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Reflow Soldering Process for Sn3.5Ag Solder on ENIG Using Rapid Thermal Processing System

(Proses Pematerian Aliran Semula bagi Pateri Jenis Sn3.5Ag di atas ENIG Menggunakan Sistem Pemprosesan Terma Pantas)

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ABSTRACT

A study on reflow soldering process for Sn3.5Ag solder on ENIG substrate was performed using the rapid thermal processing (RTP) system. The reflow soldering process by RTP system can be successful, but it is sensitive to some typical defects. A poor RTP system design can lead to significant temperature differences where non-uniform heating or cooling may result in material failure due to increase in thermal stresses or serious damage. From this study, it was found that at a peak temperature (T_{peak}) of 251°C, the reflowed solder was observed to be smooth joint appearance over the solder pad and formed a regular joint shape of the solder due to the efficient reflow profile and sufficient heating input during the reflow process. The Ni_3Sn_4 intermetallic compounds were found to be continuous, thus resulting in a good metallurgical bonding between Sn3.5Ag solder and ENIG substrate. Meanwhile, an uneven reflowed solder and defect mechanism was detected at T_{peak} of 246 and 260°C. This is due to the inadequate reflow profile and insufficient heating input during the reflow soldering process in the RTP system. Visual micrographs of reflowed solder and cross-sectional micrograph and elemental analysis were presented in this paper for better understanding of the defect mechanism in order to optimize the reflow soldering process using RTP system. The reflow soldering process can be performed better with appropriate reflow profile in the RTP system in order to achieve a good solder joint of Sn3.5Ag solder and ENIG substrate.

Keywords: Cross-sectional micrographs; elemental analysis; reflow profile; soldering defects

ABSTRAK

Kajian berkenaan proses pematerian aliran semula ke atas pateri jenis Sn3.5Ag di atas substrat ENIG telah dijalankan menggunakan sistem pemprosesan terma pantas (RTP). Proses pematerian aliran semula menggunakan sistem RTP boleh dilaksanakan dengan jayanya tetapi ia sensitif kepada kecacatan tipikal. Reka bentuk sistem RTP yang lemah akan menyumbang kepada perbezaan suhu yang signifikan dengan pemanasan atau penyejukan yang tidak seragam akan memberi kesan kepada kegagalan bahan disebabkan oleh peningkatan tekanan terma atau kerosakan yang serius. Daripada kajian ini, pateri yang telah mengalami proses pematerian aliran semula pada suhu puncak 251°C dikenal pasti mempunyai penyambungan yang licin pada pad pateri dan menghasilkan bentuk penyambungan pateri yang baik hasil daripada profil aliran semula yang lebih baik dan input pemanasan yang mencukupi semasa proses aliran semula pematerian dilakukan. Sebatian antara logam jenis Ni_3Sn_4 didapati berkeadaan selanjar lalu menghasilkan ikatan metalurgi yang baik antara pateri jenis Sn3.5Ag dan substrat jenis ENIG. Sementara itu, pematerian yang tak seragam dan mekanisme kecacatan diperhatikan terhasil pada pateri yang telah melalui proses aliran semula pematerian pada suhu puncak 246 dan 260°C. Ini adalah disebabkan profil pematerian aliran semula yang tidak memadai dan input pemanasan yang tidak mencukupi semasa proses pematerian aliran semula di dalam sistem RTP. Gambaran mikrograf pateri yang telah melalui proses aliran semula pematerian dan mikrograf keratan rentas dan analisis unsur bahan juga disampaikan di dalam kajian ini untuk lebih memahami mekanisme kecacatan yang berlaku di samping dapat mengoptimumkan proses pematerian aliran semula di dalam sistem RTP. Proses pematerian aliran semula dapat dilaksanakan dengan baik menggunakan profil aliran yang sesuai di dalam sistem RTP untuk mendapatkan penyambungan pateri antara pateri jenis Sn3.5Ag dan substrat jenis ENIG yang lebih baik.

