Microstructure, adhesion strength and thermal conductivity of AlN/(Ti, W)/Cu substrate system

Yingfei Lin, Yangyang Hao, Jianning Lu and Tianlong Liu

Abstract

AlN/(Ti, W)/Cu substrates were successfully fabricated by the combination of magnetron sputtering and electroless copper plating, exhibiting layered distribution without obvious defects or delamination. The adhesion film in AlN/Ti/Cu was composed of TiN, Al, and Ti crystallites due to the reaction between the sputtered Ti layer and the AlN substrate, while in AlN/W/Cu was α-W and β-W crystallites with a mixed distribution but a thin W-rich amorphous layer at the interface towards Cu contact. In AlN/TiW/Cu was W-rich Ti₆W, and α-Ti with the interlayer distribution. The scratch failure of the AlN/(Ti, W)/Cu substrates included the peeling of the Cu plating layer and adhesion film. The nanoscale hard phase layered combination of the adhesion film in AlN/TiW/Cu exhibited better peeling resistance, resulting in the most prominent adhesion strength among the substrate system. The existence of an amorphous layer in AlN/W/Cu led to the lower thermal conductivity. AlN/TiW/Cu substrate showed good comprehensive properties including adhesion strength and thermal conductivity.

1. Introduction

Aluminum nitride (AlN) has gradually gained prominence in optical or surface-acoustic wave devices, high-power and high-temperature electronic devices, particularly in microelectronics for electronic packaging, due to its high thermal conductivity, insulation, excellent optical and dielectric properties, high mechanical strength, strong corrosion resistance, thermal and chemical stability, and nontoxic nature, among others. In most applications of AlN, a mechanically stable and strong interface between AlN and metals is required for the carrying and connecting with semiconductors [1, 2]. However, AlN has a thermal expansion coefficient of about 4.5 × 10⁻⁶ K⁻¹, which is quite different compared with most metals, moreover, AlN is a strong covalent compound resulting in difficulties in metallization. Owing to the significant differences in the physical and chemical properties of AlN and metals, some efforts have been made to find better ways to bond metals and AlN.

Due to its relatively high thermal conductivity, low coefficients of thermal expansion (CTE), excellent heat-resistance and chemical-resistance, AlN/Cu has been increasingly used in the high-power module applications, such as LED lighting and IGBT packaging [3–5]. The bonding between AlN and Cu is challenging due to the poor wettability [6]. AlN-bonded-copper is a metallization method in which copper and AlN are combined through eutectic reaction with high operating temperature and complicated procedures, which the interface would be prone to defects generation [7, 8]. AlN-plated-copper is a method of physical deposition with lower metallization temperature and easier control process. However, the direct-plated-copper AlN normally exhibits low interface bonding strength and high CTE mismatch, and thus result in a reliability problem [9, 10]. This problem may be solved by adding an active metal adhesion film to form a transition layer with a matching CTE, while increasing the adhesion of the AlN/Cu interface and ensuring good thermal conductivity [11–14].
It’s crucial for metal adhesion film to play a role to promote the formation of a stronger solid bond between the AlN and Cu. Ti is the active metal that is widely used as the adhesion layer for AlN/Cu substrate [15, 16]. Barlak [17] experimented that Ti implantation in the interface of AlN/Cu had a positive effect on the joint quality of AlN/Cu. Tao [19] indicated that Ti had the largest driving force for nucleation on AlN substrates among Al, Cu, Ti, and Zr, leading to the formation of a strong interface with AlN.

Zhang [20] revealed that the presence of the Ti transition layer significantly improved the bond strength of the AlN/Cu interface, which resulted from the formation of Ti–N bond caused by the orbital hybridization of Ti-sp and N-p. It’s reported that adding W in Ti adhesion film has many significant properties from the technological point of views such as low electrical resistance, thermal stability, chemical inertness, and good adhesion towards metal contact and the substrate [21, 22]. Callisti [23] investigated the thermal stability and structural evolution of the sputtered Ti-W thin film and determined that the film eventually formed a stable dual-phase nanocrystalline structure of alternate Ti-rich and Ti-depleted with good thermal stability. However, there are few systematic studies on the AlN/Cu substrates with TiW film as the interface adhesion layer, which the correlation among the interface structure, adhesion strength, and the thermal property is worthy to be further discussed.

In this paper, AlN/(Ti, W)/Cu substrate system was prepared by adjusting the adhesion films of Ti, W, and TiW. The influence of the adhesion films on the interface microstructure of the AlN/(Ti, W)/Cu substrates was elaborated in detail, hereby the effect of interface characteristic on the adhesion strength and thermal conductivity was systematically discussed, in order to clarify the internal mechanism.

