Development of LTCC-M structures for high power applications

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Abstract

Low temperature co-fired ceramic on metal (LTCC-M) technology offers benefits in high-power applications. Metal plate can be used as support to increase the mechanical strength of the LTCC module. In addition, the metal base can act as heat spreader in high-power applications and should have high thermal conductivity. The coefficient of thermal expansion of the metal should be closely matched with the LTCC dielectric to enable a reliable joint. This paper presents the development work of the LTCC-M concept made at VTT Electronics.

Introduction

New ceramic technologies, like Low Temperature Co-fired Ceramics (LTCC), are a rapidly (15-20%) growing part of the hybrid module market in Europe. The total proportion is still fairly small (10%) but exploitation in the market is progressing. LTCC is now an established technology for producing integrated multilayer substrates. The system is finding new emerging applications in military, aerospace, automotive, data processing, telecommunications, and biomedical modules. Nowadays, there are several LTCC components and modules volume manufacturing facilities globally.

One of the major advantages of LTCC technology is the use of multilayer structures, which allows the integration of passive and active components in an efficient way. Currently, there are some low-loss LTCC tape and conductor systems available, which allow the realisation of electrical circuits with good performance up to millimetre waves. Integration of high-power devices increases the heat levels inside the substrates and, hence, efficient methods to dissipate heat from integrated circuits are needed. Typical methods in LTCC technology have included, e.g., thermal vias from IC through a substrate. A more efficient way would be to use LTCC-M technique where the green tape layers are laminated directly on the metal base plate, followed by a co-firing process. The metal base plate acts as a constraining layer during sintering, enabling almost zero shrinkage of the LTCC layers in the x,y-plane. Furthermore, the semiconductor die can be mounted directly onto the metal heat sink. The principle of such a module concept is shown in Fig. 1.

In this specific application, a basic module structure was slightly modified. Very thin high-permittivity LTCC tape was needed for the realisation of capacitors and it was added between conventional low-permittivity tapes and metal base plate. The coefficient of thermal expansion and firing temperature of this high-permittivity tape were higher than most commercial tapes and therefore, only a limited amount of base plate materials was available.

In this study, thermal simulation was made to find out possible restrictions on the selection of materials and dimensions. Processing of LTCC-M structures using different metal base plates was characterised. Also the effect of firing conditions on the quality of LTCC-M was studied. This paper presents the most significant results from this research.

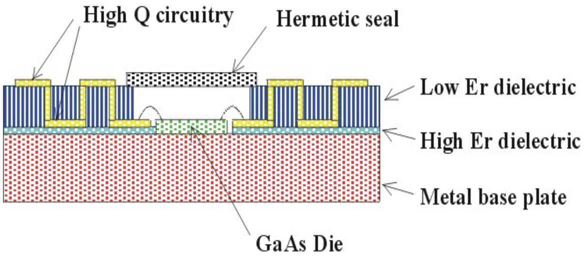

Figure 1. Principle of high-power LTCC-M module.

Thermal simulations

Simulation was made by IDEAS software. The dimensions and material properties used in the simulation are listed in Table 1. It was assumed that the LTCC-M module would be attached on an aluminium block. The LTCC-M module consists of a high-power chip directly attached on metal base plate. Thermal conductivity of LTCC dielectric is typically 2-4 W/mK and in the simulation it was kept as constant (i.e. 3 W/mK). The thermal conductivity of the metal plate was varied from 100 to 200 W/mK corresponding to the values of nickel and CuW, respectively. Also the thickness of the metal plate was taken into account in the simulation. Experimental and simulation work has shown that the attachment method between the LTCC-M module and aluminium is an important issue. Thermal grease is typically used in screw attachment to increase the effective contact area and hence improve the heat dissipation. The power generated from the IC was assumed to be 22.5 W in these simulations. The simulation gave temperature distribution profile as shown in Fig. 2 and the highest temperature was recorded.

TABLE 1. Thermal conductivity and thickness of materials used in the simulations.

Parameter	Thermal conductivity [W/mK]	Thickness [mm]
Al heat sink	220	2.0
Metal base plate	100-200	0.5-1.0
Thermal grease	1-3	0.01-0.1
Solder joint	57	0.012
GaAs chip	45	0.066

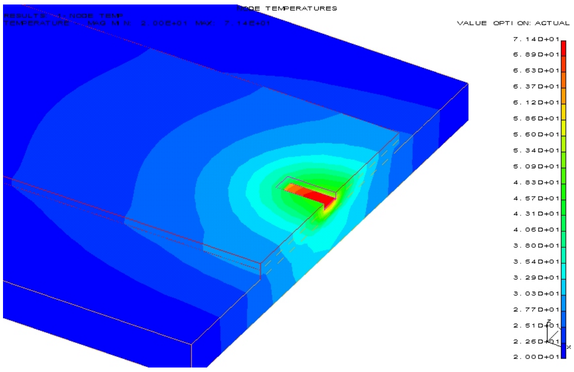

Figure 2. Heat distribution around chip in LTCC-M module.

Simulation results

The maximum temperature achieved in an ideal connection (i.e., perfect contact between Al block and CuW metal base, which were joined together by screws) is shown in Table 2. The lowest temperature was 60 °C, obtained when high thermal conductivity for the metal base was used.

TABLE 2. Maximum temperature in an ideal situation at a power dissipation of 22.5 W. The thickness of base plate is varied from 500 to 1000 µm.

