# Comparison of low cost, insulated aluminium substrates used as integrated heat sinks with conventional technology

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**Abstract**

*This paper describes two new thick film paste systems (one glass based and the other polymer based) for insulating aluminium substrates and allowing components like high intensity light emitting diodes (LEDs) to be attached to a conductor deposited on the dielectric. Comparative measurements of the thermal resistance of different substrates mounted with MOSFETs were made and the thermal advantages of these two technologies have been proved.*

Key words: LEDs, thermal conductivity, insulated aluminium substrates, thick film pastes

## 1. Introduction

LEDs are used as low voltage light sources in automotive applications. The heat that is generated by this modern, high intensity, lighting system needs to be dissipated rapidly. LEDs are mounted on regular printed circuit board material (copper on glass epoxy FR4) and this is bonded to a metal substrate to enable good dissipation of heat generated from the LEDs. An alternative substrate that is both electrically insulating and thermally conducting has been desired for some years.

Other substrates with good thermal characteristics such as direct bonded copper (DBC) and insulated metal substrate (IMS) have been used to fabricate power circuits but the manufacturing costs are high due to the sophisticated processes involved. Two materials in particular, copper and aluminium, are excellent thermal conductors (**pure** aluminium has a k of ~230 $W.m^{-1}K^{-1}$). If they could be insulated in some way and conductors superimposed on these insulated metals using an additive process then the thermal advantages could be used to good effect.

The insulation of copper with glasses is difficult due to the oxidation that takes place during relatively high temperature processing in air. Furnaces that accept a flow of nitrogen can be used but the processing costs can often outweigh the advantages gained by using this metal. Furthermore nitrogen fireable glasses must be used in the paste composition.

This paper describes the insulation of aluminium substrates and the printing of a top conductor to accept components using two material systems. The first of these is a two-component glass based system and the second an all-polymer system (single dielectric with polymer conductor tracks).

The purpose of testing these insulated substrates was to find the optimum thermal performance for electronic devices. Thermal resistance measurements were carried out to determine the capability of each substrate type to transfer heat from the components to the aluminium. Therefore absolute thermal resistance values of the different samples were measured and compared.

## 2. Aluminium substrates

As well as the high thermal conductivity a further advantage of using aluminium is that its density is low at $2.70g.cm^{-3}$ – copper, for example, is at least three times as dense as aluminium whose density does not really differ between alloys. The International Alloy Designation System (IADS), introduced in 1970, employs a classification method developed by the Aluminium Association of the United States. Each aluminium alloy is given a 4-digit number depending on the alloying elements.

Some of the aluminium alloys (1050, 4917, and 5005 for example) were tried in earlier work that is not reported here but 3103 gave the best results with the glass insulation. Its composition is shown in Table 1.

### Table 1 Composition of 3103 alloy

| Si | Fe | Cu | Mn | Cr | Mg | Ni | Zn | Others | Al |
|------|------|------|-----------|------------|------------|------------|------------|-----------------------------------|-----------|
| 0.6 max | 0.7 max | 0.1 max | 0.5 – 1.5 | 0.05 max | 0.1 max | 0.2 max | 0.2 max | Pb 0.05 Sn 0.05 Ti + Zr 0.2 max | remainder |

Source www.quantumalloys.com.  All figures are in weight %. 63mm x 63mm x 3mm was the preferred substrate size. The thermal conductivity of 3103 alloy is only 160 $W.m^{-1}K^{-1}$ and its thermal coefficient of expansion (TCE) is 23.1ppm/ºC. Source www.aluminium.matter.org.uk

## 3. Experimental

### 3.1 Preparation of samples for initial testing

The earliest work was carried out to determine a suitable glass based system for insulating aluminium. This involved the testing of a number of glasses, conductors, firing temperatures, adhesions, breakdown voltages and these tests are not reported here. 580ºC was chosen as the optimum firing temperature. The two dielectric pastes that were used in all experiments were 4603 and 4604-A. They were applied by screen printing through a 145 mesh screen. 4603 was used as the seed layer and needed to have a TCE that closely matched that of the aluminium alloy. The TCE of 4603 is ~19ppm/ºC. At least two layers of 4603 were used in all initial experiments to give a thickness in excess of 50µm.  The final dielectric layer was 4604-A which has a TCE of ~10ppm/ºC. This was used as the electrically insulating layer. 9912-K silver was screen printed as the conductive track and pads. This was also fired at 580ºC.