2. Experimental procedure

2.1. Preparation of AlN/(Ti, W)/Cu substrate

AlN/(Ti, W)/Cu substrates were manufactured by magnetron sputtering and electroless plating methods. AlN ceramic substrate is 1 mm thick with a density of 3.24 g cm$^{-3}$. The phase and morphology of AlN are illustrated in figure 1. It can be seen that the phases detected by x-ray diffraction analysis are mainly AlN (JCPDS 25-1133) and a little of Al$_2$Y$_4$O$_9$ (JCPDS 34-0368). The AlN ceramic substrate has a homogeneous microstructure composed of AlN grains and yttrium aluminate particles distributed at the boundaries of AlN grains. The AlN grains exhibit a faceted morphology. The thermal conductivity of the AlN substrate is 173 W/(m · K).

Before the deposition of materials on AlN, the substrates were ultrasonically washed using ethyl alcohol and deionized water to remove surface pollutants and sputter-etched prior to sputtering to remove impurity. Afterward, Ti, W, or TiW adhesion films were deposited by sputtering on the surface of AlN. Ti and W targets were 99.99% pure. The sputtering temperature varied from 423 K to 473 K with 0.3 ~ 0.5 Pa working pressure under an Ar atmosphere. The thicknesses of the Ti, W, and TiW were controlled to be 0.6 ~ 0.7 μm, respectively.

Electroless copper plating was performed at the deposited AlN substrates for about 60 min at 60 °C. The thickness of the final Cu layer was about 30 μm. Prior to carrying out the experiments, CuSO$_4$·5H$_2$O (15 g l$^{-1}$) solution were prepared; Na$_2$CO$_3$ (15 g l$^{-1}$), HCHO (30 ml l$^{-1}$) solution were used as reducing agents.
K₂[Fe(CN)₆] (20 mg l⁻¹) and 2’2’-bipyridyl (20 mg l⁻¹) were prepared as stabilizing agents; EDTA-2Na (20 g l⁻¹), C₆H₅KNa (15 g l⁻¹) and their mixture were prepared as complexing agents. Adjust the pH value of electroless plating solutions to 12 ~ 13 by adding an appropriate amount of NaOH solution. Finally, the AlN/(Ti, W)/Cu substrates was vacuum treated at 300 °C for 1h to eliminate the slight bubbling on the surface of the electroless copper plating layer.

2.2. Characterization

The phase structure of the AlN/(Ti, W)/Cu substrates was investigated by x-ray diffraction (XRD, Rigaku D/max2200, Japan) with Cu Ka radiation. The data acquisition in the 2θ range is 10°–90°, with a scanning step of 2° min⁻¹. The surface and cross-section morphology of AlN/(Ti, W)/Cu substrates were characterized by a scanning electron microscope (SEM, HITACHI S8220, Japan) equipped with an energy dispersive x-ray (EDXA) spectrometry system. The microstructural features in the zone of interface for AlN/(Ti, W)/Cu substrates were investigated by a transmission electron microscopy (TEM, JEM-2100F). The focus ion beam (FIB) (FEI Scios) was applied to prepare the TEM specimens.

2.3. Adhesion strength

A scratch test was conducted to evaluate the adhesion strength of the AlN/(Ti, W)/Cu substrates. In the scratch test, a Rockwell C diamond indenter with a 200 μm radius tip was used for the scratch test. The load applied during the scratching process was gradually increased from 0 N to 100 N. The scratch length was 5 mm with a loading speed of 50 N min⁻¹. The adhesion strength of the (Ti, W)/Cu coating to the AlN substrate was determined by acoustic emission (AE) analysis. Each type of coatings was repeated 2–3 times tested. The scratch tracks on the sample surface were captured using SEM and three-dimensional profile measuring apparatus (BRUKER DektakXT, Germany).

2.4. Thermal conductivity measurement

The thermal conductivity of the AlN/(Ti, W)/Cu substrates was determined by the equation λ = α × ρ × C_p, where λ, α, ρ, and C_p represent the thermal conductivity, thermal diffusivity, sample density, and specific heat capacity, respectively. The thermal diffusivity α was measured by a laser flash apparatus (NETZSCH LFA447, Germany) at room temperature with disk-shaped samples of Ø12.7 mm. The sample density ρ was determined by the Archimedes method. The specific heat capacity C_p was derived from the rule of mixture (ROM) according to the mass fraction of each component. Each type AlN/(Ti, W)/Cu substrate was repeated 3–5 times tested.