Kata kunci: Analisis unsur; kecacatan pematerian; mikrograf keratan rentas; profil aliran semula

INTRODUCTION

Soldering reaction is the oldest metallurgical process to join metal parts and solder is ubiquitous in modern microelectronic technology for interconnections. The soldering reaction has been extensively studied and the core issue in soldering is the formation and growth of intermetallic compounds (IMCs) at the interface of solder and substrate. Due to good mechanical properties, adequate wetting characteristics, low surface tension, good ductility as well as the comparable melting temperature, eutectic

Sn-Ag lead free solder has been considered to replace the lead-tin solder (Chih et al. 2006). In addition to solder, electroless nickel immersion gold (ENIG) is widely used in the substrate metallization due to the good interfacial diffusion barrier for most Sn-containing solder.

In this study, reflow soldering process was performed using rapid thermal processing (RTP) system. RTP can be easily conducted and is capable of precise control of thermal budget compared to annealing processes by using regular furnace (Mu & Liwei 2001). The reflow soldering process was performed in the chamber without modification to the RTP system. The IR systems in the RTP use tungsten-halogen lamps provide a convenient, efficient and fast-reacting thermal source that is easily controlled. However, a poor RTP system design can lead to significant temperature differences where non-uniform heating or cooling may result in material failure due to increase in thermal stresses or serious damage. An inefficient reflow profile, poor solder processing and extreme temperature can contribute to the soldering defects.

The aim of this study was to optimize the reflow soldering process using RTP system for Sn3.5Ag on ENIG substrate at different T_{peak} of 246, 251 and 260°C. The reflow soldering process was optimized to obtain an appropriate reflow profile using RTP system and supported with microstructure and elemental analysis.

Materials and Methods

The solder ball used in this study was a Sn3.5Ag (in wt. %) spheres with a diameter of 300 μm. The FR-4 substrate used was a copper pad deposited with ENIG surface finish in a thickness of 1 mm. The solder bonding pad was designed as a non-solder mask defined (NSMD) type with a pad opening of 300 mm in diameter and a pad pitch of 0.5 mm in length. The metallization of the pad was electroplated Au (0.02 mm)/Ni (5 mm) over an underlying Cu (17.5 mm) pad.

Solder balls were attached manually on the solder bonding pads of the FR-4 substrates using a commercial flux (Indalloy Tacflux 023, Indium Corporation). Then, the solder balls on ENIG substrate were placed on the wafer in the chamber of RTP system (Jipelec Jetfirst 100/150 system) for reflow soldering process at T_{peak} of 246, 251 and 260°C. Reflow soldering profile was analyzed using Process Image Management Station (PIMS) software. After the reflow soldering process, the samples were cleaned in distilled water at 70-80°C for flux removal.

After reflowing the samples images were observed and captured using a 3D digital video microscope system (Hirox Hi-Scope KH-2700). Then, the samples were mounted in cold epoxy, grounded using SiC papers through a row of solder balls and polished with 3 mm, 1 mm and 3000 Å alumina suspension. The cross-sectional morphologies of the samples were observed by using Field emission scanning electron microscopy (FESEM) model LEO 1500 series in back scattered electron imaging (BSE) mode. The EDX analysis was performed in order to analyze the chemical composition of the IMCs.

Results and Discussion

The results of the present study were described in four sections. The first was on the reflow profile, the second was on visual micrographs, the third was on cross-sectional micrographs and elemental analysis and the fourth was on thickness of the IMCs.

Reflow Profile

Table 1 lists the reflow soldering profile for Sn3.5Ag solder on ENIG substrate after reflow soldering process using RTP system. The reflow soldering process was performed at three different temperatures T_{peak} of 246, 251 and 260°C with the same reflow parameters. The same reflow parameter was chosen in order to identify the best reflow profile for Sn3.5Ag solder on ENIG substrate using RTP system. The reflow soldering process was performed according to joint industry standard (IPC/JEDEC J-STD-020D.1 2008). The reflow profile applied in this study was based on ramp to peak profile. Three different T_{peak} were performed in the reflow soldering process as a function of the liquidus temperature with the heat source 25-40°C greater than the melting temperature of the selected alloy to ensure complete melting of the solder and good formation

TABLE 1. Reflow profile parameter for lead free assembly (current specification) and actual assembly

