Development of Printed Circuit Boards with High Thermal Conductivity and Low Thermal Expansion by Applying Cu-Mo Composite Materials

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Abstract

In recent years, electronic devices are strongly required to be smaller, lighter, and more powerful. As a result, mounted components have become smaller, more powerful, and denser, and the heat generation density on printed circuit boards (PCBs) has increased. Since temperature rise of components can lead to component failure, efficient heat removal from the generated heat has become an urgent issue. Since general PCBs have low thermal conductivity, when high heat dissipation is required, methods to increase the thermal conductivity of PCBs have been employed by increasing the copper (Cu) content in the PCB or by placing an aluminum (Al) alloy in the inner layer. However, while Cu and Al have high thermal conductivity, they also have high coefficients of thermal expansion (CTE) and young's modulus, and the CTE of a PCB with increased thermal conductivity using these materials is high. If the thermal expansion difference between the PCB and mounted components is large, reliability against heat cycles cannot be obtained. Thus, it is difficult to achieve both heat dissipation and low thermal expansion in current PCBs. Therefore, we have focused on copper-molybdenum (Cu-Mo) composite materials with high thermal conductivity and high elastic modulus, but with low thermal expansion. We have been utilizing Cu-Mo for the development of our PCBs and fabricated multilayered Cu-Mo composite PCBs; therefore, this report will focus on the results regarding thermal characterization of prototype PCBs.

Key words

Printed circuit board, thermal conductivity, thermal expansion, copper-molybdenum composite materials

I. Introduction

In recent years, electronic devices are strongly required to be smaller, lighter, and have higher performance to meet increasingly sophisticated requirements. To meet these demands, mounted components are being made smaller and more powerful, and components are being mounted more densely, resulting in increase of heat generation on printed circuit boards (PCBs). The increase in the heat generation density leads to a rise in the temperature of mounted components, causing component operation instability, malfunctions, and failures. Therefore, it is an urgent issue to efficiently cool-off the heat generated on the PCB.

Heat generated from mounted components on a PCB can be transferred from the mounted components to the ambient gas by thermal convection, to the PCB by thermal conduction, and from the mounted components by thermal radiation. In general, cooling of electronic devices are often performed by methods using thermal convections, such as natural air cooling by attaching heat sinks to mounted components, forced air cooling by blowing air using a fan, and liquid cooling by coolant circulation. Recently, a cooling method that circulates refrigerant without a pump by means of a phase change between evaporation and condensation has also been applied [1,2].

Unlike these methods, we focus on the path of thermal conduction from the mounted components to the PCB, and are investigating ways to efficiently cool components by thermal conduction from the PCB by improving the thermal conductivity of the PCB. Glass epoxy PCBs are often used as general-purpose PCBs. Glass epoxy PCBs have low thermal conductivity, making it difficult to ensure sufficient heat dissipation when the heat generation density is high [3]. A method to increase the residual copper (Cu) content in the

PCB to improve heat dissipation can be considered, but in such a case, the CTE of the entire PCB becomes close to that of Cu due to the high young's modulus of Cu.
The composite CTE of a multilayer laminate consisting of n different materials can be calculated using (1) [4].

$$\alpha_s = \frac{\sum_{i=1}^{n} \alpha_i V f_i E_i}{\sum_{i=1}^{n} V f_i E_i} \quad (1)$$

