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Initial Success on Aluminum Circuit Board Technology

Shou-Jen Hsu, Chu-Hsuan Sha, and Chin C. Lee, *Fellow, IEEE*

Abstract—In this paper, aluminum circuit boards (ACBs) were designed, fabricated, and tested to demonstrate the possibility and advantages of the ACB technology. Processes were developed to grow high quality alumina (Al_2O_3) on Al boards and coat thick copper (Cu) layer over the alumina to produce an Al/alumina/Cu structure. The measured resistance and breakdown voltage of the as-formed 50 μm alumina layer is > 40 MΩ and 600 VDC respectively. In this design, heat generated by a high power circuit component attached to the Cu layer can conduct through the alumina layer and reach the Al base. Alumina has much higher thermal conductivity than epoxy-glass insulating layer of the popular FR-4 printed circuit boards. The quality of the boards produced in this paper was evaluated rigorously using scanning electron microscope. To test the reliability of the boards, they were put through 500 cycles of thermal cycling test between −40 °C to +85 °C and 100 h of high temperature storage test at 250 °C. To ensure its compatibility with soldering operations, 10 mm × 12 mm Cu substrates were bonded to the Al boards using a fluxless tin process. The thickness of the joint is 9.4 μm including the intermetallic layers. Despite significant coefficient of thermal expansion mismatch of the structure and large Cu size, the bonded samples show no sign of cracks, breakage, or degradation.

Index Terms—Aluminum, soldering, substrate.

I. INTRODUCTION

THE MOST popular printed circuit board is constructed of epoxy-glass insulating board laminated with thin copper (Cu) foils on both sides where the circuits are built, as shown in Fig. 1(a) [1]. The most widely used board material is known as FR4. As the industry has, however, moved to lead-free soldering process, the use of higher melting point solders has driven the requirement of laminate materials with higher thermal stability. Laminates should be able to survive soldering temperatures that could be as high as 260 °C. FR4 has glass transition temperature (T_g) of 140 °C, making it inadequate in lead-free soldering process. Higher T_g materials have been developed. Examples of these laminates include those based on polyimides and liquid crystal polymers, where the T_g could be as high as 280 °C [2]. For high power circuit boards such as automotive power convertors, automotive power invertors,

and microwave transmitters, the demand of thermal stability is even higher. The alumina substrate is therefore adopted as the board material because of its excellent thermal stability and higher thermal conductivity than any of the polymer-based laminate materials. The maximum service temperature of alumina could be as high as 150 °C, while the polymer-based laminate materials decompose at 500 °C at most. The thermal conductivity of alumina is 30 W/m K, but the highest thermal conductivity among the polymer-based laminate materials is only 0.95 W/m K. In the commonly used structure as shown in Fig. 1(b), the Cu sheets are bonded to the alumina by a direct bonded Cu (DBC) process [3], [4]. The DBC process involves a precisely controlled high-temperature oxidation process in the atmosphere of nitrogen containing ∼1.4 mol% of oxygen, thus increasing the manufacturing cost. In general, the bottom Cu layer on the alumina substrate is soldered to a thick Cu heat spreader to dissipate heat. The alumina thickness is however, constrained to be not < 0.25 mm due to mechanical reliability concern. Although the thermal conductivity of alumina is reasonably good, this results in significant thermal resistance for heat to conduct through the alumina and reach the Cu heat spreader. Another issue is the solder joint quality. For soldering largearea alumina substrates, such as 20 mm × 20 mm, it is very difficult to achieve void-free joint. The solder joint adds additional thermal resistance. To increase heat conduction through the circuit board, insulated metal substrate (IMS) was developed [5]–[7], as shown in Fig. 1(c). It consists of aluminum (Al) or Cu base plate laminated with ceramic epoxy and Cu foil. Ceramic fillers are added to increase the thermal conductivity [8], [9]. This structure provides a thick base plate as heat spreader. It does not however, entirely solve the heat conduction problem because the ceramic epoxy insulating layer has low thermal conductivity, 2–3 W/m K. The tradeoff between the performance and cost depends on the selection of filler types, size, shape, and so on, and the use of special wetting and dispersing agent. Thus, it is yet to find high volume applications due to the complexity in the fabrication process.