A polymer system was also tested on aluminium up to 3mm thick. ESL 243-S, a screen-printable, thermo-setting, epoxy coating that is resistant to solvent attack when fully cured at 150ºC, was screen printed as the insulating dielectric up to a thickness of 60µm. ESL 1901-S silver was used as the conductor. This system may be printed on 1XXX aluminium substrates which have higher thermal conductivities than the 3103 aluminium. The theoretical overall thermal conductivity of the insulated aluminium should be higher as well.

Further work was performed on a simple test pattern (Bilinski et al, 2008). A similar device was made using ESL 243-S as the polymer dielectric. Silver loaded conductive epoxy was used to attach the components.

### 3.2 Thermal conductivity

Once it was established that the circuits worked, the important thermal conductivity issue was addressed. Thermal modelling of the glass based material system was performed. The thermal conductivity of ESL 4603 was unknown but an estimated figure of 1$W.m^{-1}K^{-1}$ was used in the simulation.

### 3.2.1 Modelling for thermal simulation

Simulation was carried out using ANSYS Classic 11 software and based on a model of 1.5 cm diameter 3103 aluminium parts with both the glass dielectric layers and the aluminium substrate itself at increasing thicknesses. A schematic for the thermal simulation tests is shown in Figure 1. The copper slug in the centre represents the internal heat sink of an actual LED component.
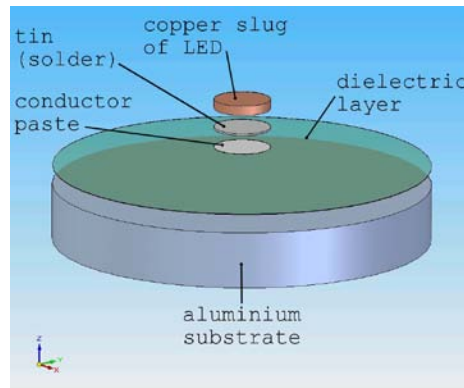


**Figure 1 Schematic of test sample for thermal simulation**

The integrated circuit is not shown as a constant power source of 1W was used in the calculations. The dielectric layer is also shown as covering the whole of the area. No modelling of solder joints was made; however, it is conceded that voids in solder joints can adversely affect thermal transfer. The power source was considered in intimate contact with the dielectric which is printed onto the substrate. A number of different temperature differentials were plotted to determine the thermal characteristics of a component on a coated aluminium substrate. The transfer of heat was considered in both axial and radial directions. Of the many temperature differential models that were made, two were chosen to show the effect of the thickness of the dielectric layer and the thickness of the aluminium – one through the substrate and the other laterally from its centre.

### 3.2.2. Preparation of samples for thermal conductivity measurements

Aluminium discs, 1.5 cm diameter, were coated with various thicknesses of ESL 4603 and ESL 243-S dielectrics. 3103 was used for both dielectrics and 1050 aluminium alloy was also coated with ESL 243-S. 55mm x 55mm x 1mm aluminium parts were laser cut to give 9 x 1.5cm diameter pieces per tile as shown in Figure 2. The diameter of the dielectric pattern was 14mm. In contrast to the simulation only one thickness of aluminium was used due to time constraints and availability of aluminium sheets. Each layer of the ESL 4603 was separately fired at 580°C. Each layer of the ESL 243-S was cured at 150ºC.

The thicknesses for each layer of the dielectrics are shown in Table 2.