where α is the CTE, Vf is the volume fraction, E is Young's modulus, the subscript s indicates the entire PCB, and i is material i. As can be seen from (1), the CTE of a multilayer PCB depends on the properties of the material with the higher Young's modulus.
If the difference in CTEs between the mounting components and the PCB becomes larger, the stress generated in the solder joints during heat cycling becomes larger, resulting in lower mounting reliability. Therefore, it is necessary to improve the heat dissipation of the PCB and at the same time suppress the CTE between the PCB and the mounted components. Even when using low-thermal-expansion PCB materials, there is a limit to reducing the CTE of PCBs because the young's modulus of Cu is higher than that of low-thermal-expansion PCB material.
As a PCB with high heat dissipation, an aluminum (Al) core PCB is known, in which an Al alloy with high thermal conductivity is inserted as a core material between the layers of the PCB [5]. While Al has high thermal conductivity, its CTE and young's modulus are high, resulting in a high CTE of the entire PCB when used as the core material. Therefore, as with glass epoxy PCBs with higher residual copper content, the difference in CTE between the Al core PCB and the mounted components becomes large, resulting in low mounting reliability.
As a PCB with low CTE, there is a Copper-Invar-Copper (CIC) PCBs with a laminate of Cu and invar (64Fe/Ni) inserted as a core material between the layers of the PCB as well as an Al core PCB [6]. However, invar has a low CTE, but also has a low thermal conductivity. Therefore, the thermal conductivity of the entire PCB is low, making it difficult to ensure heat dissipation. Table 1 shows the physical properties of materials used in conventional PCBs. Table 2 also shows a comparison of the properties of conventional PCBs.
Thus, it is difficult to achieve both heat dissipation and component mounting reliability with general-purpose PCBs, Al-core PCBs, and CIC PCBs. Therefore, we focused on copper-molybdenum (Cu-Mo) composites, which have high thermal conductivity and low thermal expansion. We are working on the development of PCBs that apply this material to realize PCBs with high heat dissipation and low thermal expansion, which can achieve both heat dissipation and component mounting reliability.
In this paper, to confirm the feasibility of multilayer PCBs using Cu-Mo composite materials, we report the results of fabricating a prototype PCB with Cu-Mo composite materials placed in the inner layer of the PCB and evaluating its performance.

II. Prototype PCB

Considering the consistency with the PCB manufacturing process, we focused on Cu-Mo composites as a copper-based material.
There are two types of Cu-Mo composite materials: a particle-dispersion type in which molybdenum particles are dispersed in Cu and a laminate type in which molybdenum foil and Cu foil are laminated. Fig.1 shows a schematic diagram of the structure of Cu-Mo composites. Cu-Mo composites are materials whose physical properties can be adjusted by changing the molybdenum content. For the same molybdenum content, the laminated type has been reported to have a lower CTE [7].
To confirm the feasibility of PCBs to which Cu-Mo composite materials are applied and to evaluate their basic performance, we fabricated prototype multilayer PCBs with

Table 1 Properties of Materials Used in PCBs

Material	κ (W/mK)	CTE (10^{-6}/K)	E (GPa)
Substrate material	0.4	12-16	20
Low CTE substrate material	0.4	4-6	30
Copper	390	17	120
Aluminum	240	24	80
Invar (64Fe/Ni)	13	1.2	145

Table 2 comparison of the properties of conventional printed circuit boards

PCB type	Heat dissipation	Mounting reliability
Glass-Epoxy PCB	Poor	Good
Aluminium core PCB	Good	Poor (Restricted to components)
CIC PCB	Poor	Good

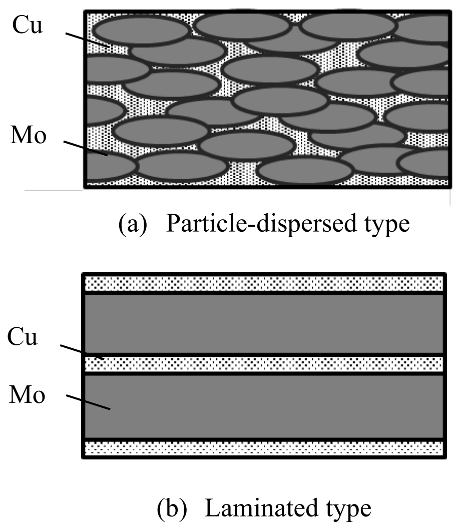

Fig.1 Schematic diagram of the structure of Cu-Mo composites.

particle-dispersion type Cu-Mo composite materials and laminated Cu-Mo composite materials in the inner layers. For comparison, we also fabricated a prototype PCB with the same configuration but with the Cu-Mo composite material replaced with Cu. They will be referred to as particle-dispersed Cu-Mo PCB, multilayer Cu-Mo PCB, and Cu PCB, respectively. Table 3 shows the physical properties of the Cu-Mo composite and Cu for comparison. The layer structure of the prototype PCB is shown in Fig.2. As shown in Fig.2, the prototype PCB consists of particle-dispersed Cu-Mo composite, laminated Cu-Mo composite, or Cu, and PCB materials (prepreg, substrate material). The thicknesses of the particle-dispersion Cu-Mo composite material and the laminated Cu-Mo composite material were set in consideration of their respective availability, and so that the CTE of the prototype PCB would be smaller than that of a general-purpose PCB (12 × 10-6/K or less). The CTEs of the PCBs were calculated using (1).

