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Mechanical and electrical cold bonding based on metallic nanowire surface fasteners

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Abstract
Mass production of surface mount devices (SMDs) relies heavily on reflow soldering and has become the cornerstone of today's electronic industry. However, the traditional reflow soldering technique is characterized by high heating temperatures, toxic solder materials and low recycling rate of SMDs. Here, we propose a new patterned structure of Au nanowire arrays named a surface fastener through which cold bonding for surface mount technology can be realized. The mechanical bonding enables normal and shear bonding strengths of more than 5 N cm^{-2}. Simultaneously, the parasitic resistance of a pair of surface fasteners is only approximately 2 Ω. The present technique can be performed at room temperature, thereby improving the process compatibility and reliability of SMDs. Surface fasteners based on high melting point metallic nanowires are temperature-resistant for many critical applications. In addition, bonding without solder material is positive for the recycling of rare metals in SMDs.

(Some figures may appear in colour only in the online journal)

1. Introduction

Mass production of surface mount devices (SMDs) relies heavily on reflow soldering and has become the cornerstone of today's electronic industry. However, heating temperatures of up to 220 °C during reflow soldering may cause not only energy consumption but also thermal damage to the surface mount components. Additionally, the toxicity of traditional Sn–Pb solder has led to a trend of worldwide legislation that mandates the removal of lead from electronics. Although various types of lead-free solder have been proposed and adopted in the electronics industry, the melting points of these lead-free solders are always 5–20 °C higher than Sn–Pb solder. In addition, the recycling of rare metals in the surface mount components and printed circuit boards is not easy due to the difficulties in detaching the components, circuit boards and solder materials. Therefore, there is an increasingly urgent need for a nontoxic and low-temperature bonding technique to afford good mechanical support as well as electrical contact, especially for micro/nano-electronic circuits and flexible electronic devices.

With regard to developing a cold bonding technique for surface mount technology (SMT), one possible approach is to make use of cold welding. Cold welding of thin gold films on elastomeric supports has been carried out under ambient conditions and low loads [1]. However, only the lower limit of approximately 0.1 N cm^{-2} was reported for the adhesion strength. In recent years, researchers have succeeded in joining individual low-dimensional nanostructures [2–6]. Although direct heating was not performed and large forces were not applied in these nanoscale welding techniques, fine manipulation of an individual nanowire or nanotube by specific equipment was always needed. Additionally, these techniques, in which the connection of two nanowires or nanotubes was performed in one process, are sufficient for nanoscale connection but are inefficient for use in the mass production of SMDs. On the other hand, the discovery of van der Waals interactions as the primary adhesive mechanism in geckos [7, 8] has led to an explosion of efforts to try to replicate this adhesion mode by some well-arranged micro-/nanostructure arrays [9]. Micro-/nanostructures of soft polymers [10–19] were cast or formed within porous