**Table 2 Dielectric thicknesses**

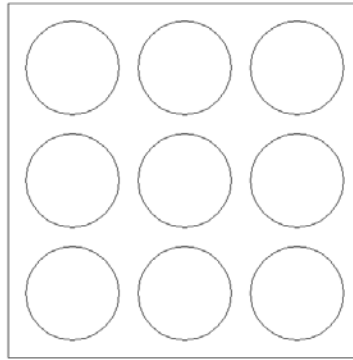| Number of layers | ESL 243-S thickness µm | ESL 4603 thickness µm |
|---|---|---|
| 1 | 12 | 16.5 |
| 2 | 25 | 34 |
| 3 | 39 | 53 |
| 4 | 54 | 73 |
| 5 | 65 | 91 |
| 6 | 77 | 110 |
| 7 | - | 129 |

**Fig 2 Diagram of aluminium tile with individual substrates**

### 3.2.3 Experimental setup

Thermal conductivity measurements were performed using the equipment shown in Figure 3 and described in "Thick film pastes for the manufacture of low cost, insulated aluminium substrates for use as integrated heat sinks for high intensity LEDs" (Bilinski et al, 2008).
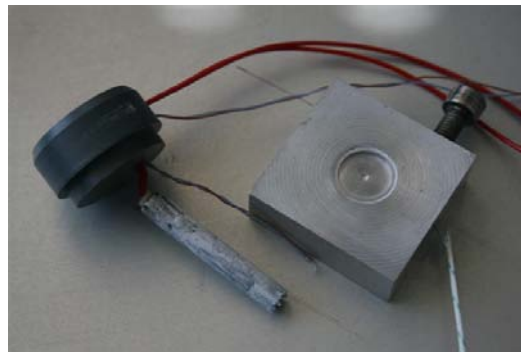


**Figure 3a Thermal measuring equipment**
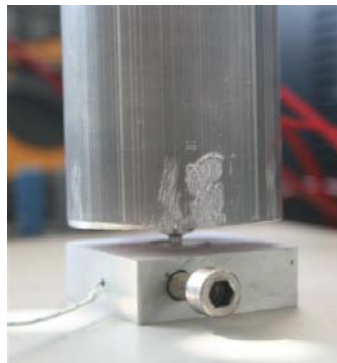


**Figure 3b Heater and sample block**



**Figure 3c 3mm heater assembly and sample block**

### 3.3 Thermal resistance

### 3.3.1 Sample set up

A special test pattern was created on 10cm x 10cm substrates for the measurements of the thermal resistance of different substrate sample set ups. Different technologies could be compared by measuring absolute thermal resistance values. An example of the final set up is presented in Figure 4 and Table 3 shows the sample set ups.
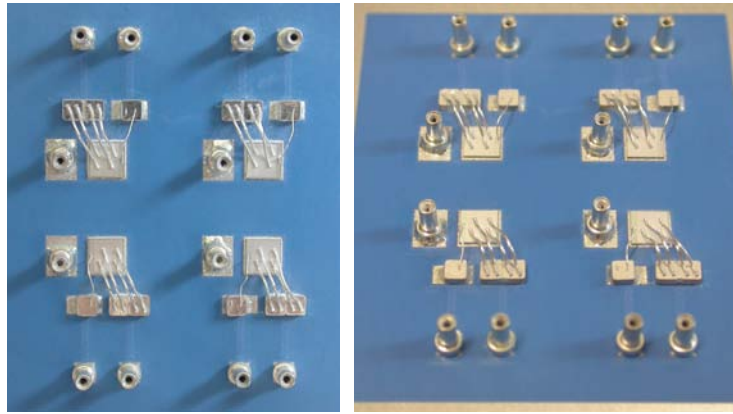
**Figure 4  Polymer system – final setup; 4 MOSFETS on every substrate; wire bonded from solder preforms to MOSFETs to minimize heat dissipation**