III. Performance Evaluation

Thermal conductivity and thermal expansion measurements were conducted to evaluate the performance of PCBs with Cu-Mo composite materials.

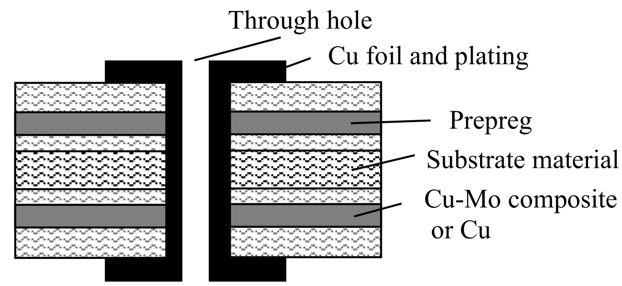

Fig.2 Layer structure of prototype PCBs

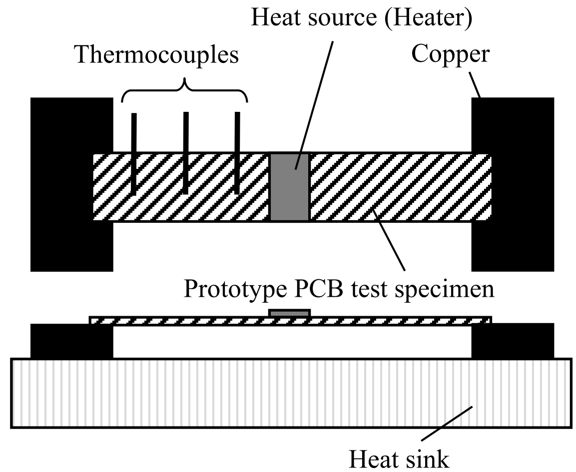

Fig.3 Schematic diagram of the measurement setup. The upper figure shows the top view, and the lower figure shows the side view.

A. *Thermal conductivity measurement*

The in-plane directional thermal conductivities of the prototype particle-dispersed Cu-Mo PCB, the laminated Cu-Mo PCB, and the Cu PCB were measured. The test configuration for the thermal conductivity measurements is shown in Fig.3. Thermal conductivity measurements were performed under a vacuum environment in a vacuum chamber. The test specimens were arranged to bridge between Cu blocks, and a heater was installed in the center of the test specimen as a heat source. The size of the test specimen was 20 mm × 80 mm, the size of the heater was 10

Table 3 Properties of inner layer materials

Material	κ (W/mK)	CTE ($\times 10^{-6}$/K)	Young's modulus (GPa)
Cu	398	17.1	120
Mo	142	5.2	320
Cu-Mo Composites (Particle-dispersed type)	220	8.8	210

mm × 20 mm, and the size of the Cu block was 25 mm × 50 mm. The Cu block was connected to an Al heat sink. The heater was powered by a DC stabilized power supply.

The thermal conductivity of the prototype PCB was calculated using Fourier's law shown in (2).

$$q = -\kappa \frac{\partial T}{\partial x} \quad (2)$$

where q is the heat flux, κ is the thermal conductivity and $\partial T/\partial x$ is the temperature gradient. The heat flux q was calculated using (3), assuming that all the power Q supplied by the power source is supplied to the heater and that heat is transported symmetrically from the center of the test specimen to both ends.

$$q = \frac{Q/2}{A} \quad (3)$$

where A is the cross-sectional area of heat passage through the test specimen, calculated from the width and thickness of the test specimen. The temperature gradient $\partial T/\partial x$ was calculated from the temperature measured by three thermocouples placed at 10 mm intervals from 5 mm from the edge of the heater. The power Q was calculated from the applied voltage V of the DC stabilized power supply and the current I measured by an ammeter.

Fig.4 shows the temperature gradient measurement results for each prototype PCB test specimen at a heating voltage of 8 V. The temperature gradient is smaller for Cu PCBs, particle-dispersed Cu-Mo PCBs, and laminated Cu-Mo PCBs, in that order. Therefore, it can be said that the heat transport capacity is high in this order. Measurements were performed at applied voltages of 5, 6, and 7 V, and the trend was the same for all.

The thermal conductivities of each PCB obtained from the measurements are shown in Table 4. The thermal conductivity of the particle-dispersed Cu-Mo PCB was 40.4 W/mK, that of the laminated Cu-Mo PCB was 34.6 W/mK, and that of the Cu PCB was 56.9 W/mK. The thermal conductivity of the particle-dispersed Cu-Mo PCB was about 70% of that of the Cu PCB, and that of the laminated Cu-Mo PCB was about 60% of that of the Cu PCB.