3. Results

3.1. Microstructure of AlN/(Ti, W)/Cu substrates

Figure 2 presents the phase composition and surface morphology of the AlN substrates sputtered with Ti, W, and TiW films. As shown in figure 2(a), it can be seen that TiN (JCPDS 38-1420) was mainly formed on the AlN/Ti substrate. It has been reported that the formation energy of TiN at 300 K was −299.341 kJ mol⁻¹, referring that TiN could be formed at room temperature [24]. It is notable that the Ti atoms deposited by ion sputtering possessed high activity. Accordingly, it is possible for deposited Ti to react with AlN to form TiN−. Microstructure of AlN/Ti, moreover, the granular arrangement was closer, as shown in figure 2(b). The gap between the grains in the deposited film was tiny and high compactness. The

Figure 2. X-ray diffraction pattern and SEM image of AlN/(Ti, W) substrates (a) AlN/Ti; (b) AlN/W; (c) AlN/TiW.
sputtering of TiW composite film on the AlN substrate was obtained by the simultaneous sputtering of Ti and W dual targets. The phase structure of the deposited film was TiW\(_{x}\) (JCPDS 49-1440), which exhibited a bcc structure with a dominant (110) peak (d\(_{110}\)-spacing ∼0.2236 nm corresponding to a lattice parameter of 0.3177 nm) [23]. The surface morphology of the TiW film also exhibited a granular arrangement. The tightness of the grains in TiW film was better than that in the deposited film of AlN/Ti substrate, as shown in figure 2(c).

Figure 3 shows the phase structure and morphology of the outermost surface layer of the AlN/(Ti, W)/Cu substrates. It can be observed that the electroless Cu plating layer completely covered the AlN/(Ti, W), and the Cu particles were compactly arranged. The crystallization degree of the Cu layer was high without a bubbling phenomenon. Figure 4 shows the cross-sectional morphology of the interface of AlN/(Ti, W)/Cu substrates. The results showed that the interface state of each AlN/(Ti, W)/Cu substrate appeared to be a good combination without obvious pores or delamination. The metal adhesion film in each substrate (Ti, W, and TiW layer for AlN/Ti/Cu, AlN/W/Cu, and AlN/TiW/Cu, respectively) appeared to be continuously distributed, and the thickness was relatively uniform. The thickness of the Cu plating layer in each substrate was approximately 30 μm. It is found that there was an overlap part between the area distribution of Ti and Al elements in the AlN/Ti/Cu substrate, which assumed that some interface diffusion or interfacial reaction occurred.
3.2. Adhesion strength of AlN/(Ti, W)/Cu substrates

In order to evaluate the adhesion properties of AlN/(Ti, W)/Cu substrate system, a scratch test was carried out. The typical scratch tracks are presented in figure 5. It can be seen that the scratch failure behavior of the three types AlN/(Ti, W)/Cu substrates have a similarity. First, the outermost Cu plating layer showed plastic deformation during the initial scratching process. The central area of the scratch track was subjected to tensile deformation along the direction of scratching under normal stress, while the boundary region exhibited shear deformation due to shear stress. The scratch track was gradually widened with the increase of load. Then, a particle-like morphology appeared at the central area and expanded to the boundary of both sides, and finally spanned the entire scratch section. At the end of the scratch, black particles gradually appeared in the granular enrichment area. Finally, the black particles were accompanied by obvious tearing cracks perpendicular to the direction of the scratch.

In order to better identify the composition of each characteristic morphology in the scratch tracks of the AlN/(Ti, W)/Cu substrates, energy spectrum analysis on the scratches was performed, as shown in figure 6. The result showed that the particle-like morphology was mainly the elements of metal adhesion film, namely Ti, W, and TiW corresponded to AlN/Ti/Cu, AlN/W/Cu, and AlN/TiW/Cu substrates, as shown in figures 6(a1), (b1), and (c1). Al and N were in the form of black particle morphology, indicating that the AlN substrate was exposed, as shown in figures 6(a2), (b2), and (c2). The composition of the remaining region was mainly Cu.

