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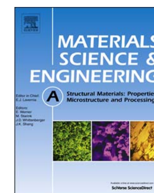

Direct silver to aluminum solid-state bonding processes

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ABSTRACT

The high thermal conductivity, light weight, and low cost of aluminum (Al) make it a promising substrate material for high power electronic packaging. A main challenge of using aluminum in electronic packaging is its poor bondability. The native aluminum oxide (Al_2O_3) prevents aluminum from bonding to commonly used die-attach materials such as solders. Thus, zincating process is often needed to dissolve the Al_2O_3 layer and deposit a protective zinc layer which provides a basis for subsequent metallization or soldering processes.

In this research, Ag-Al solid-state bonding has been developed as a novel bonding technique to bond Ag directly to Al substrates. No surface treatment was applied on Al substrates to remove the native Al_2O_3 layer prior to bonding. The shear strength of Ag-Al joints passes the military criterion (MIL-STD-883H method 2019.8) by a large margin. SEM and TEM imaging was utilized to study the microstructures. In the bonding processes conducted at 425 and 450 °C, Ag and Al atoms inter-diffused through the thin Al_2O_3 to react and form Ag_2Al and Ag_3Al compounds. To examine the fracture modes of Ag-Al joints, the fracture surfaces after shear tests were evaluated. The effect of bonding temperatures on Ag-Al joint morphology and the fracture behaviors were investigated and discussed.

An application of this new technique is to bond thin Ag foils to Al substrates and make them bondable to die-attach materials such as solders and nano-silver paste. This Ag foil bonding method provides an alternative to the zincating process. Other potential applications include making Al surfaces easier to blaze to other metals such as brass, bronze and copper.

1. Introduction

In recent years, high temperature electronic packaging has been rapidly developed due to increasing demand of power electronics applications, particularly for the automotive, aerospace, and energy production industries [1–3]. The introduction of silicon carbide and gallium nitride semiconductors has enabled power electronics to operate at high temperatures above 350 °C [4]. For continuous operations under extreme high temperatures, novel interconnection materials and packaging structures are required for power electronics systems [5,6].

Direct bond copper (DBC) substrates have been widely used in power electronics for many years [7,8]. DBC substrates have advantages of high current carrying capacity, relatively high thermal conductivity, and controlled coefficient of thermal expansion (CTE) [9]. Recently, reliability issues of DBC substrates in thermal cycling tests have been reported [10–12]. The thermal cycling stress induces cracks at the copper/ceramic interface, leading to the eventual delamination of DBC substrates [10,11]. As a possible alternative, direct bond aluminum (DBA) substrates have been developed [13,14]. DBA substrates outperform DBC substrates in thermal cycling tests [14,15]. The reason is the lower yield stress and plastic strain rate of aluminum as opposed to copper, which result in lower thermomechanical stress at the aluminum/ceramic interface and less strain hardening during thermal cycling. No crack or delamination was observed in DBA substrates after 1500 thermal cycles from −55 °C to 250 °C [15].

A main challenge of using aluminum layers or substrates in electronic packaging is its poor bondability. The native aluminum oxide layer prevents aluminum from electroless or electrolytic plating of metallization layer, which is an essential step to make aluminum bondable to die-attach materials such as solders and nano-silver paste [16]. Thus, the zincating process is required to prepare DBA substrates for further metallization processing. During the zincating process, the aluminum oxide is dissolved in the zincating solution, and a layer of zinc is deposited to protect the surface, providing a basis for subsequent metallization [17]. The zincating process exhibits a narrow process window due to its high reaction sensitivity to aluminum surface conditions [18,19]. The zincating and following metallization processes on aluminum largely increase the processing cost and add more reliability issues [20].

In this research, Ag-Al solid-state bonding has been developed as a

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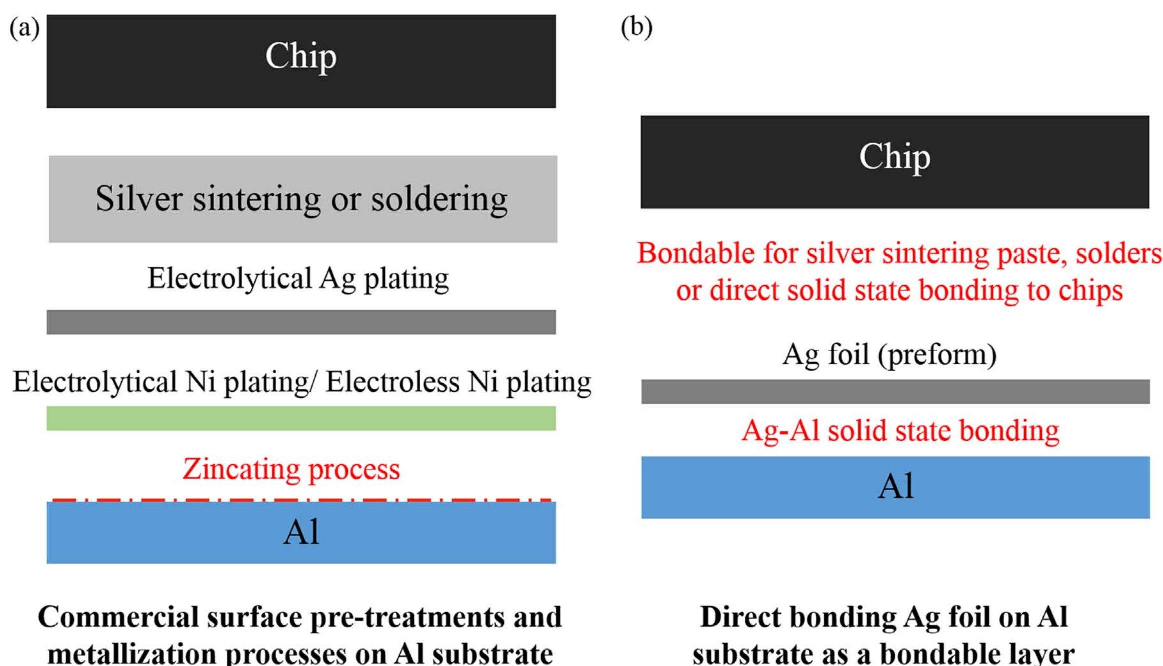