Here, we compare the thermal conductance of the Cu-Mo composites and Cu applied to the prototype PCBs. The thermal conductivities of the laminated Cu-Mo composites needed to calculate the thermal conductance ratios were calculated from content ratios and the thermal conductivities of Mo and Cu given in Table 3. The values in Table 3 were used for the particle-dispersed Cu-Mo composites and Cu. The thermal conductance ratio for each layer was calculated from the ratio of these thermal conductivities to the thickness of each layer.

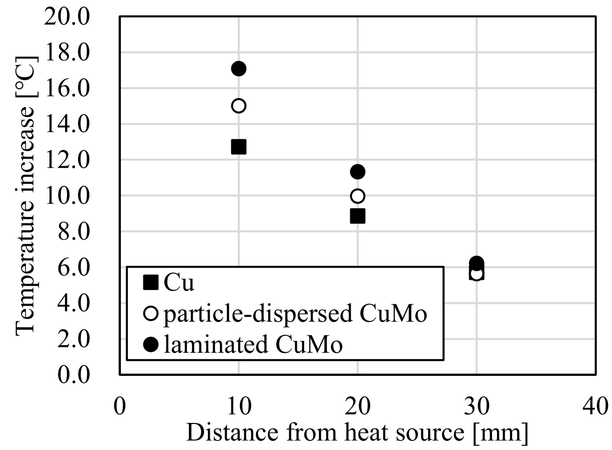

Fig.4 Temperature gradient measurement results for each prototype PCB test specimen at a heating voltage of 8V

Table 4 Thermal conductivity of prototyped PCBs

Type of Prototyped PCB	Thermal conductivity κ(W/mK)
Particle-dispersed Cu-Mo PCB	40.4
Laminated type Cu-Mo PCB	34.6
Cu PCB	56.9

The calculations showed that when the thermal conductance of the Cu layer was set to 1, the values for the particle-dispersed Cu-Mo composite layer and the laminated Cu-Mo composite layer were 0.71 and 0.59, respectively.

These values are consistent with the ratio of the thermal conductivity of the particle-dispersed Cu-Mo PCB and the laminated Cu-Mo PCB to the Cu substrate. Therefore, it is considered that the inner layer of Cu-Mo composite or Cu is responsible for most of the heat transport in these PCBs, and the thermal conductivity is dependent on these materials. It is possible to produce substrates that reflect the thermal conductivity of the material itself, as is the case with Cu, even with the application of Cu-Mo composite materials.

B. Coefficient of thermal expansion measurement

CTE measurements were performed for the in-plane direction of the prototype particle-dispersed Cu-Mo PCBs, laminated Cu-Mo PCBs, and Cu PCBs, as well as for thermal conductivity measurements.

Thermo-mechanical analyzer (TMA) was used to measure the CTE, in which a small load is applied to the test specimen to be measured via a probe and the displacement due to thermal expansion of the test specimen is measured while the test specimen is heated using a heater. The size of the test specimen was 5 mm x 5 mm. Test specimen was cut from each prototype PCB. The CTE is calculated using (4).

$$\alpha = \frac{1}{l}\frac{\Delta l}{\Delta T} \quad (4)$$

where l is the length of the test specimen, Δl is the change in length of the test specimen, and ΔT is the change in temperature.
Fig.4 shows the relationship between temperature and rate of dimensional change for each prototype PCB test specimen. The dimensional change in response to temperature change is about the same for the particle-dispersed Cu-Mo PCB and the laminated Cu-Mo PCB, and is also lower than for the Cu PCB.
The CTE obtained from the measurements are shown in Table 5. The CTE of the particle-dispersed Cu-Mo PCB, the laminated Cu-Mo PCB, and the Cu PCB are 11.4 × 10-6/K, 11.4 × 10-6/K, and 16.4 × 10-6/K, respectively
Among the materials constituting the PCB, the CTE of Cu-Mo or Cu with high elastic modulus is close to that of the CTE of the PCB is strongly dependent on the CTEs of these materials. In addition, the CTEs of both the particle-dispersion type Cu-Mo PCB and the laminated Cu-Mo PCB are closer to those of ceramic components than those of general-purpose PCPs (e.g., about 7×10^{-6}/K for alumina), and higher component mounting reliability can be expected than with general-purpose PCB.