We have studied what has been done by the electronic industry in developing a circuit board structure for highpower circuits over the last half century. It seems that no one has come up with an efficient structure. We thus investigated the fundamental requirements of an ideal structure. There are four requirements: highly conductive base plate, thin insulating layer with good thermal conductivity, Cu circuit layer, and high structure integrity. To meet these requirements, we began our structure design with Al as the base plate. Al has thermal conductivity of 237 W/m K, close to 400 W/m K of Cu. It is lightweight, corrosion resistant, and low cost. It weighs only

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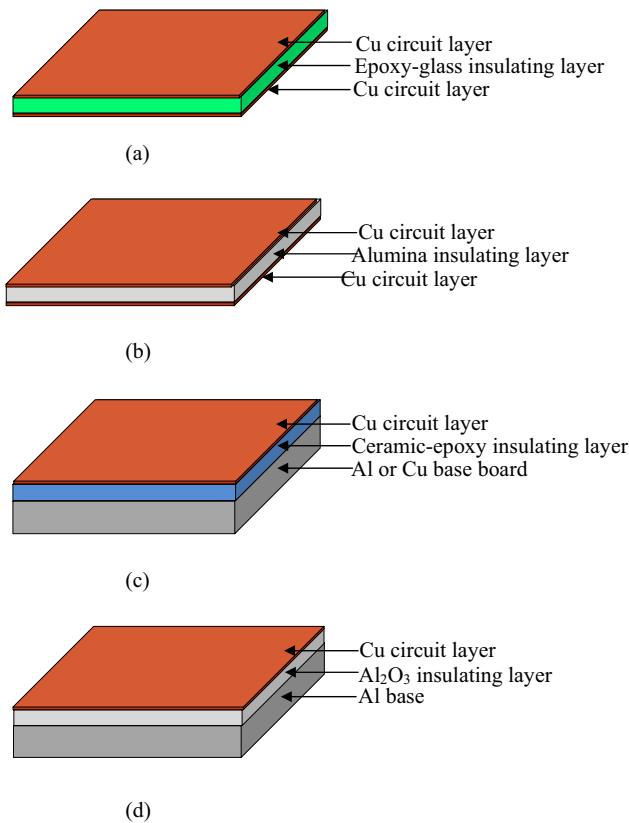C. C. Lee is with the EECS Department, University of California, Irvine, CA 92697-2660 USA (e-mail: cclee@uci.edu).

Fig. 1. Circuit board structures. (a) Conventional PCB, (b) Cu/alumina/Cu board, (c) IMS, and (d) Cu/alumina/Al board of this paper.

Fig. 2. Process flow chart of the board fabrication.

30% of Cu and 35% of iron (Fe). It costs only 25% of Cu by weight [10] and only 7.5% of Cu by volume. It is easy to machine, cast, forge, shear, and roll. What is more important is that, the thin Al_2O_3 insulating layer can be directly grown over Al base plate by anodization process, thus getting around the complicated manufacturing processes in DBC or IMS. Thin chromium (Cr) and Cu are then deposited, followed by Cu electroplating process to build up the Cu layer. Fig. 1(d) shows the resulting structure.

In what follows, experimental design and procedure are first reported. A concern of this structure is the high coefficient of thermal expansion (CTE) of Al, 23 ppm/°C. To ensure the structure integrity, several samples are fabricated and put through thermal cycling test and aging test. The boards fabricated are cut in cross section, polished and evaluated by scanning electron microscopy (SEM) with energy dispersive X-ray spectroscopy (EDX). To demonstrate the application of this structure, 10 mm × 12 mm Cu substrates are bonded to Al/Al$_2$O$_3$/Cr/Cu boards using tin without any flux. The quality and microstructure of the joints are examined using SEM and EDX. The experimental results are presented and discussed. A summary is given.