Thermal conductivity of base metal [W/mK]	1000	750	500
200	60.0	60.0	60.7
150	66.0	-	65.3
100	77.0	75.0	73.5

In reality this kind of ideal connection cannot be achieved. Therefore, the simulation was made assuming that some kind of thermal grease is added between Al and CuW. Two different thermal conductivity values for thermal grease were used (Table 3 and 4). The thickness of thermal grease in these cases was 50 µm. When the thermal conductivity of the metal base plate was increased from 100 to 200 W/mK, the maximum temperature decreased by 19-25 °C, depending on thickness of the metal plate. When the thickness of the metal base plate was increased from 0.5 to 1 mm, the maximum temperature decreased by 6-14 °C. By increasing the thermal conductivity of thermal grease from 1 to 3 W/mK the maximum temperature decreased by 5-17 °C.

TABLE 3. Maximum device temperature when the thermal conductivity of thermal grease was 3 W/mK. The thickness of base plate is varied from 500 to 1000 µm.

Thermal conductivity [W/mK]	1000	750	500
200	65.0	67.2	71.2
150	72.2	74.2	78.7
100	85.1	-	90.4

TABLE 4. Maximum device temperature when the thermal conductivity of thermal grease was 1 W/mK. The thickness of base plate is varied from 500 to 1000 µm.

Thermal conductivity [W/mK]	1000	750	500
200	70.1	73.9	81.6
150	78.6	-	-
100	93.7	-	107.0

The effect of thermal grease thickness was also simulated. In these simulations, the thermal conductivity of metal base plate was assumed to be 200 W/mK. The results in Table 5 show that the thermal grease layer should be as thin as possible. Typical thermal conductivity values for commercial thermal greases are low, in the range of 3 W/mK.

TABLE 5. Maximum device temperature when the thermal conductivity of thermal grease was 3 W/mK. The thickness of base plate is varied from 500 to 1000 µm.

Thickness of Thermal grease [µm]	1000	750	500
100	67.9	71.0	77.5
50	65.0	67.2	71.2
10	61.4	62.1	64.0

Experimental work in LTCC-M

Test materials and processing

CuW, Kovar and Ni were used as base plate materials. Some of these metal plates were plated by thin sputtered Ni or Ni/Au layer. LTCC tapes were CT765 (ε_r=65) and CT707 (ε_r=7) from Heraeus. The thickness of unfired high-K material was 50 or 107 µm. Firing was made in air or N_2 atmosphere depending on the base plate. It was also possible to alter the ratio of air and N_2. In some tests Ag and Au paste was deposited on alumina or LTCC tape and fired in similar conditions.

LTCC tapes were laminated on 1”x1” metal plates. Lamination pressure was 3000 psi and temperature 70 °C. Most firing processes were made in a batch furnace where it was possible to use N_2 flow. Some firing tests were also made in a belt furnace. These high-K LTCC tapes required higher and longer firing temperature than usually needed by LTCC tapes. The samples were hold at the peak temperature of 915 °C for 3 hours. The total firing process took 14 hours.

Test results

The main focus in the experiments was in the utilisation of CuW as a base plate. This was due to its high thermal conductivity. The ratio of Cu and W was selected so that its coefficient of thermal expansion matches well with LTCC tape. In this case, the CTE of the tape was 9.0 ppm/K.

Firing of CuW in pure air atmosphere did not work due to severe oxidation. Therefore, N_2 atmosphere was needed. The amount of O_2 was only about 5 ppm when N_2 was supplied to the furnace. This can protect CuW but the conductor materials (Ag and Au) typically used for LTCC require a certain amount of oxygen for proper burning. Therefore, the optimisation of O_2/N_2 ratio had to be made. Most of these mixtures had oxygen content in the range of 1000 ppm.

In the optimised conditions the adhesion of the thin LTCC tape to metal base plate was acceptable. However, the fired LTCC tapes had some colour changes in comparison with the tapes fired in air. This colour problem was studied by making a x-ray diffraction analysis for the powders used in the tapes. These powders were then fired in air and N_2 atmosphere. Differences in chemical compositions were not found. However, when these powders are fired on CuW, there could be chemical reduction of oxides from the powder mixtures caused by tungsten. Plating of CuW did not seem to have any significant effect on the direct joining of LTCC tape to metal. Plating will come necessary when an IC will be solder-joined to the metal base plate because solders do not wet CuW well enough.

Ni was much easier to work with and there were no problems in air-firing. In the case of nickel, the main problem could be lower thermal conductivity, which could be less than 100 W/mK. Then it depends on the application whether nickel can be used as heat spreader or not.

A few firing tests were also made for Kovar in N_2 atmosphere. In these cases there was no adhesion between Kovar and LTCC tapes. However, it could be expected that Kovar would work in air atmosphere in a similar way as nickel. Unfortunately, it has even lower heat conductivity than nickel.

Summary and future work

The concept of LTCC-M method using a high-K LTCC dielectric material was studied in this paper. Simulation of heat distribution was made by IDEAS software to find out the maximum temperature in different package material options. The effects of the most important parameters, i.e. thickness and thermal conductivity of heat sinks and thermal greases, were simulated. The simulation results can be used as guidance for material selections and package design.

The direct joining of LTCC tapes on metal was studied using different metals and firing conditions. Metals with high thermal conductivity (as CuW) were fired in different N_2/O_2 atmospheres. The ratio of nitrogen and oxygen had to be optimised to allow proper sintering without excessive oxidation of the Cu-based metal plate. The use of CuW together with N_2-assisted firing could require the use of Cu pastes on LTCC tapes. Then the LTCC tapes might need some kind of modification so that they can be properly fired. Some metals with lower thermal conductivity can be fired in air that allows the use of Ag conductors on LTCC, which would be a benefit for the processing.

Future work includes e.g. the characterisation of dielectric properties when fired in different conditions. The simulation will be continued by taking into account also stress distributions in the module.

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