**Table 3 Sample set ups**

| Version | Description |
|---|---|
| IMS 1 | Standard FR4-Material (0.4 $W.m^{-1}K^{-1}$); 1.5mm thick Al |
| IMS 2 | 1 $W.m^{-1}K^{-1}$; 1.5mm thick Al |
| IMS 3 | 2 $W.m^{-1}K^{-1}$; 1.5mm thick Al |
| IMS 4 | highest thermal conductivity; 4 $W.m^{-1}K^{-1}$; 1.5mm thick Al |
| Ceramic | Ag-Conductor on $Al_2O_3$, fired @850°C; ceramic glued on 2mm Al 3103 |
| Glass system | 3 layers ESL 4603, 1 layer ESL 4604; 2mm thick Al |
| Polymer 1 | 3 layers ESL 243-S on Al 1050; 2mm thick Al |
| Polymer 2 | 2 layers ESL 243-S on Al 1050; 2mm thick Al |

Due to the fact that the measurements were carried out on MOSFETs, vacuum soldering was chosen to reduce the number of voids under the device as voids have a deleterious effect on the thermal conductivity of the whole system.

### 3.3.2 Experimental set up
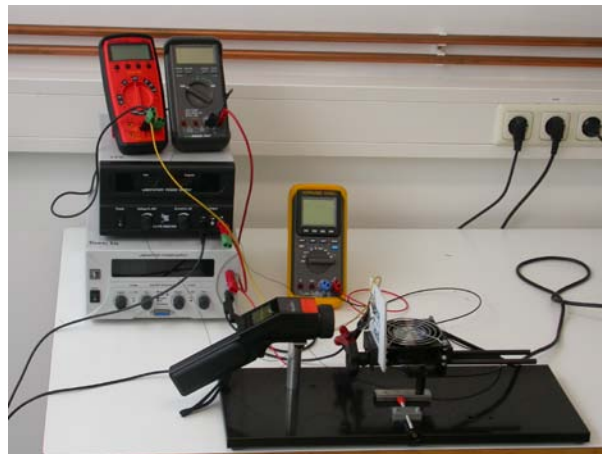
The experimental set up is shown in Figures 5 and 6.
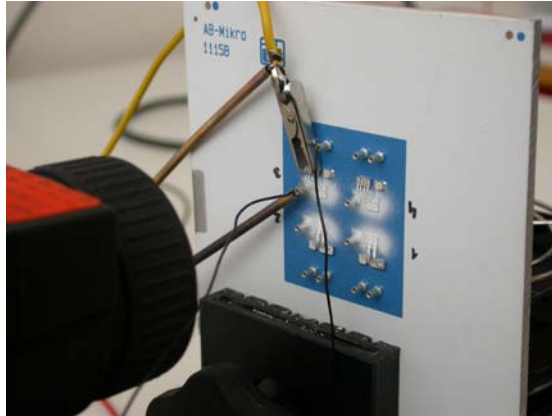


**Figure 5 Experimental set up - overview**

**Figure 6 Electrical connections**

A gate voltage of 7V and 5V was applied and a dissipated power of 1.5W and 2.5W (respectively) was attained before measurement was made. A white paint with a defined emission coefficient was applied on the MOSFET surface and on the backside of the substrates to ensure a correct temperature measurement with an IR-pyrometer (see Figure 6). A ventilator on the backside of the substrates guaranteed homogeneous air convection so that the conditions for all set ups were the same (no heat accumulation). The system was allowed to stabilise for fifteen minutes and the thermal resistance was then calculated using

$$R_{TH} = \frac{T_{junction} - T_{backside}}{P} \qquad (1.1)$$

$R_{TH}$  thermal resistance in K/W

$T_{junction}$  temperature on the MOSFET surface in K

$T_{backside}$  temperature on the backside of the substrate in K

$P$  dissipated power in W

## 4. Results

### 4.1 Initial test and simple LED circuit

Initial adhesion tests on the 9912-K gave 20N (measured on 2mm x 2mm pads over two layers ESL 4603 and one layer ESL4604-A to give >65µm dielectric thickness). Breakdown voltages in excess of 2000V AC (7mm x 7mm pads over two layers ESL 4603 and one layer ESL4604-A to give >65µm dielectric thickness) were achieved. Similar breakdown voltages were achieved at much lower thicknesses of ESL 243-S using ESL 1901-S polymer silver and the same conductor pattern (1000V AC per 15µm ESL 243-S).