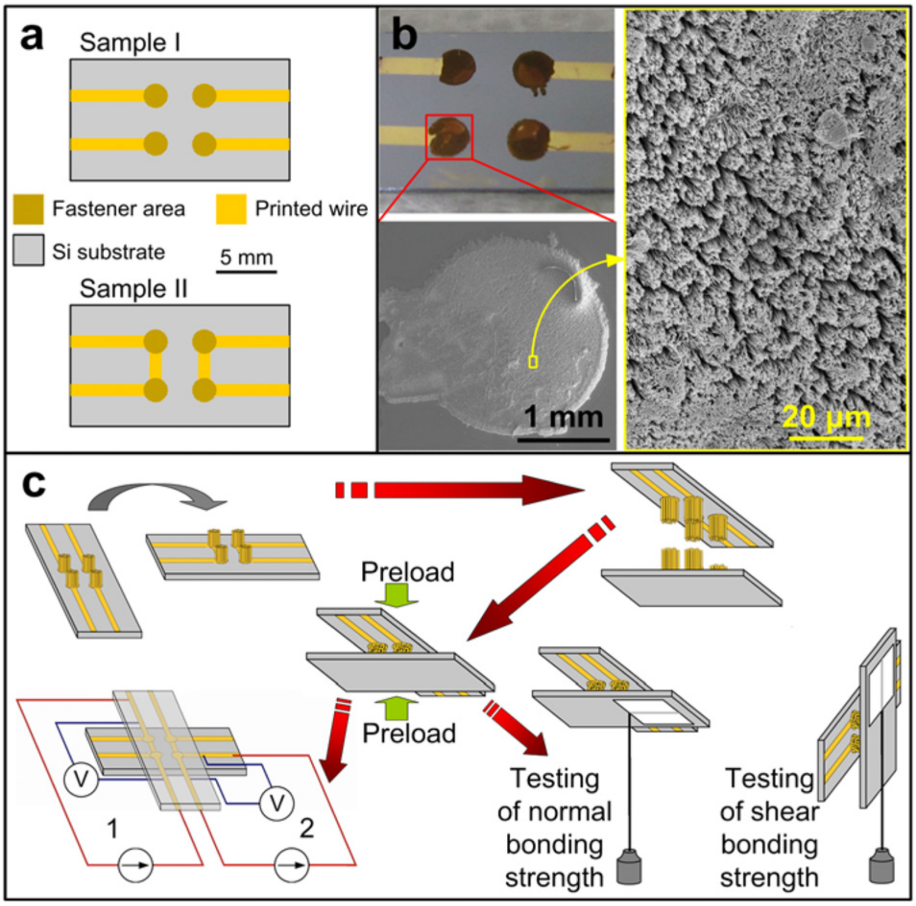

Figure 1. Sketches and micrographs of the samples under test. (a) Sketch of samples I and II with specific patterns. (b) Micrographs of sample I after the synthesis of Au nanowire arrays. (c) Connection of samples I and II, together with the electrical and mechanical testing setup.

membranes. The specific shapes of these polymer micro-/nanostructures, such as mushroom-shaped fibers [11–14], wedge-shaped fibers [15], bent fibers [16, 17], and fibers with flared tips [18] or spatula tips [19], led to considerable shear and normal adhesion strengths but also more complicated manufacturing processes. Biomimetic adhesives fabricated by gas phase methods were always made of stiff and high aspect ratio fibers [20–27]. Compared with the casting method, more expensive equipment and higher processing temperatures are needed in the gas phase fabrication method [9], and the normal adhesion strength contributed by these stiff nanostructures is always much smaller than the shear adhesion strength. Until now, most existing biomimetic adhesives have aimed to realize strong shear binding-on and easy normal lifting-off [20] for special applications such as climbing robots [18], and almost all of them have been designed to implement universal binding with large surfaces, such as walls and glass plates. Additionally, electrical connection has rarely been realized in the aforementioned work. Although electrical connection between a pair of hybrid core–multishell nanowire forests has been reported, normal adhesion was not realized [26]. Data for adhesion and electrical resistance were acquired in adhesion between carbon nanotubes (CNTs) and flat surfaces [27]. However, the contact electrical resistance was as high as several hundred ohms after the pressure was removed, which cannot be adopted for electrical connection in SMT. Therefore, to the best of our knowledge, there is no report in the literature of a biomimetic adhesive which can meet the requirements of simultaneous high normal and shear adhesion strengths and good electrical connections for SMT.

Here, we propose a new patterned structure of Au nanowire arrays named a surface fastener through which cold bonding for SMT can be realized. The mechanical bonding enables normal and shear bonding strengths of more than 5 N cm^{-2}. Simultaneously, the parasitic resistance of a pair of surface fasteners is only approximately 2 Ω. This technique can be performed at room temperature, thereby improving the process compatibility and reliability of SMDs. Besides, bonding without solder material is positive for the recycling of rare metals in SMDs.