Combined with the morphology characteristics and the energy spectrum analysis on the scratch, the failure behavior of the AlN/(Ti, W)/Cu substrates under scratching can be divided into two stages. The first stage was the scraping and peeling of the Cu plating layer, reflecting the debonding at electroless Cu layer and metal adhesion film interface, where the metal adhesion film was exposed gradually as a granular distribution. It can be noted that the metal adhesion film was a thin film of sputtering onto the AlN substrate, its surface roughness appeared to be inherited from the surface morphology of the AlN substrate. Since the substrate was composed of AlN grains, there was a grainy undulation on the surface after sputtering the metal adhesion film. As the scratch indenter passed, the metal adhesion film appeared to be distributed as particle-like morphology after the peeling off of the Cu plating layer. The second stage of the scratch was the peeling of the (Ti, W) metal adhesion film, which reflected the bonding strength with the AlN substrate. It’s found that the stripping of the metal adhesion
film to the AlN substrate has a large exposed interval, indicating that the sputtered adhesion layer was generally well bonded with the AlN substrate. At the end of the scratch, at an area greater than 90 N, a clear longitudinal tearing crack appeared in the metal adhesion film near the bare AlN, which resulted from the failure of the metal adhesion film under the tension of the indenter.

Figure 7 shows the critical load of each scratch failure stage for the three types AlN/(Ti, W)/Cu substrates. It can be seen that the critical load of the peeling off of the Cu plating layer in the AlN/Ti/Cu and AlN/TiW/Cu substrates was similar, which was superior to that of the AlN/W/Cu substrate. For the peeling critical load of the metal adhesion film, the critical value of the AlN/TiW/Cu substrate was the highest, followed by AlN/Ti/Cu substrate, and finally AlN/W/Cu substrate. In general, AlN/TiW/Cu substrate exhibited better interface adhesion strength. The difference in adhesion strength of the three types AlN/(Ti, W)/Cu substrates was closely related to the microstructure of the metal adhesion film, as well as its integrated condition in interface with Cu layer and AlN substrate. It would be discussed in conjunction with the TEM analysis below.
3.3. Thermal conductivity of AlN/(Ti, W)/Cu substrates

The thermal conductivity of the AlN/(Ti, W)/Cu substrates is shown in figure 8, which reflects the longitudinal thermal conductivity of the three types of substrates. The results showed that the thermal conductivity of AlN/Ti/Cu and AlN/TiW/Cu were 177 W/(m · K) and 175 W/(m · K), respectively, which were higher than 165 W/(m · K) of AlN/W/Cu. It is well known that the thermal conduction in metal materials is determined by electrons, while the conduction in nonmetal materials is dominated by phonons [26]. Essentially, the AlN/(Ti, W)/Cu substrate was a metal-nonmetal composite with a laminated structure, including Cu plating layer, Ti, W metal adhesion film, and AlN substrate. The thermal conduction through the AlN/(Ti, W)/Cu substrate involved the thermal transfer of electron in Cu plating layer and (Ti, W) metal adhesion film, thermal transfer of phonons in AlN, and the thermal conduction across the interfaces. The main difference among the AlN/(Ti, W)/Cu substrates is the type of metal adhesion film, which means that the microstructure of the metal adhesion film and its interface structure with Cu plating layer and AlN substrate might be the main cause for the difference in the thermal conductivity. The reason for the difference in thermal conductivity behavior of the three AlN/(Ti, W)/Cu substrates would be discussed below combined with TEM analysis.

4. Discussion

In order to further investigate the interfacial microstructure of the AlN/(Ti, W)/Cu substrates, transmission electron diffraction patterns and HRTEM analysis were performed on the interface zone of AlN/(Ti, W)/Cu substrates. Figure 9 characterized the interfacial microstructure of the AlN/Ti/Cu substrate. As shown in figure 9(a), the thickness of the sputtered Ti layer was approximately 600 nm, in which there were several fine crystalline particles forming. Figures 9(b) and (c) showed the diffraction patterns of the interface of Cu/Ti and Ti/AlN, respectively. It is found that there was obviously TiN phase existing in the interface of Cu/Ti and Ti/AlN, indicating that the Ti layer was composed of crystallized TiN particles that traversed the entire region of Ti metal adhesion film. It suggested that the Ti metal adhesion film appeared to be well bonded with the Cu coating and the AlN substrate. Figures 9(d) and (e) showed the HRTEM analysis of the microcrystalline particles in the Ti layer. The result indicated that the microcrystalline particles were confirmed as the phase TiN (JCPDS 38-1420), which was consistent with the XRD result of figure 2(a). In addition, Al (JCPDS 04-0787) and α-Ti (JCPDS 44-1294) phases were characterized in the vicinity of the TiN crystallite area, which evidenced the reaction between the sputtered Ti layer and the AlIN substrate \((Ti_3 + AlN \rightarrow Al_3 + TiN)\). It is found that there was no obvious directional relationship among the Ti, TiN, and Al, as shown in figure 9(d). Compared with the results of HRTEM analysis in figures 9(d) and (e), it is noted that there was TiN with different crystal band axes under the same incident angle of the electron beam, indicating that the formation of the TiN microcrystalline particles was independent and multidirectional.