II. EXPERIMENTAL DESIGN AND PROCEDURE

The dielectric strength of alumina is 13.4 V/μm, which is low compared with 470–670 V/μm of SiO_2 [11]. The reason for this large difference in dielectric strength has never been explained in any literatures. To sustain 500 V, the alumina thickness has to be at least 37 μm. A standard
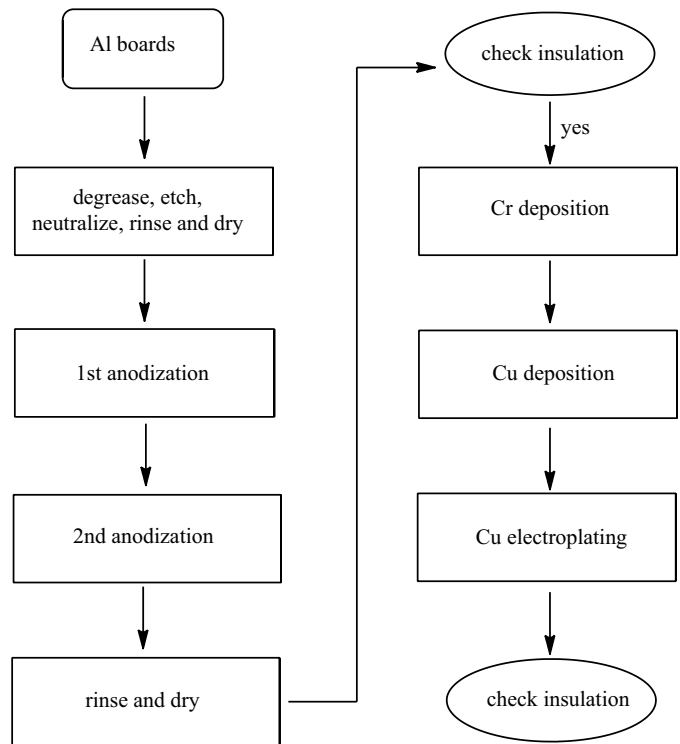
technique to grow thick alumina on Al is anodization. There are two basic anodization processes, porous-type and barrier-type, both of which are well-established [12]–[15]. The first process produces porous alumina. The pores allow the anodizing electrolyte to penetrate into the alumina for continuing growth. The alumina thickness ranges from a few μm to several hundred μm [16]. The pores make the alumina layer electrically conducting. In the industry, the pores are plugged by hydrated aluminum oxide, boehmite, which is formed in hot water at a temperature range of 96 °C–100 °C [16]. In this paper, high purity Al_2O_3 is needed and the use of sealant is not an option. We then turned to the barrier-type process. It grows alumina without pores. The thickness is, however, limited to several micrometers [16]. Numerous experiment runs were performed to grow alumina layer thicker than 5 μm that is insulating, but without success. We finally came up with a two-step anodization technique that works well and forms high quality alumina, as shown on the process flow chart in Fig. 2. The first step grows thick alumina with pores using sulfuric acid electrolyte. The second step seals the pores with alumina using boric acid electrolyte. Al 1100 (International Alloy Designation System) boards of 20.6 mm × 25.4 mm × 1.7 mm are degreased in acetone, etched in 1 M NaOH, neutralized in 1 M HNO_3, rinsed in deionized water, and dried by compressed air. After the two-step anodization process, the samples are rinsed in deionized water and dried with compressed air.

Before metallization with Cu, we have to make sure that the alumina layer is insulating. An Al foil is pressed over the anodized alumina layer and the resistance between the Al foil and the bottom side of the Al board is measured, as shown in Fig. 3(a). If the result shows that the alumina layer offers
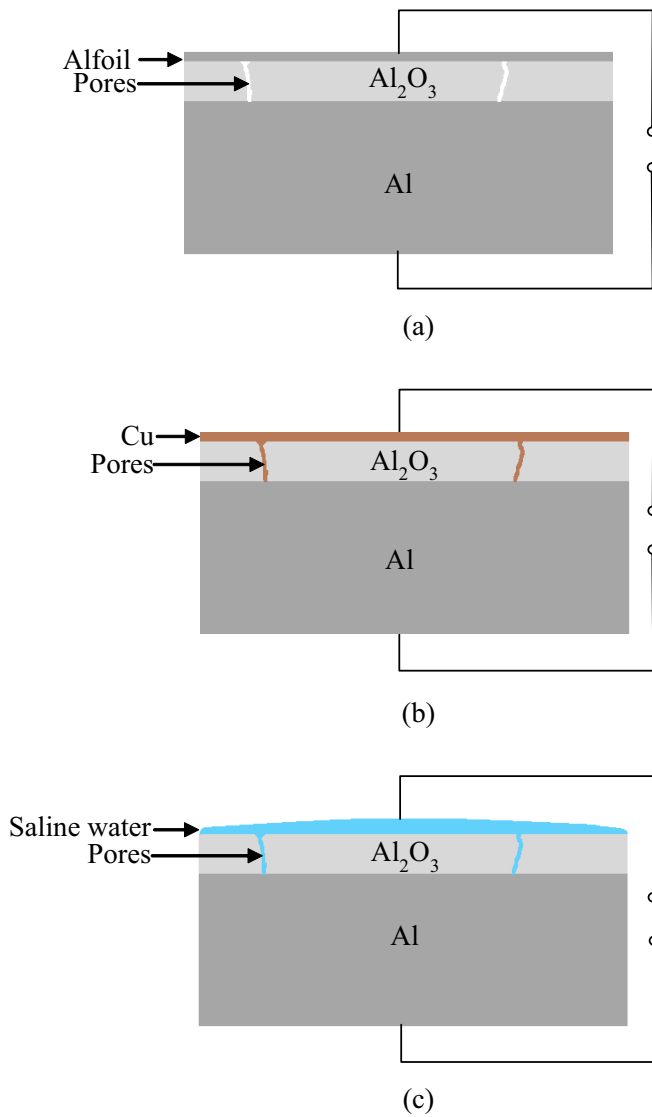
(a)