Reflow parameter	Lead free assembly (current specification)	Actual assembly (average)		
Peak temperature T_{peak}/°C	240-260	246	251	260
Preheat				
Temperature (min.)/°C	150	150	150	150
Temperature (max.)/°C	200	180	180	180
Time/s	60-120	120	120	120
Ramp up rate /°C s^{-1}	3 (max.)	0.8	1	1.3
Time above temperature/°C	217	221	221	221
Time/s	60-150	70	70	70
Ramp down rate/°C s^{-1}	6 (max.)	1.3	1.5	2.0
Time (25°C to T_{peak})/min	8 (max.)	3	3	3

of metallurgical bonding between solder and the substrate (Lau 1991). Peak temperature in the range of 240-260°C is close to the maximum temperature limit of the substrate lamination. Substrates are also often stressed even further with these peak temperatures since they are above the glass transition state of the laminate. The inspection of reflow soldered Sn3.5Ag on ENIG substrate was observed through visual micrographs and cross-sectional micrographs and elemental analysis.

VISUAL MICROGRAPHS

Figure 1 shows a visual micrograph for Sn3.5Ag solder on ENIG substrate as-reflowed at T_{peak} of 246, 251 and 260°C, respectively. Figure 1(a) shows an uneven reflowed solder of Sn3.5Ag solder on ENIG substrate at T_{peak} of 246°C. This condition occurs due to an inadequate reflow profile using RTP system. Time, temperature and reflow atmosphere have a great impact on the wetting performance. Too short of a time or too low of a temperature causes insufficient heat input which resulted in an incomplete fluxing reaction as well as incomplete metallurgical wetting, thus resulting in poor wetting (Lee 2001). An uneven heating due to the non-uniform method of heating source also contributes to the reflowed solder defect. Diepstraten (2010) reported that the substrate or part with the highest heat capacity sets the profile and the part with the lowest heat capacity can get warm fast. It is reported that in a non-uniform method of heating source, heating object will never reach the same temperature as the heating source. These reflowed solder defect can be observed in Figure 1(d). Poor RTP system design can lead to a significant temperature difference during the reflow soldering process. Non-uniform heating or cooling in the RTP system contributed to the material failure due to increasing of thermal stresses or serious damage, thus limiting the applicability of the RTP system (Ching et al. 2003).

Figure 1(b) shows a better reflowed solder of Sn3.5Ag on ENIG substrate at T_{peak} of 251°C. An efficient reflow profile with the sufficient heating input contributed to the good fluxing reaction and metallurgical wetting, thus resulting in good metallurgical bonding between Sn3.5Ag solder and ENIG substrate. An efficient RTP system design can lead to a uniform temperature distribution on the solder bonding and decreased of the thermal stress to the reflowed solder, thus enhancing the applicability of the RTP system. The adequate coalescence/wetting of the solder joint also contributes to the smooth joint appearance over the solder pad and formed a regular joint shape of the solder, as shown in Figure 1(e). The sufficient reflow process in the RTP system formed reliable solder joints while maintaining component integrity. The solder melted, coalesced and wet to appropriate terminations without damaging the materials (either components or board material).

Figure 1(c) shows charred defect due to the inadequate reflow profile at T_{peak} of 260°C. Peak temperature should be high enough to obtain a good wetting but not so high as to cause discoloration and charred to the ENIG substrate. Excessive high peak temperature and extended duration over the solder melting point introduced thermal stress to the ENIG substrate. On the other hand, an excessive heat input prior to solder melting not only oxidize the metallization pads excessively, but also will burn off more fluxes, thus resulting to the poor wetting (Gilbert 2001). As the fluxes are subjected to excessive high peak temperature, the activation systems become exhausted quicker and the viscosities of the flux are reduced, potentially leading to a reduction in the protective layer of flux that surrounds the solder before reflow process (Gilbert 2001). The wetting process occurs where the solder may be in contact but does not form a good metallurgical bonding with the substrate. This condition causes grainy, rough surface and irregular joint shape of the solder as shown in Figure 1(f).