2. Experiment

2.1. Pattern design and fabrication

Samples I and II, which have specific patterns for the fastener areas and printed wires, as shown in figure 1(a), were designed to facilitate the testing of the mechanical bonding strength and the parasitic resistance of the electrical bonding. The

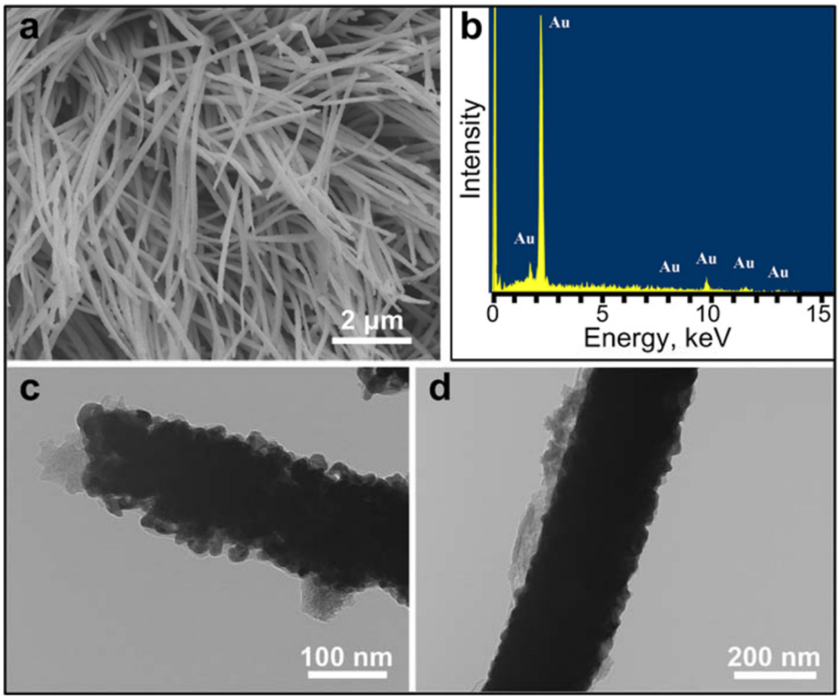

Figure 2. Microstructures and components of electrodeposited Au nanowires: (a) SEM image, (b) EDXS pattern and TEM images of individual nanowires with diameters of (c) 100 nm and (d) 200 nm.

diameter of each of the four fastener areas was 2 mm. Au films approximately 100 nm thick were deposited onto the fastener and wire areas on Si substrates with a 30 nm thick Cr adhesive layer to improve the adhesion between the substrate and the Au film. Both the adhesive layer and the Au film were deposited by electron beam (EB) evaporation.

2.2. Electrodeposition of Au nanowires

Porous alumina (PA) membranes serving as the templates for synthesis of Au nanowires were fixed right above the fastener areas by the insulation holders. Three types of commercial-grade PA membrane with nominal pore diameters of 20, 100 and 200 nm were utilized in the experiments. Au nanowire arrays were then synthesized in the fastener areas by electrodeposition under a constant current of approximately 0.001 A in 40 g l^{-1} $KAu(CN)_2$ and 100 g l^{-1} KH_2PO_4 aqueous solution at room temperature. After etching in 3 M NaOH aqueous solution to remove the PA membranes, the Au nanowires were observed by scanning electron microscopy (SEM), as shown in figure 1(b). It should be mentioned that, although uniform growth of Au nanowires can be implemented over a large-scale area, cabinet fastener areas which were 2 mm in diameter were adopted in our design according to the normal size of current solder pads in SMDs.

2.3. Testing of parasitic resistance and bonding strength

Samples I and II, which had patterned Au nanowire arrays on the fastener areas, were connected to each other under different magnitudes of preload (4.9, 9.8 and 19 N). The parasitic resistance was measured by the four-point probe method after the preload was completely removed (figure 1(c)), and was quite different from that reported in [27]. During the measurement, electrical current from 0 to 20 mA was applied by the current source to the four-point probe measuring circuits, and *U–I* curves were generated. The normal and shear bonding strengths were tested by measuring the maximum forces that the surface fasteners could afford (figure 1(c)). The weights of a balance ranging from 200 mg to 100 g were used to fulfil this testing.