(b)

(c)

Fig. 3.   Structures used during the development of Al circuit boards. (a) Al foil is pressed over the anodized alumina layer. (b) Cu gets into the pores in the alumina layer upon metallization. (c) Anodized alumina layer is covered with saline water.
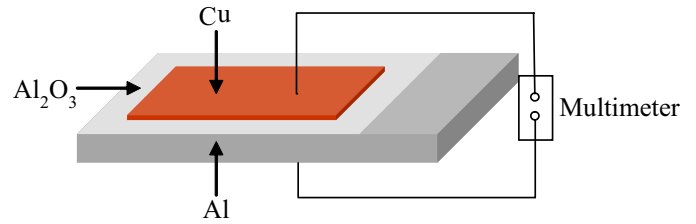

Fig. 4.   Experimental setup to measure the electrical resistance of alumina layer grown on Al base.

TABLE I

MEASURED RESISTANCE OF ALUMINA LAYERS GROWN BY VARIOUS ANODIZATION PROCESSES AND ELECTROLYTES ON Al BOARDS. THE AREA OF ALUMINA LAYER IS 20 mm × 20 mm

Anodization and electrolytes	Measured resistance
one-step: tartaric acid	0.8 - 1.5 Ω
one-step: boric acid	1.5- 3.5 kΩ
one-step: sulfuric acid	5.0 - 8.0 MΩ
two-step: sulfuric acid and boric acid	> 40 MΩ*

 * Limit of the digital multimeter

established technique. The direct Cu bonding process is not applicable because it needs a high temperature of 1067 °C [3], [4]. Electron-beam evaporation is another way to deposit metals on substrates. However, Cu does not adhere well on alumina, peeling off after deposition or during later handling. Cr is then used as the adhesion layer since it bonds to alumina and to Cu well. So, we tried our own process. Thin Cr (100 nm) and Cu (200 nm) layers are deposited sequentially on anodized Al boards in a high vacuum (2×10^{-6} torr) electron-beam evaporation system. Here, Cr is expected to bond strongly to alumina and Cu protects the Cr from oxidation. Afterward, 25-μm-thick Cu is electroplated in a pyrophosphate Cu plating bath at ambient temperature with current density 30 mA/cm^2

To test the alumina insulation, electrical resistance is measured between the Cu layer and bottom side of the Al board using a high precision digital multimeter. The breakdown voltage is measured by an adjustable high voltage dc power supply. Our concern on possible failure of the structure comes from the CTE mismatch among Cu, alumina and aluminum. They are 17, 7, and 23 ppm/°C respectively. Despite the mismatch, no samples ever broke after fabrication. Still, we want to make sure that they do not break in applications. Accordingly, 13 samples are fabricated and put through thermal cycling test between −40 °C and +85 °C. Furthermore, some samples are aged at 250 °C for 10 and 100 h, respectively.