Figure 10 depicted the interfacial microstructure of the AlN/W/Cu substrate. The thickness of the W metal adhesion film obtained by sputtering was about 600 nm. There was an amorphous thin layer of 20 nm in the interface of W/Cu and 5 nm in the interface of AlN/W, respectively, as shown in figures 10(b) and (c). The amorphous layer existed in the interface of AlN/W presumably caused by the sputter etching cleaning process of AlN substrate. From the HRTEM analysis of the W/Cu interface in figure 10(b), it is found that the phase of the Cu/W amorphous layer near the W layer was β-W, and the phases near the electroless Cu layer were β-W and Cu, indicating that the amorphous layer was a W/Cu transition zone full of W. Figures 10(d) and (e) were for the micro-domain characterization of the W metal adhesion film, the results showed that the main components of the W layer were α-W and β-W crystallites, which were dispersed and mixed.
Figure 9. Interfacial microstructure of the AlN/Ti/Cu substrate (a) STEM micrograph, (b) Diffraction pattern of the Ti/Cu interfacial zone, (c) Diffraction pattern of the AlN/Ti interfacial zone, (d) and (e) HRTEM analysis of the Ti layer.

Figure 10. Interfacial microstructure of the AlN/W/Cu substrate (a) STEM micrograph, (b) HRTEM analysis of the W/Cu interfacial zone, (c) HRTEM analysis of the AlN/W interfacial zone, (d) Diffraction pattern and (e) HRTEM analysis of the W layer.

Figure 11 was the characterization for the interface microstructure of AlN/TiW/Cu substrate. The thickness of the TiW metal adhesion film was about 600 nm, where the contrast was distributed as thin stripes of black and gray, as shown in figure 11(a). Figures 11(b) and (d) exhibited the distribution of the elements in the interface of TiW/Cu and AlN/TiW by STEM line scanning. The results showed that the black and gray stripes corresponded to the W-rich and Ti-rich element regions. The thickness of W-rich stripes was consistent with the thickness Ti-rich stripes, indicating that the combined thickness of each metal (W and Ti) was half of the total thickness of the metal adhesion layer, about 300 nm. The line scanning results showed in figure 11(b) indicated that the area of TiW layer in contact with the electroless Cu layer was a Ti-rich region. The HRTEM analysis from figure 11(c) demonstrated that the interface of TiW/Cu was translocated by Ti and Cu crystallites without an amorphous layer. Figures 11(d) and (e) were for the microstructure characterization of the AlN/TiW interface. The results
showed that there was an amorphous layer of about 5 nm in the AlN/TiW interface area, which was composed of the interdiffusion transition of AlN and W. Figures 11(f) and (g) characterized the microstructure of TiW metal adhesion film, which was composed of W-rich Ti₆W₁₋ₓ (JCPDS 49-1440) and α-Ti (JCPDS 44-1294) in a nanoscale layered distribution.

