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REVIEW ARTICLE

Nano materials for microelectronic and photonic packaging

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Abstract This paper addresses the state-of-the-art nanoscience and technology regarding next generation high density microelectronics and photonics packaging applications, including carbon nanotubes (CNTs) for electrical/thermal devices, and molecular wires for electrical interconnects, etc.

Keywords carbon nanotube, molecular wire, electrical interconnect, thermal management

1 Introduction

Microelectronics and photonics packaging technology trends have always been focused on increasing the packaging density, resulting from efforts to meet consumer demands for light-weight, compact, reliable and multifunctional electronic or communication devices. To address such demanding ultra high density packaging technology, nanotechnology and nanoscience play an important part. For over a decade, nanotechnologies such as carbon nanotubes (CNTs), nanoparticles, molecular self assembly, nano imprints, and sensors, etc., have been explored and studied for mechanical, physical, chemical, photonic, electronic and biological properties. Electronics packaging scientists prospect beyond nano materials or devices, aiming at system level components (chip-chip or chip-package interconnection, thin film component conductors, dielectrics, passives, encapsulants, coatings, power sources, etc.) leading to nano modules. This emphasis is expected to lead to a number of commercial applications during the next decade. However, the implementation of nanotechnology in the system level applications requires a thorough understanding of nano science and engineering. In this article, several fundamental researches related to nanotechnologies for microelectronics and photonics packaging are discussed, including CNTs for electrical/thermal interconnects, nano solder materials with melting point depression and molecular wires for high performance electrical interconnects.

2 CNTs for electrical and thermal interconnects

CNTs have attracted much interest due to their extraordinary electrical, thermal and mechanical properties, and their wide range of potential applications [1–3]. The quality control of the CNTs grown, e.g., purity (catalyst residual and amorphous carbon), diameter, length and defects, directly affect the final properties of CNTs. Unfortunately, the results reported so far vary much and reproducible growth of high-quality-CNTs becomes an issue. Aligned CNT (ACNT) structures make the best use of the one-dimensional (1-D) transport properties of individual CNTs and have been proposed as the promising candidate for thermal interface materials, electrical interconnects, gas sensors, and electrodes, and more. However, the problems with the chemical vapor deposition (CVD) process for ACNT growth, such as high growth temperature and few substrate materials suitable for the CVD growth, become barriers for ACNT applications. To address the key problems above, our group proposed three low-temperature ACNT transfer techniques to position ACNTs onto various surfaces, as shown in Fig. 1, which are based on *in situ* end-opening and functionalization of CNTs during CVD growth [4–8].

We introduced aluminum oxide as the catalyst support material, which not only accelerates CNT growth but also anchors the catalyst particles on the substrate. By introducing a trace amount of oxidants during the CVD process, we get rid of amorphous carbon on the CNT surface, open CNT ends and controllably functionalize CNT tips and walls, which is named “*in situ* functionalization”.

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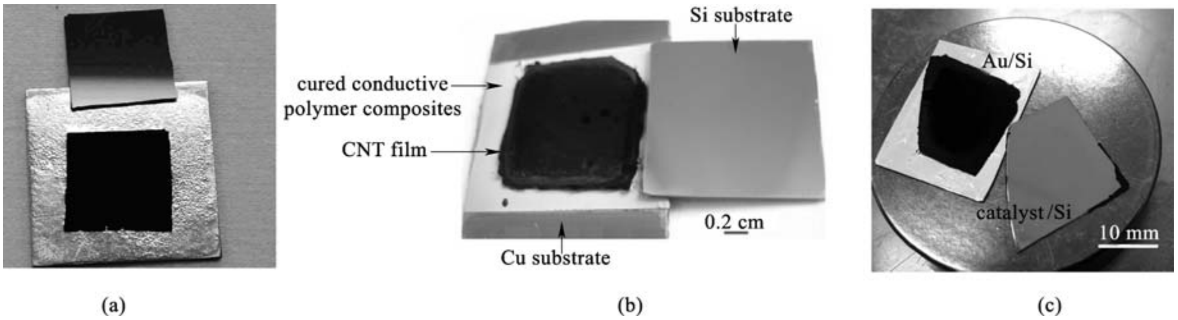

Fig. 1 Low-temperature ACNT transfer technology. (a) Solder transfer; (b) adhesive transfer; (c) chemical transfer

Consequently, the CNTs are of high purity and superior electrical conductivity. The functionalization effectiveness is shown in Fig. 2. The end-opened and functionalized CNTs have affinity to, or, in other words, are wettable by, solders; more importantly, they are chemically reactive, e.g., surface-stabilizes nanoparticles and reacts with self-assembled-monolayer modified substrate surfaces in the chemical transfer process.