To demonstrate that the components can be attached to resulting Al boards, 10 mm × 12 mm Cu substrates are bonded using fluxless tin (Sn) process. Sn of 60 μm in thickness is electroplated in a stannous bath under the condition of 43 °C and pH of 1 with current density of 30 mA/cm^2, followed by plating 100-nm Ag capping layer. The Cu substrate is degreased with acetone and rinsed in deionized water. The Cu substrate is placed over the Al$_2$O$_3$/Cr/Cu board and held with 32 psi (0.22 MPa) of static pressure.

proper insulation, the sample is then metallized to form a Cu layer in the next step of the process. However, many samples made in our early process development phase seemed insulating when tested with aluminum foil but turned conducting upon Cu metallization. It is thought that the conducting paths go through the pores in alumina, where the Al foil does not get to, but Cu does during deposition as shown in Fig. 3(b). In other words, during the metallization process, Cu gets into the pores in the alumina and shorts the alumina layer. We thus design a new measurement method to examine the insulation before Cu metallization, as shown in Fig. 3(c). Instead of Al foil, the anodized alumina is covered with saline water. If there are pores in anodized alumina, saline water will penetrate into the pores and reduce the electrical insulation. The two-step anodization process was established according to this test method. All the samples made with the two-step anodization process could be perfectly insulating after Cu metallization.

The next step is to coat the alumina with Cu. We searched the literature extensively and could not find any

(a)   (b)
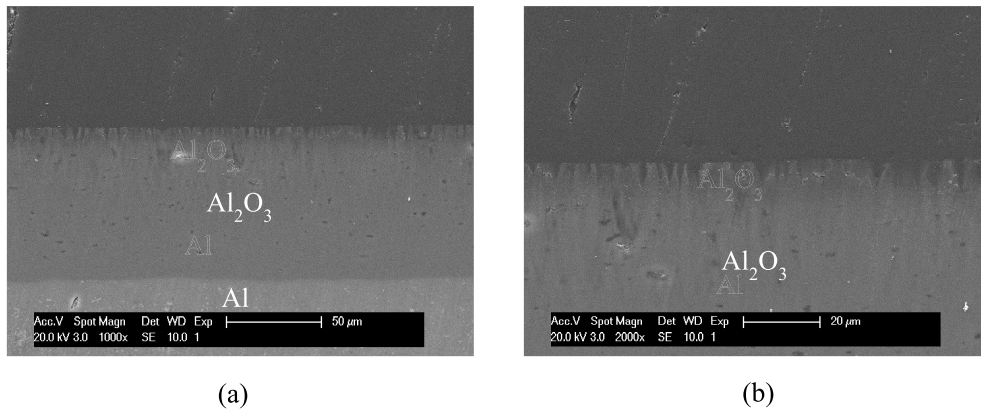
Fig. 5.   Cross-sectional SEM images of alumina layer after the first anodization step (a) 1000× magnification and (b) 2000× magnification. The alumina layer is 80-μm thick and pores are clearly seen in (b).

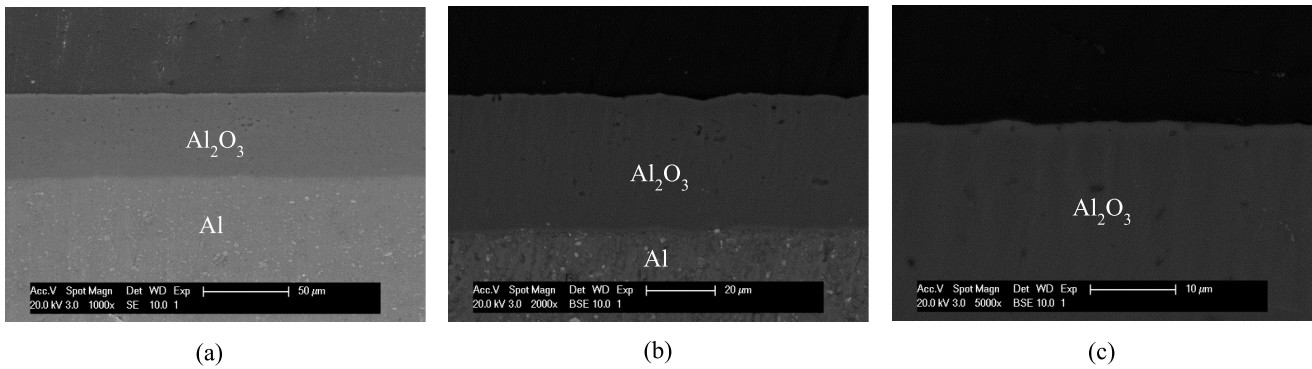(a)   (b)   (c)

Fig. 6.   Cross-sectional SEM image of alumina grown using the two-step anodization process (a) 1000× magnification and (b) 2000× magnification. The alumina layer is 50-μm thick and free of pores.