The LED circuit worked. Figure 7 shows the glass based system working at low voltage.



**Figure 7 Glass based dielectric systems working at low voltage**

## 4.2 Thermal conductivity simulation

Only a few of the many results produced are presented here.

### 4.2.1 Glass system

Figure 8 shows the temperature differential between the top of the dielectric layer and the ambient temperature for various thicknesses of both dielectric and aluminium when 1 W was applied. The thickness of the aluminium has little effect when greater than ~2mm. The thickness of the dielectric affects the thermal conductivity throughout the range considered.
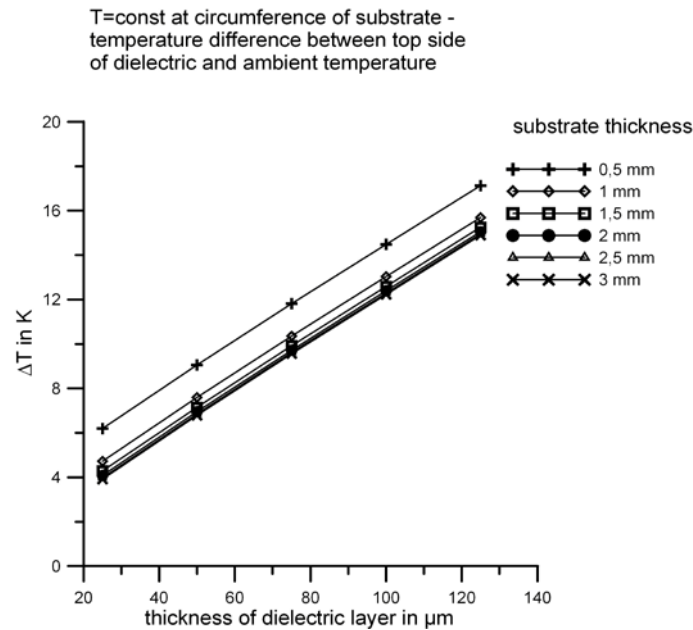


**Figure 8 Effect of aluminium and dielectric thickness on thermal resistance**

Figure 9 shows the lateral temperature difference on the top side between the aluminium and the dielectric. Consideration of the radial temperature differences of the aluminium substrate between its centre and a further point some 1.5mm away has been made.
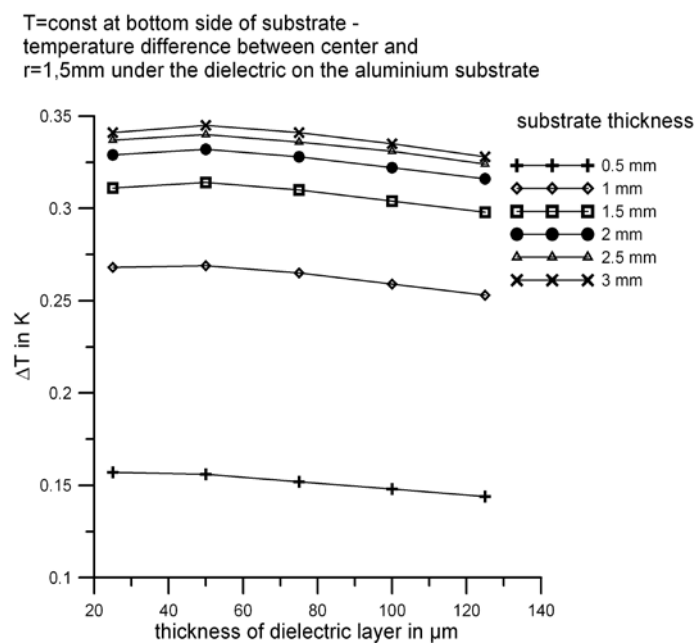


