiation by detector from area of $45 \times 47\ \mu\text{m}$.

5. Temperature, power measurements and thermal resistance analysis results

Within the research three samples were investigated. Source (T_s) and receiver (T_r) temperatures measurements were done five times for each sample in each condition to perform statistical analysis. Their value were measured and calculated temperature differences ($T_s - T_r$). The main values are presented in Figures 4 and 5, respectively. Simultaneously power measurements were done, and their mean values were calculated (Figure 6).

Adding IR window causes lowering of source and receiver temperatures. Lowering the pressure (vacuum conditions) causes increasing these temperature values in ratio to measurements in air atmosphere through IR window.

It is clear, that adding IR window to the optical path cause temperature difference increasing. On the other hand, for measurements through IR window, temperature difference

Figure 4 Mean source and receiver temperatures in air, air through IR window and in vacuum through IR window conditions

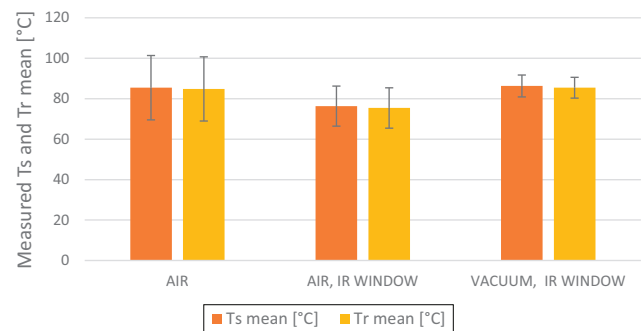


Figure 5 Mean source and receiver temperature differences in air, air through IR window and in vacuum through IR window conditions

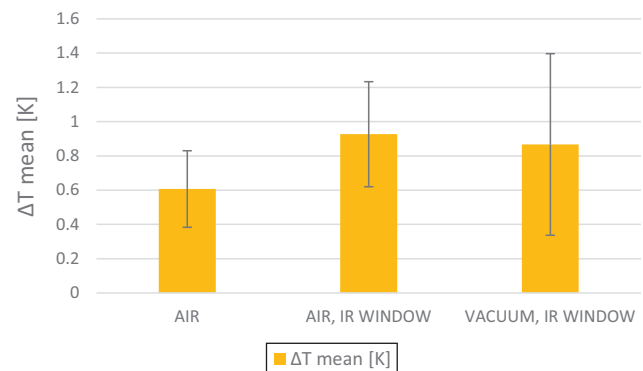
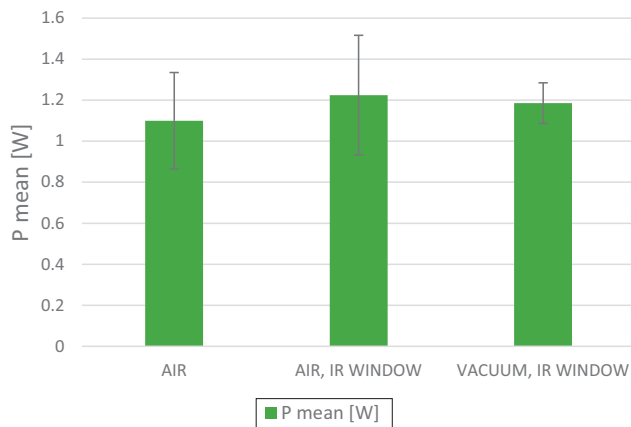


Figure 6 Mean power received to the samples in air, air through IR window and in vacuum through IR window conditions

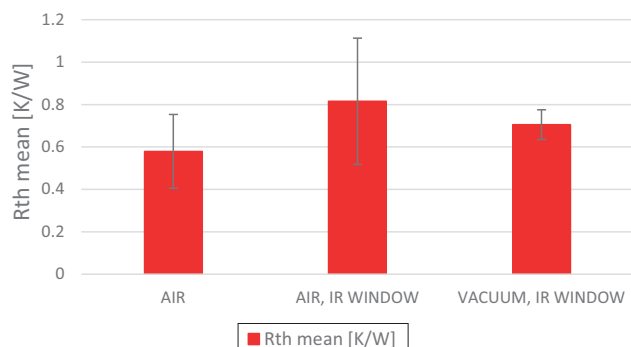
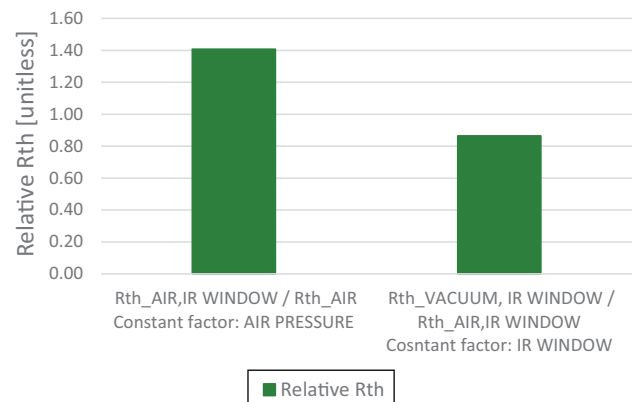
decreases with pressure lowering. Temperature value measurements were distorted by IR window absorption. Source and receiver temperature differences were calculated directly with respecting achieved values – there was no compensation for source and receiver temperature values.

Mean electrical power was the highest for measurements through IR window in air pressure conditions. It is important to underline that received electrical power was not equal within research (Figure 7).

Lowest thermal resistance was obtained for measurements in air without IR window and the highest for air pressure through IR windows. Measuring in vacuum conditions through IR window caused lowering of thermal resistance in relation to measurements in air conditions and through IR window also.