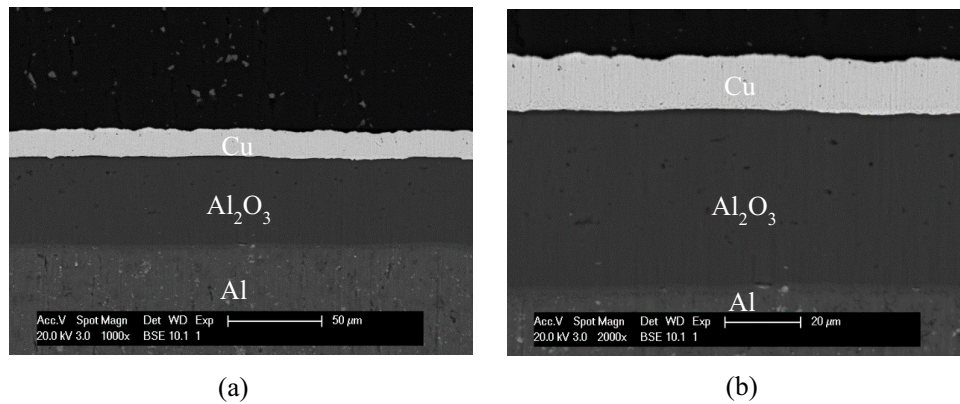(a)   (b)

Fig. 7.   Cross-sectional SEM images of an Al circuit board after test of 500 thermal cycles between −40 °C and +85 °C. (a) 500× magnification and (b) 2000× magnification. There is no visible change after the thermal cycling test.

The assembly is mounted on a graphite platform in a vacuum chamber pumped down and kept at 80 mTorr. The graphite platform is then heated and the temperature of the sample is monitored by a thermocouple during the bonding process. The bonding temperature is 240 °C with a dwell time of 3–5 min. The heater is then turned off and the assembly is allowed to cool down naturally to room temperature in vacuum environment.

To assess the structural integrity of Al boards, samples are mounted in epoxy resin, cut into halves, and polished for examination using SEM and EDX. Samples of Cu bonded to Al board are also studied by SEM for joint microstructure evaluation and EDX for composition analysis.