3. Results and discussion

After electrodeposition and removal of the PA membranes, it was easy to distinguish the fastener area from the printed wire by their surfaces because the former became dark in color (figure 1(b)). SEM observation indicated that most of the Au nanowires were grown vertically on the fastener area but with random orientation (figure 2(a)). The average length of these Au nanowires was approximately 10 μm. The nanowires were demonstrated to be polycrystalline Au nanowires by energy dispersive x-ray spectroscopy (EDXS) and transmission electron microscopy (TEM), as shown in figures 2(b)–(d), respectively.

The voltage–current (*U–I*) curves of one pair of fasteners are shown in figure 3. The solid lines in figure 3 were obtained through linear fitting of the measured values. Figure 3(a) shows the *U–I* curve corresponding to a pair of fasteners based on Au nanowires with nominal diameters of 200 nm under different preloads. It can be seen from this figure that bonding under larger preloading results in superior electrical conduction performance (with smaller parasitic resistance).

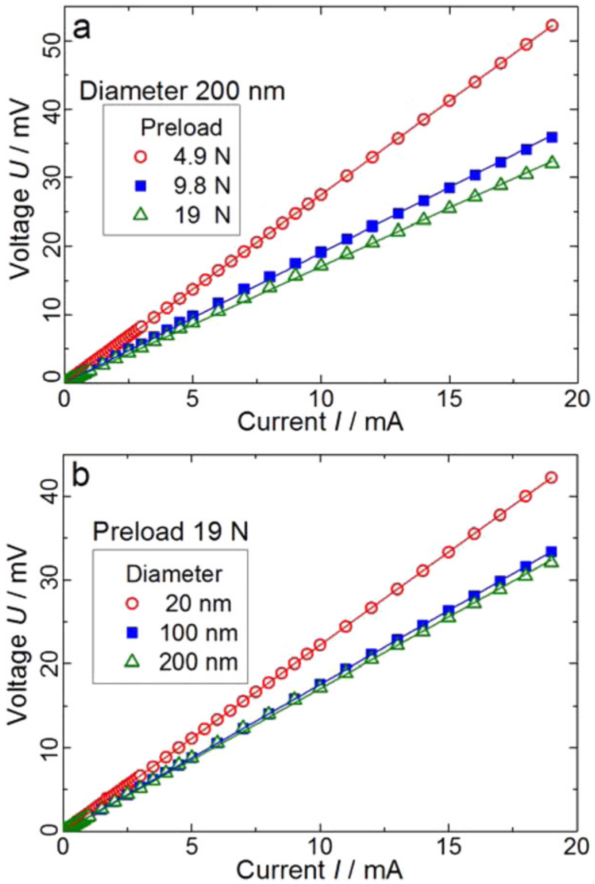

Figure 3. Measured *U–I* curves of the bonding. (a) *U–I* curves under different magnitudes of preload. (b) *U–I* curves based on nanowires with different diameters.