Temperature non-uniformity of the wafer in the RTP system also contributes to the charred defect during the reflow soldering process. Ching et al. (2003) reported that the temperature gradient induces thermal stress which is compressive in the central region of the wafer where the sample was placed in the RTP system. The amount of stress depends on the initial temperature distribution and power distribution. It is also indicated that the induced temperature non-uniformity can cause plastic deformation

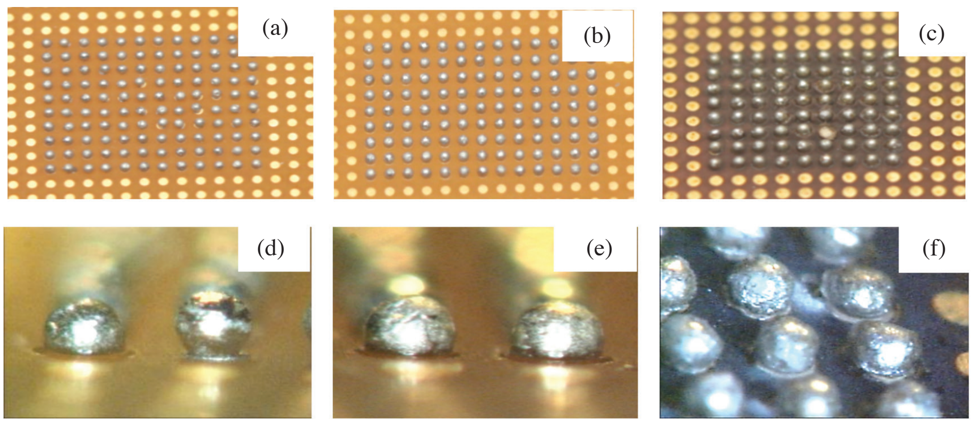

FIGURE 1. Sn3.5Ag solder on ENIG substrate after reflow soldering process with T_{peak} of (a) & (d) 246°C, (b) & (e) 251°C and (c) & (f) 260°C

of the substrate during the RTP cycle and the problem is exacerbated by single-side heating, increased processing temperature and ramp rate (Ching et al. 2003). The adequate reflow profile and uniform method of heating source should be optimized to ensure better wetting process between solder and substrate in order to achieve a good metallurgical bonding between solder and substrate during the reflow soldering process using RTP system.

CROSS-SECTIONAL MICROGRAPHS AND ELEMENTAL ANALYSIS

Figure 2 shows the microstructures and EDX spectrum of the as-reflowed interface between Sn3.5Ag solder and ENIG substrate at three different T_{peaks} of 246, 251 and 260°C. The composition of phases formed during reflow soldering process was shown in Table 2. Figure 2(a) shows the formation of scallop and plates shape with big chunks type IMCs occurred along the interface of reflowed solder at T_{peak} of 246°C. The discontinuous formation of IMCs was observed along the Sn3.5Ag solder and ENIG interface, thus leading to the weakness of the metallurgical bonding between the Sn3.5Ag solder and ENIG metallization pad. EDX analysis shows that the IMCs formed at the Sn3.5Ag solder and ENIG interface was identified to be Ni_3Sn_4 with approximate composition of 56.4 at.% Sn and 43.6 at.% Ni as shown in Figure 2(b). The EDX spectrum analysis for Ni_3Sn_4 IMC can be observed in Figure 2(c). In as-reflowed solder process, the topmost Au layer dissolved into the molten solder and a reaction layer of Ni_3Sn_4 IMC was formed at the interface of reflowed solder. In addition, Ni-P layer were also observed at the interface between the Ni_3Sn_4 IMC and the Ni layer.

The morphology of the IMCs was plane and large chunks shaped at the Sn3.5Ag solder and ENIG interface as-reflowed in the RTP system at T_{peak} of 251°C as shown in Figure 2(d). The continuous formation of the IMCs layer was observed to attach very well at the interface of reflowed solder and denoted as Ni_3Sn_4 from the EDX analysis with approximate composition of 54.8 at.% Sn and 45.2 at.% Ni. At T_{peak} of 251°C, Au signal could not be detected and the effects of Au on the interfacial reaction is minimal if the Au concentration is < 0.05 wt.% in the solder (Ruihong et al. 2009). The Ni-P layer was also found to be formed at the interface of the Ni_3Sn_4 IMC and the Ni layer as shown in Figure 2(e). The EDX spectrum analysis for Ni_3Sn_4 IMC can be observed in Figure 2(f).