The scratch failure characteristics of the AlN/(Ti, W)/Cu substrates included the peeling of Cu plating layer and metal adhesion film, reflecting the bonding in the interfaces of Cu/metal adhesion film and AlN/metal adhesion film, respectively. For the AlN/Ti/Cu and AlN/TiW/Cu substrates, the interface of the Cu/metal adhesion film was a microcrystalline mixed transition, which would be conducive to the load transfer in the interface between the Cu plating and metal adhesion film during scratching process. For AlN/W/Cu substrate, the W-rich amorphous layer existed in the interface of Cu/W was poor in ductility, leading to the disadvantage of the interfacial load transfer, as a result, the Cu plating layer tended to peel off earlier with the lower critical load during the scratching process. The intrinsic microstructure of the metal adhesion film takes an important part in determining its peeling from AlN substrate. In the AlN/Ti/Cu substrate, the Ti metal adhesion film contained a rich TiN hard crystallites, while in the AlN/W/Cu and AlN/TiW/Cu substrates, there was W or W-rich Ti₆W₁₋ₓ hard phase in the metal adhesion film, which led to the good wear resistance of the metal adhesion film. As a result, the peeling of the metal adhesion film in AlN/(Ti, W)/Cu substrates exhibited a high critical load. In the AlN/TiW/Cu substrate, the TiW metal adhesion film was a nanoscale layered combination of Ti₆W₁₋ₓ and α-Ti, which to a certain extent enhanced the peeling resistance within the adhesion film, finally enabled AlN/TiW/Cu to obtain the excellent critical load.
The thermal conduction of the AlN/(Ti, W)/Cu substrates was influenced by the interlayer features across the metal adhesion film. Since the composition of the metal adhesion film in AlN/Ti/Cu substrate was Al, Ti, and TiN crystallites, the thermal transfer mechanism in the interface of Cu/metal adhesion film included the coupling of electrons and phonons among Cu, Al, Ti, and TiN. In the metal adhesion film, Al appeared to be distributed in a microcrystalline dispersion, leading to forming a connected electrons thermal conduction pathway to achieve a good thermal conductivity. The thermal transfer mechanism of AlN/TiW/Cu was similar to that of AlN/Ti/Cu substrate. There were electrons coupling thermal transfer in the interface of Cu/TiW due to the microcrystalline mixed transition of Cu and Ti. It was the electrons coupling thermal transfer between Ti and Ti₃W₁₋ₓ within the TiW film, resulting in good thermal conduction. It is well known that an interfacial amorphous layer would act as a thermal barrier with relatively large thermal resistance, resulting in a decrease in the effective thermal conductivity [27, 28]. In AlN/W/Cu substrate, the amorphous W layer at the W/Cu interface induced a thermal loss to increase the thermal boundary resistance, further led to the decrease of thermal conductivity in the substrate. As a result, the thermal conductivity of AlN/W/Cu substrate was lower than that of AlN/Ti/Cu and AlN/TiW/Cu substrates.

5. Conclusions

AlN/(Ti, W)/Cu substrates with different metal adhesion films have been successfully prepared through magnetron sputtering and electroless Cu plating method. XRD, SEM-EDS, and TEM were employed to characterize the interfacial microstructure of the AlN/(Ti, W)/Cu, and the adhesion strength and thermal conductivity were evaluated by a scratch test and a laser flash apparatus. Several conclusions were obtained as follows:

- AlN/(Ti, W)/Cu substrates were hierarchical homogeneously distributed without obvious defects or delamination. The thickness of the metal adhesion film in each substrate (Ti, W, and TiW layer for AlN/Ti/Cu, AlN/W/Cu, and AlN/TiW/Cu, respectively) was approximately 600 nm, and the Cu plating layer was about 30 μm.

- The interface of the metal adhesion film in each composite substrate has its own characteristics. In AlN/Ti/Cu, the metal adhesion film was composed of TiN, Al, and Ti crystallites resulting from the reaction between the sputtered Ti layer and the AlN substrate. The metal adhesion film of AlN/W/Cu was α-W and β-W crystallites with a mixed distribution, while in the AlN/TiW/Cu, the adhesion film was W-rich Ti₃W₁₋ₓ and α-Ti with the interlayer distribution. The interface of Cu/metal adhesion film in AlN/Ti/Cu and AlN/TiW/Cu was a microcrystalline transition, while in AlN/W/Cu, there was a 20 nm W-rich amorphous layer at the interface.

- The scratch failure behavior of the AlN/(Ti, W)/Cu substrates included the peeling of Cu plating layer and metal adhesion film. The serious peeling of the metal adhesion film would be accompanied by longitudinal tearing. The presence of the W-rich amorphous layer in AlN/W/Cu would be detrimental to the interfacial load transfer in the interface of Cu/W, resulting in the lower critical scratch load of Cu plating stripping. The metal adhesion film in AlN/TiW/Cu was a nanoscale layered combination of α-Ti and Ti₃W₁₋ₓ hard phase, which exhibited better peeling resistance.

- AlN/(Ti, W)/Cu substrates showed stable thermal conductivity, which can be attributed to the uniform interface microstructure and the good interfacial adhesion. The metal microcrystalline dispersion in adhesion film tended to form a connected electrons thermal conduction pathway, thereby achieving good effective thermal conductivity. Among the AlN/(Ti, W)/Cu substrates system, the low thermal conductivity of AlN/W/Cu can be attributed to the increase of thermal boundary resistance resulted from the W amorphous layer. AlN/TiW/Cu substrate showed better in terms of comprehensive performance including adhesion strength and thermal conductivity.

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ORCID iDs

Yingfei Lin  
https://orcid.org/0000-0002-0353-5436

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