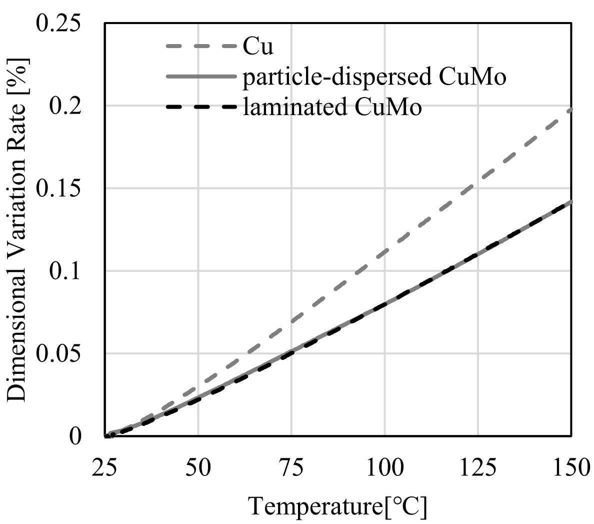

Fig.4 Relationship between temperature and dimensional change rate for prototyped PCBs

Table 5 Coefficient of thermal expansion of prototyped PCBs

Type of Prototyped PCB	CTE ($\times 10^{-6}$/K)
Particle-dispersed Cu-Mo PCB	11.4
Laminated Cu-Mo PCB	11.4
Cu PCB	16.4

IV. Conclusions

In order to achieve both high heat dissipation and low thermal expansion in printed circuit boards, we are investigating the use of Cu-Mo composites, which have high thermal conductivity and low coefficient of thermal expansion.
We are investigating the feasibility of a PCB using Cu-Mo composite materials, which have high thermal conductivity and low coefficient of thermal expansion. To confirm the feasibility of multilayer PCBs using Cu-Mo composite materials, we fabricated prototype multilayer PCBs with particle-dispersion type Cu-Mo composite materials and laminated Cu-Mo composite materials in the inner layers of the PCBs and measured thermal conductivity and coefficient of thermal expansion. The results obtained are shown below.

- The thermal conductivity of the PCB with particle dispersion type Cu-Mo composite is 40.4 W/mK and that of the PCB with laminated Cu-Mo composite is 34.6 W/mK, which is about 60-70 % of the thermal conductivity of the PCB with Cu-Mo composite replaced by Cu in a similar configuration.

- The CTE of PCBs with particle dispersion type Cu-Mo composite and laminated Cu-Mo composite is 11.4 × 10-6/K, which is closer to the CTE of mounted parts than that of general-purpose PCBs, and higher reliability in mounting parts can be expected than that of general-purpose PCBs.

- The developed Cu-Mo PCB has a CTE 30% lower than that of general-purpose PCBs, while maintaining a thermal conductivity 60-70% that of Cu PCBs, thus achieving both low thermal expansion and high heat dissipation.

References

[1] S. S. Anandan and V. Ramalingam, "Thermal Management of Electronics: a Review of Literature", *THERMAL SCIENCE*, 12, 2008, pp. 5-26.
[2] R. J. McGlen, R. Jachuck and S. Lin, "Integrated thermal management techniques for high power electronic devices", *Applied Thermal Engineering*, 24, 2004, pp.1143–115.
[3] K. Azar, and J. E. Graebner, "Experimental determination of thermal conductivity of printed wiring boards", *Proc. of Twelfth Annual IEEE Semiconductor Thermal Measurement and Management Symposium*, 1996, pp. 169-182.
[4] H. Nakayama, H. Kawazoe, S. Shiota, M. Nakao and A. Shimizu, "Design of Thermal Expansion Coefficient for Multilayer Printed Wiring Boards", *Circuit technology, Japan*, 8, 1993, pp. 201-208.
[5] K. C. Yung, "Using metal core printed circuit board (MCPCB) as a solution for thermal management", *J. HKPCA*, 24, 2007, pp.12–16.
[6] K. Takagi, and S. Yasufuku, "Recent Japanese developments in printed wiring boards for SMT", *IEEE Electrical Insulation Magazine*, 7, 1991, pp. 9-27.
[7] T. Arikawa, A. Ichida and E. Takegoshi, "Mechanical Properties of Cu-Mo Composites", *J. Soc. Mat. Sci., Japan*, 48, 1999, pp. 295-300.