Figure 2(g) shows the formation of IMCs at Sn3.5Ag/Ni interface as-reflowed at T_{peak} of 260°C. It was observed that the IMCs tend to be independent with one another, thus represent a discontinuous type of IMC formed at the interface of Sn3.5Ag solder and ENIG substrate. The formation of IMCs layer was observed at T_{peak} of 260°C not much different with the formation of IMCs layer at T_{peak} of 246°C. The significant differences for both of IMCs layer were IMC spalling at T_{peak} of 260°C was detected to leap to the surface of the solder materials from the interface of Sn3.5Ag solder and ENIG. However, the formation of IMC spalling was detected less occurred at the Sn3.5Ag solder and ENIG interface at T_{peak} of 260°C. Sharif et al. (2005) reported that beyond 60 min reflow at 260 and 270°C, the thickness of the Ni-P layer does not increase in the Sn3.5Ag solder system. In this work, IMC spalling was observed less occurred due to the high soldering temperature at 260°C for 70 s caused the sample more easily be burnt. It also exhibited less dissolution of Ni-P and thus, reducing of the IMCs formation at the interface of Sn3.5Ag solder and ENIG substrate. However, the IMCs formation at T_{peak} of 260°C exhibits the formation of voids in the Ni-P and IMCs layers due to the rapid dissolution of Ni-P layer. The IMCs composition were also identified to be Ni_3Sn_4 with approximate composition of 55.4 at.% Sn and 44.6 at.% Ni from the EDX analysis. The Ni-P layer was also observed to be formed at the interface of Ni_3Sn_4 IMC and Ni layer as shown in Figure 2(h). The EDX spectrum analysis for Ni_3Sn_4 IMC can be observed in Figure 2(i). After reflow soldering process at T_{peak} of 260°C, Au signal also cannot be detected due to the concentration of Au was minimal.

The formation of IMCs at interface of Sn3.5Ag solder and ENIG substrate was formed better at T_{peak} of 251°C compared with the formation of IMCs at T_{peak} of 246°C and 260°C using RTP system. It's essential to optimize the reflow soldering process using RTP system in order to achieve a good metallurgical bonding between solder and substrate, thus enhancing the better performance of the solder joint.

THICKNESS OF INTERMETALLIC COMPOUNDS

Table 3 shows the average thickness of the initial IMCs for the three different T_{peak} after reflow soldering process in the RTP system. The average thickness of IMCs shows that the thickness of IMCs at T_{peak} of 246°C was the lowest, followed by the IMC thickness at T_{peak} of 251°C with the differences of 0.13 μm. However, the IMC thickness for both of soldering temperatures did not show significant differences due to the temperature different for both soldering temperature was 5°C. The IMCs growth was in line with the temperature increased which the temperature rise will further promote IMCs growth faster thus increasing the thickness of the IMCs. Meanwhile, the thickness of IMCs at T_{peak} of 260°C was observed to be higher and more significant compared with the IMC thickness at T_{peak} of 246 and 251°C. The difference between the IMC thicknesses at T_{peak} of 260 and 251°C was 0.51 μm. The increasing in soldering temperature encouraged the growth of IMCs at the Sn3.5Ag solder and ENIG interface. In addition, the discontinuous formation of IMCs layer at T_{peak} of 260°C in the RTP system was detected along the Sn3.5Ag solder and ENIG interface despite the temperature supplied increased compared with the T_{peak} of 246 and 251°C. The thicker IMCs degrade the interface integrity between solder and the substrate owning to the mismatches of the brittle nature of IMCs for physical properties, such as elastic modulus. In addition, overgrowth of the IMCs formed at the interface will deteriorate the mechanical properties of the solder joints.