III. EXPERIMENTAL RESULTS AND DISCUSSION

After the anodization process, the electrical resistance of the sample was measured using the setup shown in Fig. 4. Table I shows resistance values during the process development phase. The area of alumina layer on the Al boards is 20 mm × 20 mm. Using a two-step process, the measured resistance is > 40 MΩ which is the upper limit of the digital multimeter. The process
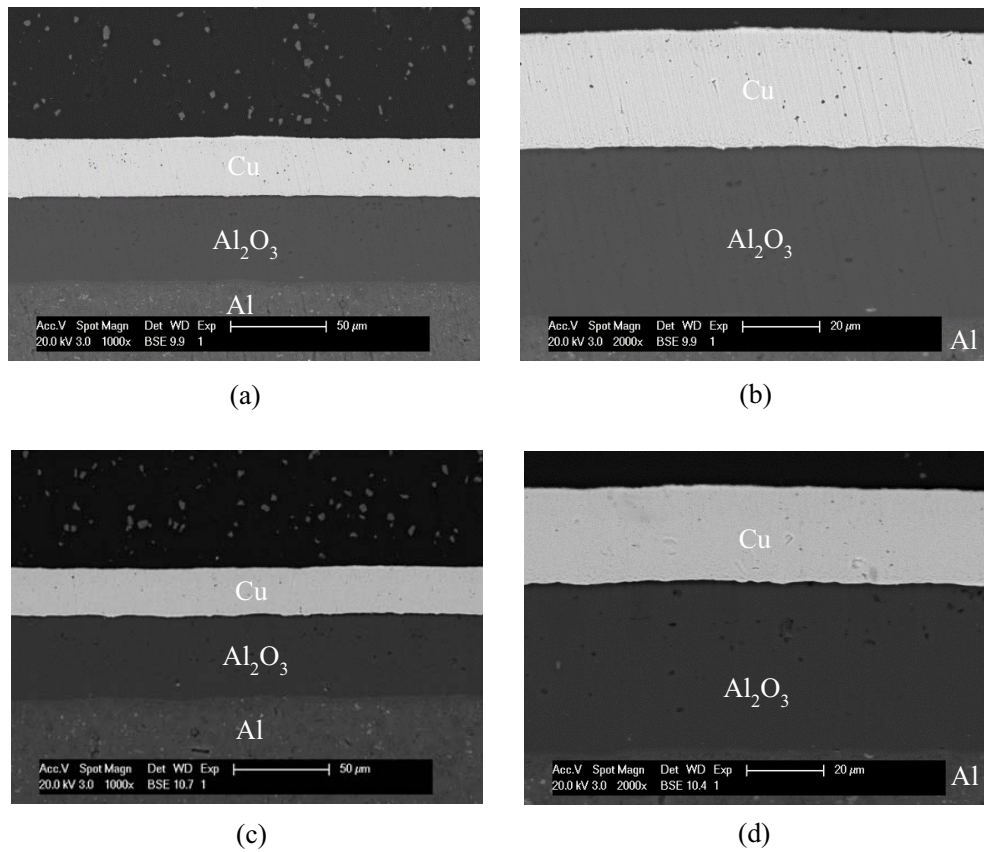
Fig. 8. Cross-sectional SEM images of Al circuit boards after storage at 250 °C for 10 h. (a) 1000× magnification, (b) 2000× magnification and 100 h, (c) 1000× magnification, and (d) 2000× magnification, respectively. There is no visible change after the high temperature storage test.
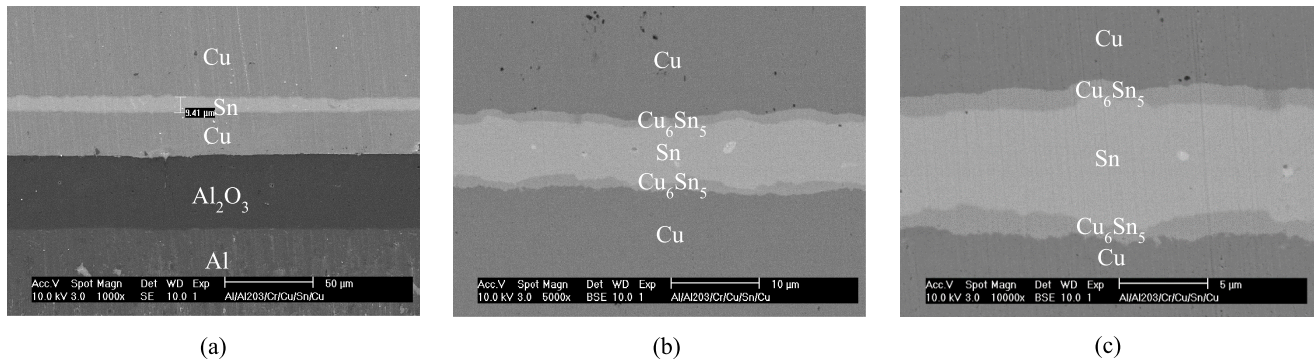

Fig. 9. Cross-sectional SEM images of Cu substrate bonded to an Al circuit board using fluxless tin at 240 °C. The joint thickness is 9.4 μm including Cu_6Sn_5 layers. The Cu substrate is 10 mm × 12 mm in size.

was adjusted until 40 MΩ or higher resistance was achieved consistently. Cr and Cu were deposited over the alumina layer on the Al board. The electrical insulation was verified again.

Fig. 5(a) and (b) exhibits cross-sectional SEM images of a typical sample after the first anodization step. The alumina layer thickness is 80 μm. It was a challenge to polish an SEM sample that shows the pores. Fig. 5(b) does expose the pores clearly. Fig. 6(a) and (b) exhibits the SEM image after the second anodization step. The thickness of the alumina reduces to 50 μm and no pores are observed. The electrical resistance is > 40 MΩ. The mechanism for the anodization

step is still being investigated. The breakdown voltage of the alumina layer was measured. It can withstand 600 VDC. The measured dielectric strength is 600 V/50 μm = 12 V/μm, close to 13.4 V/μm reported of pure alumina substrate [7].