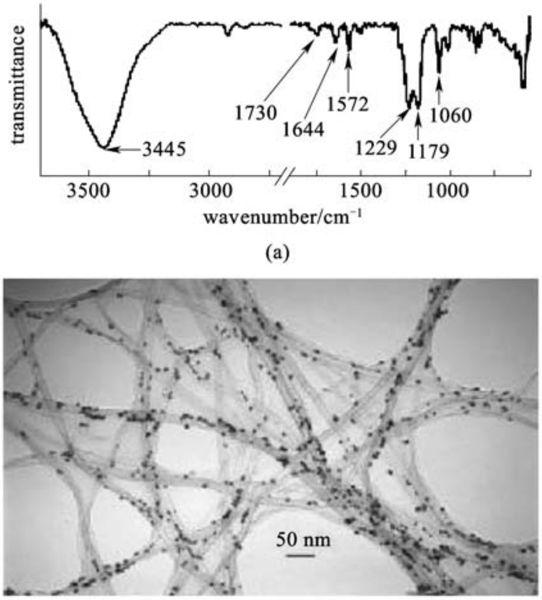

Fig. 2 Functionalization effectiveness. (a) Fourier transform infrared spectra of *in situ* functionalized CNTs; (b) nanoparticles synthesized on *in situ* functionalized CNTs

3 Tin/silver alloy nanoparticle pastes for low temperature lead-free interconnect applications

Tin/silver (96.5Sn3.5Ag) is one of the promising alternatives for Sn/Pb solders [9]. However, the melting point (T_m) of 96.5Sn3.5Ag alloy is around 40°C higher than that of eutectic Sn/Pb solders. The higher T_m requires the higher reflow temperature in the electronics manufacturing process, which has adverse effects not only on energy consumption, but also on the package reliability. Therefore, studies on lowering down the melting point of lead-free metals are necessary. The melting point can be dramatically decreased when the size of substances is reduced to nanometer size [10]. To date, the size dependent melting behavior has been found both theoretically and experimentally [11–13]. The high ratio of the surface area to volume of nanoparticles has been known as one of the driving forces for the size dependent melting point depression.

Different sized SnAg alloy nanoparticles were successfully synthesized by the chemical reduction method. An organic surfactant was used to not only prevent aggregation, but also protect the SnAg alloy nanoparticles from oxidation. Both the particle size dependent melting point depression and latent heat of fusion have been observed (Fig. 3). It has already been found that surface melting of small particles occurs in a continuous manner over a broad temperature range, whereas the homogeneous melting of the solid core occurs abruptly at the critical temperature T_m [13]. For smaller size metal nanoparticles, the surface

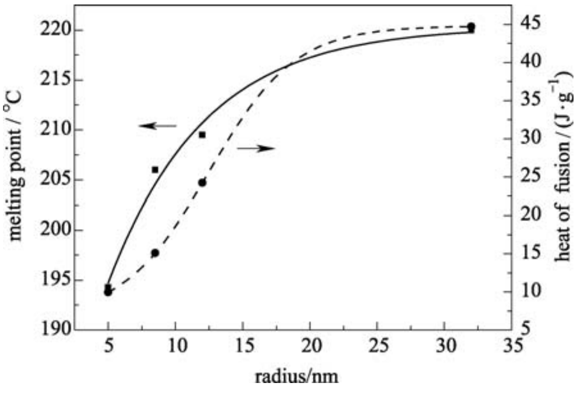

Fig. 3 Relationship between radius of as-synthesized SnAg alloy nanoparticles and their corresponding melting points and heat of fusion, respectively

melting is strongly enhanced by curvature effects. Therefore, with the decreasing of particle size, both the melting point and latent heat of fusion will decrease too. Among all the synthesized particles, the 5 nm (radius) SnAg alloy nanoparticles have a melting point at ~194.3°C, which will be a good candidate for the low melting temperature lead-free solders and can solve the issues from the high temperature reflow for the micron sized lead-free particles. The wetting properties of the (32 nm in radius) SnAg alloy nanoparticles pasted on the cleaned copper surface were studied in a 230°C oven with an air atmosphere. The cross-section of the sample after reflow is shown in Fig. 4. It was observed that the SnAg alloy nanoparticles completely melted and wetted on the cleaned copper foil surface. The energy dispersive spectroscopy (EDS) results revealed the formation of the intermetallic compound (Cu_6Sn_5), which showed scallop-like morphologies in Fig. 2.

This study demonstrated the feasibility of the SnAg alloy nanoparticles paste as a candidate for the low processing temperature lead-free interconnect applications.