Fig. 1. (a) Commercial surface pre-treatments and metallization processes on Al substrate in electronic packaging. (b) Proposed Ag-Al solid-state bonding technique to direct bond Al foil on Al substrate as a bondable layer which is compatible with nano-silver paste and solders. In a more advanced level, device chips can be bonded to the Ag foil on Al substrates at 300 °C using solid-state bonding technique.

novel bonding technique to directly bond Ag to Al substrates. SEM and TEM analyses were utilized to study the microstructures and fracture mechanisms. In the solid-state bonding process at 425 and 450 °C, Ag and Al atoms inter-diffused through the thin aluminum oxide layer to react and form Ag_2Al and Ag_3Al. The shear strength of the Ag-Al joints passes the military criterion with a large margin. As shown in Fig. 1, an application of this new technique is to bond Ag foils to Al substrates and make them bondable to solders and nano-silver paste. This foil bonding technique provides an alternative to the zincating and metallization processes on aluminum substrates. At a more advanced level, device chips can be bonded to Al substrates using Ag foils as the bonding medium at 300 °C.

2. Experimental design and procedures

To achieve Ag-Al solid-state bonding, Ag disks (10 mm in diameter and 1 mm in thickness) and Al substrates (15 mm × 12 mm × 1 mm) with 99.9% purity are employed. Ag disks were grown through the ingot casting method followed by annealing [21,22]. Ag shots with 99.99% purity were loaded into 150 mm long quartz tubes with 10 mm in inner diameter. After loading, the tubes were evacuated by a vacuum pump and sealed by a hydrogen torch to form capsules. The capsules were brought to and kept at 1000 °C for 2 h, followed by 48-h annealing at 850 °C to ensure complete homogenization. After annealing, the ingots (50 mm long and 10 mm in diameter) were cut into disks with a thickness of 1.5 mm. Ag disks and Al substrates were ground with silicon carbide-coated papers up to 2000 grits and polished with 1 µm diamond powder suspended fluid to achieve clean surfaces for bonding. During the bonding process, the Ag disk is placed over the Al substrate and held by a fixture with 1000 psi (6.89 MPa) static pressure to ensure intimate contact. The assembly is loaded on a graphite platform in a vacuum furnace and heated with temperature monitored by a miniature thermocouple. The solid-state bonding is performed at a vacuum level of 0.1 Torr (13.33 Pa) to suppress oxidation. The bonding temperatures are selected as 400 °C, 425 °C, and 450 °C, respectively, with a bonding time of 10 min.

The microstructures and phase compositions of the resulting Ag-Al joints are examined using scanning electron microscopy/energy dispersive X-ray spectroscopy (SEM/EDX, FEI Philips XL-30, FEG SEM) in back-scattered electron (BSE) mode. The standard single-strap-joint configuration [23,24] was used to evaluate the shear strength of the Ag-Al joints. The shear test was conducted at room temperature using a tensile testing machine (Model 8800, Instron Corporation) with a crosshead speed of 1 mm/minute. After the shear test, the fracture surfaces of the joints are evaluated. The phase compositions of the fracture surface are probed by SEM/EDX and X-ray diffraction (XRD). The area ratios of the fractured phases are analyzed using ImageJ software. To further investigate the phase distribution at the Ag/Al interface and the failure mechanism of the Ag-Al joint, transmission electron microscopy (TEM) analysis is conducted with a model JEOL-2100F equipped for scanning TEM (STEM) [25]. The TEM specimens are prepared with an in-situ method of dual-beam focused ion beam (FIB) on Tescan GAIA3 SEM/FIB.

3. Experimental results and discussions

In experiments, Ag disks, produced in house, were bonded to Al substrates using solid-state bonding technique without any flux or interlayer. Fig. 2 shows cross-section back-scattered electron images of Ag-Al joints bonded at 400 °C, 425 °C, and 450 °C, respectively, for 10 min. For the Ag-Al joint bonded at 400 °C, Fig. 2(a), no intermetallic compound (IMC) formation was observed. During solid-state bonding, Ag and Al conformed to each other through elastic deformation to achieve intimate contact on the interface. On the bonding interface, no cracks or voids were observed. As the bonding temperature was raised above 425 °C, Ag-Al IMC formed at the bonding interface, as exhibited in Fig. 2(b) and (c). With 425 °C bonding temperature, the microstructure reveals island-like IMC. With 450 °C bonding temperature, a continuous IMC layer was produced. These results indicate that the IMC morphology and growth are strongly dependent on the bonding temperature. In solid-state bonding process, higher bonding temperature accelerates interdiffusion of Ag and Al and thus enhances IMC growth. The SEM images at higher magnification show the IMC grew into both Al and Ag regions away from the bonding interface. A thin black line was observed. This line was later identified as the aluminum oxide (Al_2O_3) layer on the Al substrate before bonding. Thus, this line can act

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