報告番号	※ 甲 第 10394 号

主 論 文 の 要 旨

論文題目 Development of Nanowire Surface Fastener for Room-Temperature Electrical Bonding（常温導電接合ナノワイヤ面ファスナーの開発）

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論 文 内 容 の 要 旨

Surface mount technology (SMT) is widely used in microelectronics. Compared with traditional through-hole technique, it leads to smaller components, much higher component density and faster assembly. Reflow soldering is the necessary process of SMT. However, the high heating temperature in reflow soldering tends to result in undesired thermal excursions and residual stress at the bonding interface which not only lead to reliability issues but also restrict the application of temperature-sensitive components. Therefore, developing a bonding technology which not only has good mechanical and electrical properties but also does not need a high processing temperature is always a goal of researchers.

On the other hand, the unusual ability of geckos to climb on any vertical face and hang from one ceiling with one toe has received more and more attentions. Recent studies revealed that the driving force for holding geckos on a surface arises from the strong van der Waals forces induced by millions of aligned microscopic elastic hairs named setae which further splits into hundreds of smaller spatula in the end. Motivated by these observations, carbon nanotubes, core-shell type nanowires, and regularly ordered high-aspect-ratio polymer fibers have been introduced as a permanent or reversible adhesive. In addition, the core-shell type nanowire arrays can be used as an electrical connector with the deposition of a thin metal film. However, the high temperature, which is still needed in the fabrication process, and the relative high electrical resistance prohibit their application to the bonding technology for the microelectronics. Recently, a new electrical room-temperature bonding technique based on Au nanowire array has been demonstrated, which shows relatively low electrical resistance and simultaneous adhesive strengths. However, compared with the traditional technologies, many works are still needed to do to improve the adhesive and electrical properties.

This dissertation aims to develop a novel room-temperature bonding technique based on freestanding nanowire arrays on the substrate named nanowire surface fastener. This room-temperature bonding technique was realized through pressing two nanowire arrays against each other. The van der Waals forces between the interconnected nanowires contributed to the room-temperature bonding which exhibited excellent mechanical and electrical properties simultaneously.

Chapter 1 is a general introduction of research background, such as the challenge of surface mount technology, the description of gecko toe pad, and biomimetic adhesives.

In chapter 2, a room-temperature bonding technique based on copper nanowire surface fastener was described in detail. Two additional immersion methods were introduced so that freestanding copper nanowire array can be fabricated on the substrate directly with the help of rigid aluminum anodic oxide. Although the two additional immersion processes were quite easy, these innovative methods were shown to be crucial in the experimental process. SEM observation indicated that a copper nanowire array grew in the entire patterned area and the length of the nanowire array was uniform in most areas. TEM images indicated that the copper nanowire was single-crystalline. This room-temperature bonding technique was realized by pressing two nanowire arrays against each other. The van der Waals forces between the interconnected nanowires contributed to the room-temperature bonding which exhibited a macroscopic adhesive strength of 8.17 N/cm^2 and an electrical resistance of $0.69\times10^{-2}\ \Omega\cdot cm^2$. Furthermore, through observing the SEM images of interconnection interface, the upper and lower nanowire arrays were found to be interconnected at an arbitrary angle. Hence, two extreme conditions (parallel-contacting mode and perpendicular-contacting mode) were considered in the theory analysis, which showed that a much higher adhesive strength can be obtained if most copper nanowires could interconnect with each other. In addition, tilted copper nanowire array was obtained through applying directional shear force onto the freestanding copper nanowire array. In term of pressing the straight copper nanowire array against the tilted nanowire array, the electrical bonding was achieved. The room-temperture bonding technique based on tilted nanowire surface fastener further exhibited anisotropic adhesive properties, and the shear adhesive strengths were 9.36 and 1.56 N/cm^2, respectively, for the two opposite directions those are parallel and antiparallel to the tilted direction of the nanowires. The according electrical resistance of tilted nanowire surface fastener is $\sim 0.94\times10^{-2}\ \Omega\cdot cm^2$. In addition, the ideal adhesion strength and electrical resistance of the surface fastener were analyzed and the similar orders as those of traditional solders were obtained.

In chapter 3, a room-temperature electrical surface fastener consists of copper-parylene core-shell nanowire arrays were prepared. Interestingly, the parylene-C film becomes conductive due to dielectric breakdown when the thickness of it is miniaturized to nanoscale. This surface fastener consists of core-shell nanowire array with the copper core and parylene shell. The copper nanowire array was firstly prepared on the glass substrate through template-assisted electrodeposition, which provided the electrical conductive function. The porous glass plate and a peculiar cell were introduced to achieve the uniform contact between the flexible polycarbonate membrane and the substrate. Consequently, the flexible polycarbonate membrane can also be used as the template for the fabrication of nanowire array. The parylene shell was then deposited on Cu nanowire array through CVD method, which provided surface compliance to increase contact areas, so as to realize larger bonding strength. Through pressing core-shell nanowire arrays against each other, the van der Waals forces between the interpenetrating nanowires had a contribution to the room temperature bonding. Consequently, this electrical surface fastener exhibits high macroscopic adhesive strength (~25 N/cm^2) and low electrical resistance (~4.22×10^{-2} $\Omega\cdot cm^2$). Until now, the expression of the van der Waals forces between two core-shell cylinders was not available. Based on the assumption of additivity, the corresponding van der Waals expression was derived in this study and was proved to be effective.

In chapter 4, an innovative fabrication method of core-shell nanowire array was presented. At first, polystyrene nanotube array was fabricated into the AAO template through spin-casting method. Second, copper nanowires were fabricated into polystyrene nanotubes through template-assisted electrodeposition method. Finally, after selectively etching the AAO template in NaOH solution, freestanding copper-polystyrene core-shell nanowire array on the Au/Cr/glass substrate was obtained. After the treatment of polystyrene shell with toluene solution, the polystyrene shows viscosity so that the interaction forces between two polystyrene nanoshells can increase dramatically. Based on this phenomenon, a new kind of surface nanowire fastener based on copper-polystyrene core-shell nanowire array was realized. The bonding strength of approximately 23.52 N/cm^2 (in normal direction) and 47.04 N/cm^2 (in shear direction) were obtained. Electrical measurement indicated that the electrical resistance of the interconnected nanowire array on the fastener is around 0.78×10^{-2} $\Omega\cdot cm^2$ under the preload of about 9.8 N. Therefore, this kind of copper-polystyrene nanowire fastener is hopeful to be used as electrical and mechanical room-temperature bonding in the surface mount.

In chapter 5, the conclusion of this dissertation was made. Many innovative works have been done to develop the room-temperature bonding technique based on nanowire surface fastener. (1) Two innovative methods have been introduced so that either rigid or flexible porous template can be used to electrodeposit metal nanowire array on the substrate directly. Compared with other methods, these two methods have the advantage of cost effciency and technically simple. (2) Interestingly, the parylene-C film becomes conductive due to dielectric breakdown when the thickness of it is miniaturized to nanoscale. Based on this phenomenon, the core-shell nanowire surface fastener consists of copper core and parylene shell can be used for electrical bonding. (3) Based on the assumption of additivity, the van der Waals expression for core-shell cylinder mode was derived, which can be used to explain the adhesive mechanism of the core-shell structure. (4) An innovative method to fabricate core-shell nanowire array was introduced through electrodepositing copper nanowire into open-ended polystyrene nanotube array on the AAO template.