To test the integrity of the board structure, 13 samples were put through thermal cycling test between −40 °C and +85 °C. A sample was randomly selected after 500 cycles and evaluated. Fig. 7 shows the crosssectional SEM images. The Al/Al_2O_3 interface and $Al_2O_3/Cr/Cu$ interface remain sharp without any voids or cracks. The 50-μm-thick Al_2O_3 layer shows no cracks, no pores, and no voids. Several samples were subjected to high temperature storage at 250 °C for

1 and 100 h, respectively. Fig. 8 shows the crosssectional SEM images of two samples stored at 250 °C for 10 and 100 h, respectively. No defects were detected. Despite the significant CTE mismatch among Cu, alumina, and aluminum, the Al circuit boards survived the thermal cycling test and 250 °C storage test without any degradation.

To demonstrate that the Al circuit boards can sustain soldering operations, 10 mm × 12 mm Cu substrates were attached to Cu side of the boards using fluxless Sn bonding technique [17]. 60-μm-thick Sn was plated on the Cu side of the board, followed by capping with 100-nm Ag layer to prevent Sn from oxidation. The Cu substrate was placed over the Sn solder and held with 32 psi (0.22 MPa) static pressure. The assembly was then mounted on a graphite platform in a vacuum chamber which was pumped and kept at 80 mTorr to suppress oxidation. The graphite platform was heated and the temperature of the sample was monitored by a thermocouple during the bonding process. The bonding temperature was 240 °C with a dwell time of 3–5 min. The heater was turned off and the assembly was allowed to cool naturally to room temperature in vacuum environment. Most of the Sn was squeezed out because of the 32-psi pressure applied. Shear strengths of the solder joints were not measured, but the Cu substrate could not be pushed off by a hand tool. Fig. 9 shows the cross-sectional SEM images of a typical sample. The joint exhibits high quality without any cracks, defects, or voids. The Sn joint bonds well to the Cu substrate and to the Cu layer on the Al board. Intermetallic compound (IMC) Cu_6Sn_5 is formed on Sn-Cu interfaces. The solder joint including the IMC layers is only 9.4 μm in thickness.

The Al boards have 50-μm alumina and 25-μm Cu. Since both the alumina and Cu are much thinner than the Al base thickness of 1700 μm, we can approximate the CTE of the board to be the same as Al. The CTE mismatch between the Cu substrate and Al board is then 17 ppm/°C versus 23 ppm/°C. A commonly used indicator on the severity of CTE mismatch of bonded structures is the maximum stress-free shear strain calculated assuming that the Cu substrate and the Al board are free to contract or expand [18]

$$\gamma = \frac{(\alpha_1 - \alpha_2)(T_2 - T_1)}{h} \quad (1)$$

where α_1 and α_2 are the CTE of Al and Cu, respectively, T_2 is the solder solidifying temperature, T_1 is the room temperature, L is the diagonal of the Cu substrate, and h is the bonding layer thickness. The maximum stress-free shear strain calculated is 120%. This is much higher than that of typical solder joints, at most 30%. We actually expected the bonded structures to break during cooling down. But they all survived without any cracks.

IV. CONCLUSION

Aluminum has thermal conductivity of 237 W/m K, close to 400 W/m K of Cu. It is lightweight, corrosion resistance, and low cost. It weighs only 30% of Cu and 35% of Fe. It costs only 25% of Cu by weight and 7.5% of Cu by volume. It is easy to machine, cast, forge, shear, and roll. Two challenges of using Al as circuit board material are the

growth of insulating layer and its high CTE. In this paper, thin Al_2O_3 layer was grown on Al boards by a two-step anodization process to achieve high electrical insulation. Thin Cr and Cu were then deposited over the alumina layer, followed by Cu electroplating process to build the Cu layer to 25 μm. The alumina layer is as thick as 50 μm. The electrical resistivity measured is $> 3.2 \times 10^{10}$ Ω cm, limited by the instrument. Thermal cycling test of 500 cycles between -40 °C to $+85$ °C and 250 °C storage test for 100 h show no effects on the structural integrity and the electrical properties of the Al boards. To evaluate soldering operations on the Al boards, Cu substrates were bonded to the Cu side of the boards using a fluxless Sn process. High quality Sn joint with Cu_6Sn_5 on the Sn-Cu interface was achieved. Despite significant CTE mismatch between the Cu substrate and the Al board, no breakage and cracks are observed. This aluminum circuit board technology should open up applications where efficient heat transport from the circuit components to the base of the boards is essential. Application examples include high power light-emitting diode modules, automobile convertors and invertors, microwave transmitters, and space electronics.

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