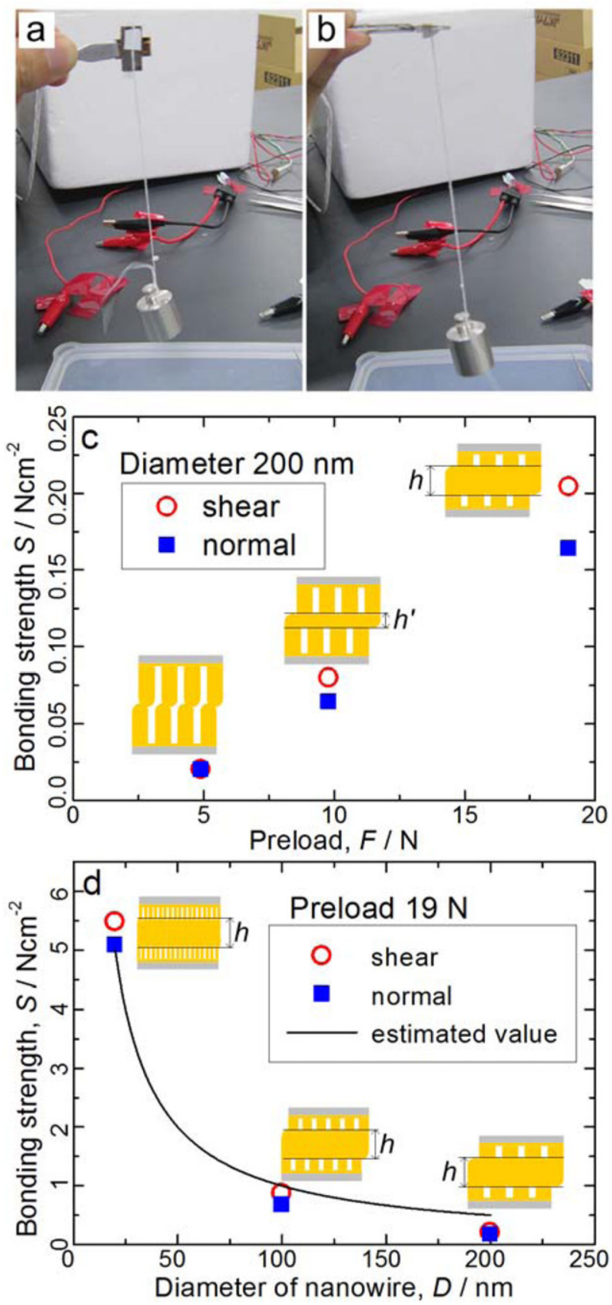

Figure 4. Testing of bonding strengths. (a), (b) A pair of surface fasteners sustaining a weight of 50 g in the shear and normal directions, respectively. (c) Bonding strengths of samples under different preloads. (d) Bonding strengths of samples with different diameters of nanowires.

The reason for this relationship is that the electrical bonding is implemented by the connection between two groups of Au nanowires, and a relatively large preload can make the connection of the nanowire arrays stable enough to enable electrical conduction. Taking the total area of the four fastener areas into account, the preload pressures resulting from loads of 4.9, 9.8 and 19 N are 0.39, 0.78 and 1.51 MPa, respectively. It is noted from this figure that preload pressures of 0.78 and 1.51 MPa give rise to similar parasitic resistances of about 1.89 and 1.71 Ω, respectively. Therefore, cost-effective electrical bonding may occur under a preload pressure of approximately 1 MPa. The *U–I* curves of bonding based on Au nanowires with different diameters of 20, 100 and 200 nm under a preload of 19 N are presented in figure 3(b). Typical Ohmic contact performance was observed for each of these three bonding conditions. Parasitic resistances of 2.20, 1.75 and 1.71 Ω can be extracted from the slopes of the fitted lines of the three groups of nanowires with diameters of 20, 100 and 200 nm, respectively. It should be mentioned that the parasitic resistance of bonding based on 20 nm thick nanowires is approximately one quarter larger than those of 100 and 200 nm thick nanowires. The cause of this relationship is that the parasitic resistance consists of the intrinsic resistances of the nanowires and the contact resistance, while nanowires with lateral dimensions down to 100 nm or even smaller are characterized by higher intrinsic resistivity than the bulk material [28]. However, it is possible to use a resistance of approximately 2 Ω in a 2 mm diameter bonding area for electrical bonding in SMT.