4 Enhanced electrical properties of anisotropically conductive adhesive with π-conjugated molecular wire junctions for enhanced electrical properties

As microelectronics requirements are driven toward smaller, higher density and lower cost solutions, anisotropically conductive adhesives (ACAs) are becoming widely used in the electronics industry [14,15]. The ACA joint is established by trapping conductive particles dispersed in the polymer matrix in between integrated circuits and conductive pads when heat and pressure are applied. ACAs can provide electrical conductivity in *Z*-direction as well as a mechanical interconnect between integrated circuit and conductive pads. The most significant advantage of ACAs is fine pitch capability. However, the ACA joints have lower electrical conductivity and poor current carrying capability due to the restricted contact area and poor interface between conductive particles and integrated circuit (IC)/conductive pads, compared to the metallurgical joint of metal solders. In order to enhance the electrical performance of ACA joints, our research group has introduced π-conjugated self-assembled molecular wire junctions to improve the electrical properties of anisotropically conductive adhesives (ACAs) [16,17] and nonconductive films (NCFs) [18] for the electronic interconnects. Crucial for successful applications of molecular wires in ACAs and NCFs are interfacial properties (chemisorption or physisorption), the characteristics of the molecules (conjugated or unconjugated, thermal stability and so on), surface binding geometry and packing density. Therefore, current work will investigate the effects of these factors on the performance of ACAs in detail by using a series of molecules with different functional groups. We investigated the electrical properties of ACA joints using submicron-sized (~500 nm in diameter) silver (Ag) particle as conductive filler with the effect of π-conjugated self-assembled molecular wires (Fig. 5(a)). The ACAs with submicron-sized Ag particles have higher current carrying capability (~3400 mA) than those with micron-sized Au-coated polymer particles (~2000 mA) and Ag nanoparticles (~2500 mA). More importantly, by construction of π-conjugated self-assembled molecular wire junctions between conductive particles and the IC/substrate, the electrical conductivity of ACA joints has increased by one order of magnitude and the current carrying capability has improved by 600 mA (Fig. 5(b)).

5 Conclusion

Fundamental understanding and technological progresses on some novel nanomaterials for microelectronic and photonic packaging have been discussed, including ACNT interconnects, thermal interface materials, nano solders,

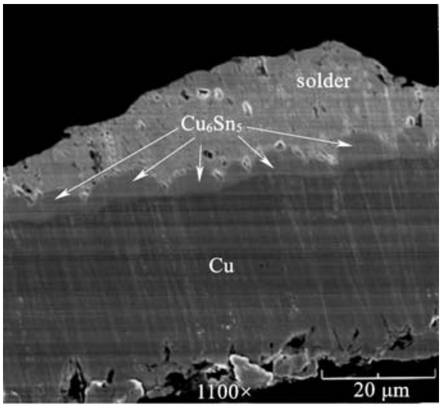

Fig. 4 SEM image of cross-section of wetted SnAg alloy nanoparticles (32 nm in radius) on cleaned copper foil

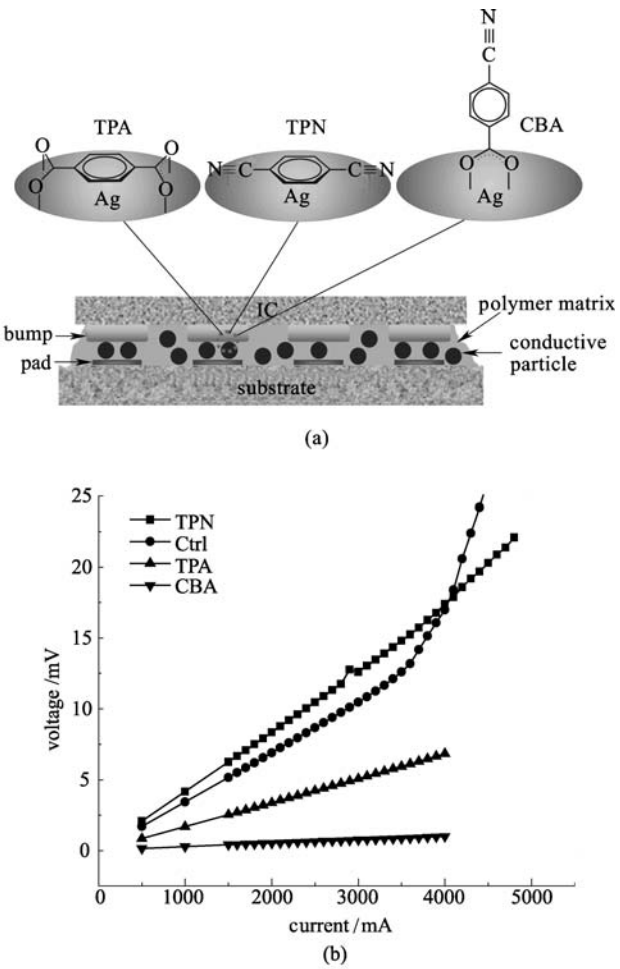

Fig. 5 Illustration and electrical characterization of ACA joints. (a) Cross-section of ACA joints with π-conjugated molecular wire junctions; (b) *I-V* curve of ACA filled with Ag particles (Ctrl), TPN-treated Ag particles, TPA-treated Ag particles and CBA-treated Ag particles

and molecular wire interconnects. These materials and technologies are expected to find wide applications for next generation high performance system packaging.

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