6. IR window and convection impact on thermal resistance analysis

Related thermal resistance calculations allowed us to determine the impact of IR window and pressure lowering impact on thermal resistance (Figure 8). With calculating the relation of thermal resistance in air pressure through IR window ($R_{th_AIR, IR WINDOW}$) to thermal resistance in air pressure without IR window (R_{th_AIR}) we were able to determine quantitatively their impact on results. In such

Figure 7 Mean thermal resistance in air, air through IR window and in vacuum through IR window conditions**Figure 8** Related thermal resistance results affection by IR window and convection

case the air atmosphere was constant factor and the IR window was one and only variable. Similar calculations were done for relation of thermal resistance in vacuum ($R_{th_VACUUM, IR WINDOW}$) to thermal resistance in air conditions through IR window ($R_{th_AIR, IR WINDOW}$), where IR window was constant factor, and pressure was one and only variable.

Adding IR window to optical path caused thermal resistance improvement for about 41% and convection (vacuum conditions) caused lowering of thermal resistance in about 15%.

7. Infrared window calibration

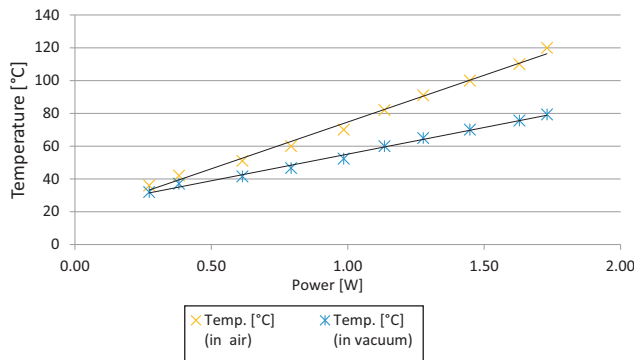
In two previous chapters, research approach is based on analysis for direct measurements of source and receiver temperature difference. But still there is present absorption in IR window and thermal signal distortion (lowering). Silicon three-inched die was used as an IR window. To estimate source and receiver real values for measurements through this IR window, calibration was performed. Its impact measurements based on analysis in air atmosphere and were performed in steady-state conditions. At the beginning, the temperature of the source was stabilized in given electrical power points (I and U), and source temperature was measured without IR window. In next step, the similar concept was used, but during these measurements the silicon IR window was placed in the optical path and then again steady-state analysis was done with the same electrical power supply (Figure 9).

Given results were fitted with linear function and given formulas for setup with (y_1) and without (y_2) IR silicon window were obtained in form, respectively:

$$\begin{cases} y_1 = 9.5 \cdot x + 23 \\ y_2 = 5.5 \cdot x + 25 \end{cases} \quad (2)$$

Another step was to calculate the y_1 , where y_1 is calculated temperature real value estimation for measurements done through silicon IR window. The temperature value were lowered because of such window transmission lower than 100%:

Figure 9 Results of temperature measurements for setup with and without IR silicon window as a function of supplied power



$$y_1 = 9.5 \cdot \left(\frac{y_2 - 25}{5.5} \right) + 23 \quad (3)$$

In such manner, every temperature measurement through IR window was estimated for real value (analysis in air and vacuum conditions) of direct (measured) and calibrated (calculated) mean temperature (Figure 10).

The results confirmed that using silicon IR window affects temperature measurements on about 40%.

8. X-ray inspection

It is unclear what factors caused the increase in joint thermal resistance after surface metallization. Theoretically, this can be caused by adding to a chain of thermal resistances of a joint additional thermal resistances of metal layers and thermal contact resistance between layers and substrate (Felba, 2011). But the observed differences can also be the result of defects in the sintered layers. In fact, in X-ray images (Figure 11) defects

Figure 10 Source and receiver measured and calibrated mean temperatures

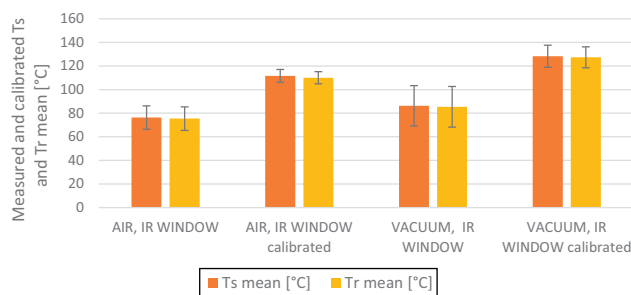
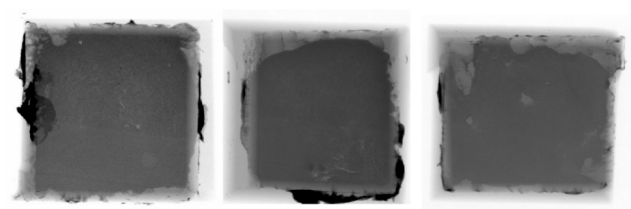


Figure 11 X-ray inspection of measured joints



are clearly visible – mostly in form of void spaces (brighter areas) and it seems that the surface of these voids is larger in the case of metallized surfaces. This would explain the higher R_{TH} value in these samples.

9. Conclusions

The convection impact on thermographic thermal resistance analysis reached about 15%. Convection removal was done by putting samples in vacuum chamber in lowered pressure circumstances. Silicon IR window impact on thermal analysis were discussed and its impact on method was calibrated. Thermal resistance increased with using silicon IR window for measurements in air conditions and in lowered pressure. X-ray inspection showed the defects in layers but required further research.

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Further reading

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