Figures 4(a) and (b) show photographs of surface fasteners sustaining a weight of 50 g in both the shear and normal directions. Considering the 2 mm diameter of each pad, the total contact area for each sample is 12.56 mm^2. The bonding strength is determined by dividing the maximum load which can be sustained by the fastener by the total

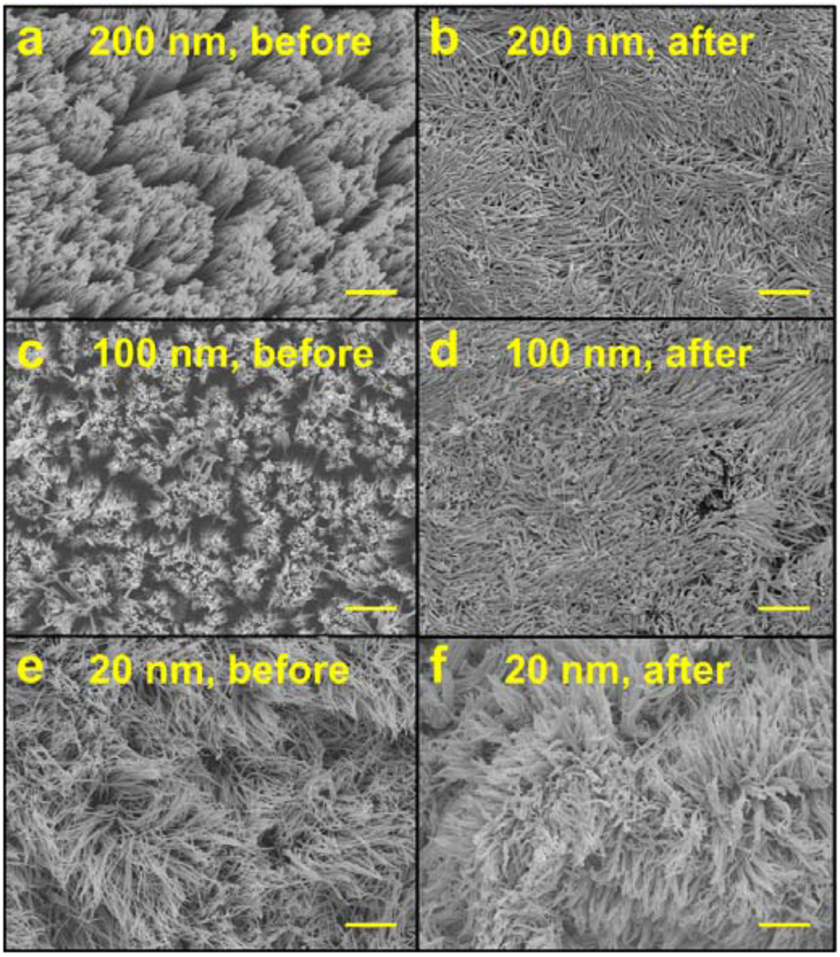

Figure 5. Micrographs of the surface fasteners before and after bonding and debonding. Surface fasteners with ((a), (b)) 200 nm, ((c), (d)) 100 nm and ((e), (f)) 20 nm Au nanowires ((a), (c), (e)) before and ((b), (d), (f)) after bonding and debonding. The scale bar is 5 μm.