**Figure 9 Lateral thermal differences between the dielectric and the aluminium substrate**

Figure 10 shows the temperature differential for a 1 mm thick aluminium substrate. The effect of the dielectric thickness is clearly seen in the measured data though the correlation between the predicted and measured data could be improved. The difference in the temperature drop between simulation and measurement is caused by imperfect contact between heat sink and sample and probe head and sample.
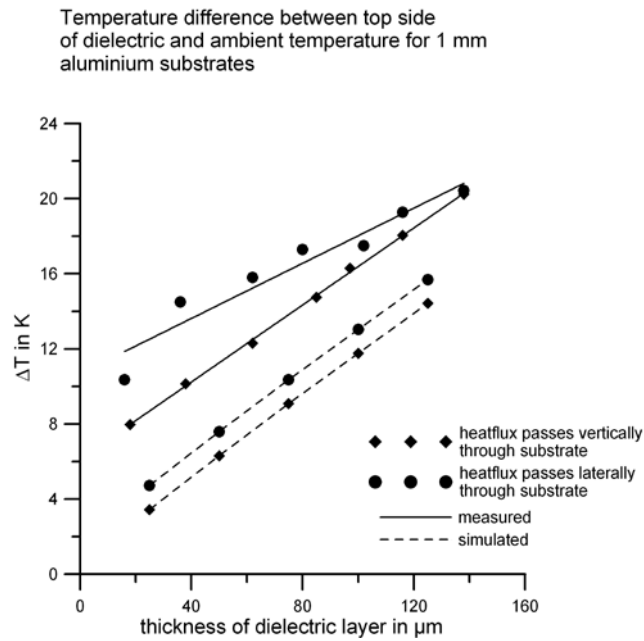
Temperature difference between top side
of dielectric and ambient temperature for 1 mm
aluminium substrates



**Figure 10 Difference between measured and simulated temperature differences – glass based system**

### 4.2.2 Polymer system

The thermal conductivity measurement results for the polymer system (on both 1 mm thick 1050 and 3103 discs) are shown in Figure 11.
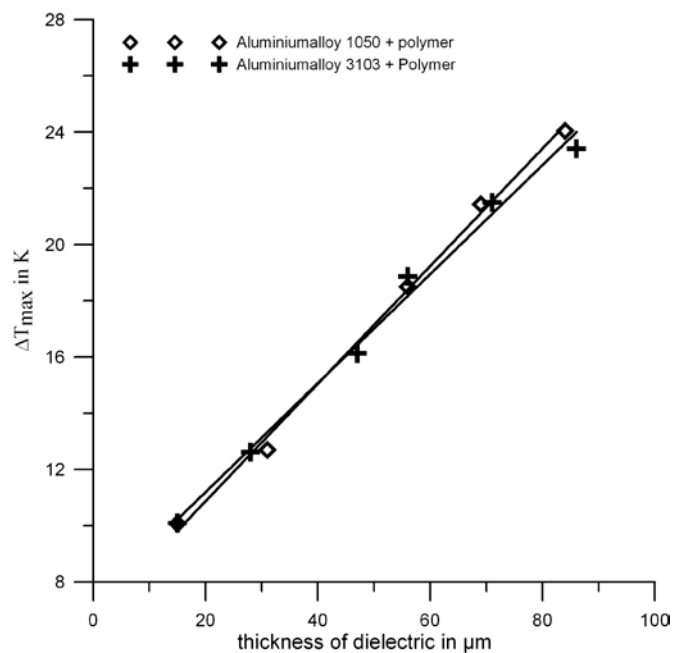


**Figure 11 Thermal conductivity measurements for the polymer based system**

## 4.3 Temperature differential measurements – calculation of the thermal conductivity

The thermal conductivity of the dielectric can be calculated by the gradient of the curve. It was assumed that the temperature changes in the contact areas stayed the same when the samples were changed.

$$P = \frac{(\Delta T_2 - \Delta T_1)kA}{d_2 - d_1}$$

(1.2)

| | |
|---|---|
| $k$ | thermal conductivity in $W.m^{-1}K^{-1}$ |
| $\Delta T_1,\ \Delta T_2$ | temperature difference at two points on the gradient in K |
| $A$ | heat dissipating area in $m^2$ |
| $d_1,\ d_2$ | thickness of dielectric layers at two points on the gradient in m |
| $P$ | dissipated power in Watts |

From the measurements conducted on the glass based system the thermal conductivity was 1.38 $W.m^{-1}K^{-1}$. For the polymer based system the measured value was 0.76 $W.m^{-1}K^{-1}$. The value used for the simulation for the glass based system was 1 $W.m^{-1}K^{-1}$.