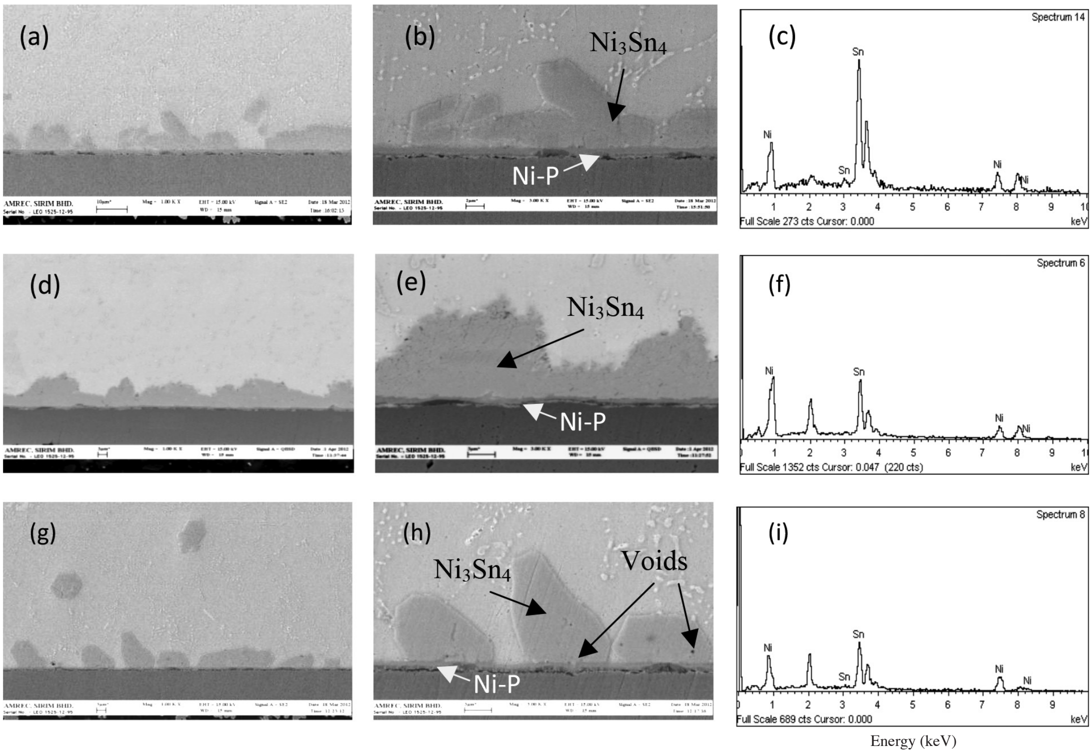

FIGURE 2. Cross-sectional micrographs and EDX analysis spectrum of IMCs formation at Sn3.5Ag solder and ENIG interface with T_{peak} of (a), (b) & (c) 246°C, (d), (e) & (f) 251°C and (g), (h) & (i) 260°C

TABLE 2. Composition (at.%) of phases formed in the solder joint of Sn3.5Ag on ENIG at T_{peak} of 246, 251 and 260°C

Composition (at.%)			Phase	
Sn	Ni	P		
56.4	43.6	-	Ni_3Sn_4	Figure 2(b)
54.8	45.2	-	Ni_3Sn_4	Figure 2(e)
55.4	44.6	-	Ni_3Sn_4	Figure 2(h)
-	75.0	25.0	Ni_3P	Figure 2(b)
-	73.5	26.5	Ni_3P	Figure 2(e)
-	70.2	29.8	Ni_3P	Figure 2(h)

TABLE 3. The IMCs thickness after reflow soldering process at T_{peak} of 246, 251 and 260°C

Peak temperature T_{peak}/ °C	Average IMC Thickness /μm	Standard deviation
246	3.64	0.8134
251	3.77	0.6314
260	4.28	0.6126

CONCLUSION

Reflow soldering process was performed in the RTP system for Sn3.5Ag solder on ENIG substrate at T_{peak} of 246, 251 and 260°C. An uneven reflowed solder and discontinuous formation of IMCs occurred at Sn3.5Ag solder and ENIG interface at T_{peak} of 246°C due to inadequate reflow profile for soldering process. Reflow soldering process was performed better at T_{peak} of 251°C with an efficient reflow profile contributed to the good metallurgical wetting between solder and substrate. The continuous formation of IMCs was observed at Sn3.5Ag solder and ENIG interface, thus resulting in good metallurgical bonding between Sn3.5Ag solder and ENIG substrate. Charred defect was observed after the reflow process at T_{peak} of 260°C due to excessive high peak temperature and extended duration over the solder melting point which introduced thermal stress to the ENIG substrate. The discontinuous formation of IMCs was detected at Sn3.5Ag solder and ENIG interface, thus resulting in a weaker metallurgical bonding between solder and substrate. Thicker IMCs was also found at the interface of reflowed solder at T_{peak} of 260°C compared with the thickness of IMCs at T_{peak} of 246 and 251°C, respectively. As a conclusion, reflow soldering process using RTP system can be performed better with an appropriate reflow profile in order to achieve a good solder joint of Sn3.5Ag solder and ENIG substrate.

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