contact area. The test results for the shear and normal bonding strengths for the samples with 200 nm thick nanowires under different preloads are shown in figure 4(c). It is indicated from this figure that the bonding strengths rely heavily on the magnitude of the preload. A larger preload can give rise to higher shear and normal bonding strengths. The main reason is that a larger preload can make the two groups of nanowires insert deeper into each other (with larger h), as shown in the inset of figure 4(c), thereby increasing the contact area and bonding strength. Large preload can also cause plastic deformations to nanowires to form hook-and-loop structures, thereby introducing mechanical forces in addition to the van der Waals interactions, which further enhance the bonding strength. For bonding strength testing of samples with different diameters of nanowires, a preload of 19 N was adopted; the testing results are shown in figure 4(d). It can be seen from this figure that both the shear and the normal bonding strengths become much higher when the diameter of the nanowires decreases from 200 to 20 nm. Since the bonding strength is contributed by the interaction between two groups of nanowires through their contact area [25], it is reasonable to assume that the bonding strength, S, is proportional to the contact area, i.e. $S \propto n\pi dh$, where h is the insertion depth while n and d denote the number density and diameter of nanowires, respectively. This relation contains another assumption that the contact area is proportional to the total surface area of the nanowires. For fasteners with nanowires of different diameters, if the total volume of nanowires, i.e. $V \propto n\pi d^2 h$, is the same, the total surface area of the nanowires, and thus the bonding strength, will be inversely proportional to the nanowire diameter, i.e. $S \propto 1/d$. The solid line in figure 4(d) illustrates the estimated relationship between the bonding strength and the nanowire diameter, in which 5 N cm^{-2} is adopted as the bonding strength provided by fasteners with 20 nm thick nanowires according to our measured values. The trend of the measured values corresponds well with the estimated values. It is also noted from figures 4(c) and (d) that the normal bonding strengths of the present samples are almost the same in magnitude as the shear bonding strengths; this is not common for adhesives based on nanowires or nanotubes with simple shapes [20, 25]. The reason for this is that preloads can change the original shapes of the nanowires, forming many randomly curling structures that may serve as nanoscale hook-and-loop fasteners, as shown in figure 5. As a result, the mechanical forces provided by these curling structures together with the van der Waals interactions can contribute to the enhancement of normal bonding strength. It should be mentioned that the diameters used here are nominal values of the pore diameters of membranes. We observed the nanowires by SEM and measured their diameters by ImageJ. For wires growing from 200 and 100 nm pores, the measured diameters were 230 ± 25 and 166 ± 33 nm, respectively, while for wires growing from 20 nm pores, the measured diameters were distributed between 60 and 120 nm. The actual diameters of the nanowires were determined by the actual values of the pore diameters of the membranes.

It should be mentioned that the maximum bonding strength of the present samples (around 5 N cm^{-2}) is smaller than that of adhesives based on long CNT arrays [20]. However, these CNT array adhesives were designed for strong binding-on and easy normal lifting-off from large surfaces for use as clamps or adhesives; therefore, no electrical connection was realized. In contrast, the purpose of our research is to develop a novel surface fastener for electrical and mechanical cold bonding for SMT. In SMT, there are some design guidelines regarding the ratio between the weight of the component and the bonding area. If we consider this weight–area ratio to be $R = 50$ g cm^{-2}, which is more than ten times as large as the standard value for second side reflow mounting (30 g in^{-2}) [29], the bonding strength of $S = 5$ N cm^{-2} can withstand an acceleration of $a = S/R = 100$ N kg^{-1}, which is ten times larger than the acceleration of gravity ($g = 9.8$ N kg^{-1}). This result means that SMDs assembled using the present surface fasteners based on metallic nanowire arrays can be used in all manned vehicles, including airplanes and spacecraft. For the surface fasteners with 20 nm nanowires, mechanical testing was also performed after several cycles of bonding and debonding under a preload of 19 N. No obvious change of the bonding strengths was observed within 3–5 cycles of bonding and debonding.

4. Conclusions

In conclusion, a new kind of surface fastener composed of metallic nanowire arrays has been proposed through which electrical and mechanical bonding can be realized at room temperature. Electrical testing indicates that the parasitic resistance of one fastener is around 2 Ω under a preload pressure of approximately 1 MPa. Mechanical testing indicates that larger preloads and smaller diameters of the nanowires are helpful for achieving higher shear and normal bonding strengths. A maximum bonding strength of more than 5 N cm^{-2} is demonstrated to exist in the present fastener samples with 20 nm thick nanowires. Therefore, the present metallic nanowire surface fasteners are suitable for electrical and mechanical cold bonding for SMT. In comparison to conventional reflow soldering, the present cold bonding technique can be performed at room temperature, which improves the process compatibility and component reliability. Furthermore, a type of surface fastener without solder enables easier detachment of the surface mount component from the circuit board, by which recycling of rare metals becomes significantly more convenient. Finally, mechanical bonding based on high melting point metallic nanowires is temperature-resistant, which is necessary for many critical applications.

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