## 4.4 Thermal resistance measurements

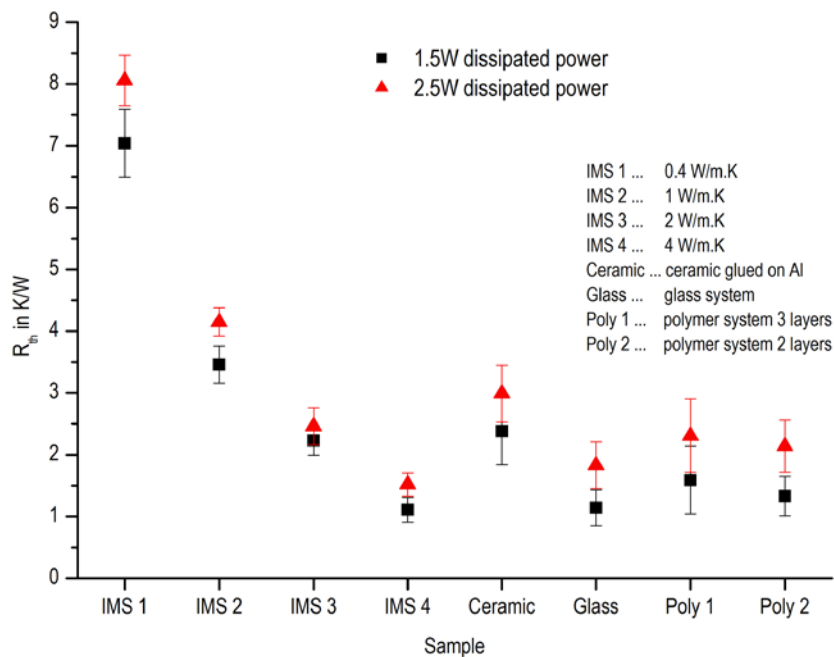Figure 12 shows the thermal resistance for all measured samples.



**Figure 12 Thermal resistance for different samples**

This graph shows the superior thermal properties of the glass and polymer system compared to standard substrate technologies (IMS and ceramic). With the exception of the 4 $W.m^{-1}K^{-1}$ IMS all other samples have a significantly higher thermal resistance and consequently thermal conductivity is worse even though all IMS samples were built using 1.5mm thick aluminium. However, thicker aluminium gives higher temperature differences in equation (1.1) and this results in higher thermal resistances. Further work with new samples using the polymer and glass system on 1.5mm aluminium would prove the superiority of the new systems.

## 5. Conclusions

1. A thick film paste system that is suitable for insulating aluminium substrates for use as heat sinks in modern LED lighting systems has been made. There is also great potential in a polymer system. A solderable polymer conductor is required to make it a viable system.

2. It is conceded that it is difficult to obtain a definitive figure for the overall thermal conductivity of an insulated aluminium substrate. It has been shown that the dielectric thickness affects the overall thermal conductivity of the whole substrate and that the thickness of the aluminium substrate has to be considered. An increased understanding of the thermal management benefits anticipated in the use of the new paste and substrate has been achieved.

3. Comparative data from a replicated application using different combinations of substrates (alumina versus IMS, etc. and including the two new systems) have been collected. The superior properties of the two new systems have been proven by thermal resistance measurements. From a thermal point of view it is only the expensive 4 $W.m^{-1}K^{-1}$ IMS that competes with the 'low cost' systems.

## References

Bilinski M., Eisermann E., Jones-Williams K., Smetana W., Unger M., and Whitmarsh J., "Thick film pastes for the manufacture of low cost, insulated aluminium substrates for use as integrated heat sinks for high intensity LEDs" IMAPS Nordic September 14, 2008

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www.quantumalloys.com/data/aluminium/l61.html opened on 110908.