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High-performance Bonding Wires for Semiconductor Packaging

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Abstract

New types of bonding wires that can replace Au wires for LSI semiconductor packaging have been developed as the key materials for electrical interconnection of electronic devices. One such wire is EX1, a high-functionality Pd-coated Cu wire that brings about a radical cost cut. Thanks to adequate measures to improve oxidizing resistance, bonding properties, and reliability in long-term use, which were the shortcomings of conventional Cu wires, EX1 is used widely by world-leading semiconductor manufacturers as a de-facto standard bonding wire. A new thin Cu wire with multiple coating layers and improved bonding properties, EX1p, has been developed more recently for next-generation, high-density packaging; its commercial use for the most advanced LSIs is expanding. In addition, a high-functionality wire of Ag alloy has been developed for memory semiconductor use.

1. Introduction

Smart phones and digital home appliances have been widespread throughout the world, and against this background, large-scale integrated circuits (LSIs) are requested to have higher functions and smaller sizes. In parallel, enhanced reliability is strongly required for on-vehicle LSIs, which are responsible for the electronic control of hybrid and electric vehicles (HVs and EVs). On the other hand, the Internet of things (IoT), artificial intelligence (AI), automated car driving, etc. are expected to produce a substantial increase in demands in many fields of industry, and high-functionality electronic and semiconductor devices, which support these new trends, will enter into a new era of growth. In this situation, development of a semiconductor packaging method will play an important role in the performance enhancement of these devices.

In an LSI or semiconductor package, thin conductors electrically connect an IC chip with relay terminals as shown in **Fig. 1**; high-purity Au bonding wires (hereinafter “bonding wire” is often referred to simply as “wire”), 15 to 30 μm in diameter, have been widely used for this purpose. Bonding wires are excellent in wiring flexibility, workability, etc., and as such, they are considered to continue serving and remain as a fundamental material for semiconductor packaging. Higher density, better heat resistance, and other enhanced functionality are required for semiconductor packaging, and in view of this, it is necessary in the development study for new wire products to improve the performance of bonding wires such as higher strength and longer service life at high-temperature use at as low costs as possible.

Ever since the first transistors were made by the Bell Laboratory in the 1950s, Au has always been the material of bonding wires. In the meantime, owing to reasons such as the valuation of Au, and the increase in the wire length per package, alternative materials that can replace Au have been eagerly sought. Accordingly, bonding wires of Cu and Ag were developed over a period of 40 years in appreciation of low costs and high conductivity,[1, 2] but neither of them have been commercially used because they failed to satisfy the performance required for the LSI packaging, the largest market sector of semiconductors.

Eventually, responding to the desire of the semiconductor industry for substitutes for Au wire, Nippon Steel & Sumitomo Metal Corporation and its group companies have developed two new types of bonding wires: the EX1 series which were coated Cu bonding wires excellent in oxidation resistance and bonding properties and

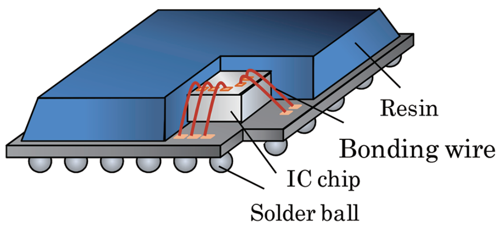

Fig. 1 LSI package

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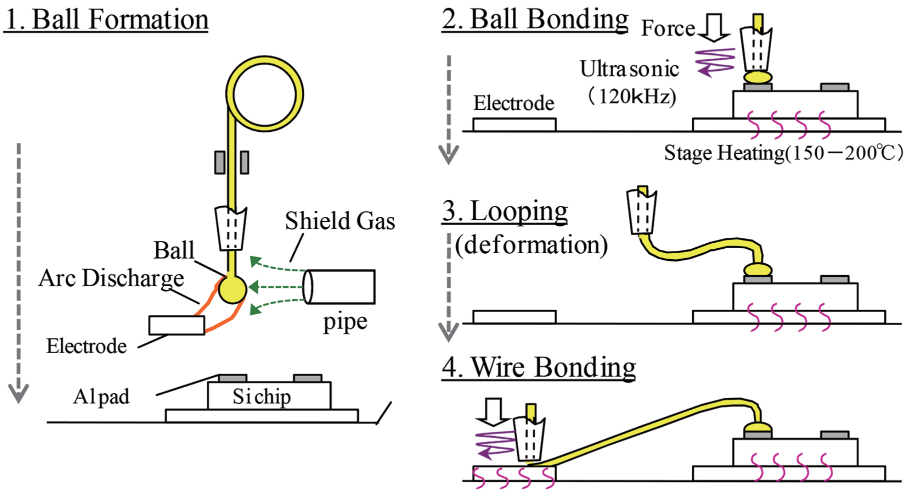


Fig. 2 Wire bonding process

applicable to LSI packages;[3–7] and the GX bonding wire of Ag alloy having bespoke functionality for memory semiconductors. The present paper introduces these bonding wire products.

2. Bonding Process and Required Wire Properties

Since the properties required for bonding wire are closely related to the process of continuous bonding, its process steps are briefly explained here (see **Fig. 2**). Using bonding machines specially designed for a specific type of package, the following work steps are repeated sequentially: (1) forming a molten metal ball at the wire tip by arc discharge; (2) bonding the ball to an aluminum electrode on the semiconductor (first bonding); (3) forming a loop by deforming the wire; (4) bonding the wire to a relay terminal (second bonding); and (5) cutting the wire. To help the bonding work, loads and ultrasonic vibrations are applied, and a cycle of the above steps is completed within 0.1 s or less.

As the wire is used for these operations they are requested to meet requirements typically such as the following in commercial quantity production: a) stable melting at the arc discharge and solidification so as to form a spherical ball aligned to the wire center line every time; b) quick material diffusion at the bond interface and formation of a metal bond to obtain a sufficient bond strength within a matter of milliseconds; c) homogeneous texture to allow quick and stable loop forming and, at the same time, maintain linearity; and d) long-term reliability in hot and humid use conditions. To create such a bonding wire product, it is necessary in the material development to examine and improve the material functionality from the aspects of weldability, solid-phase welding, texture, etc. as well as the long-term reliability of the final semiconductor package composed of a variety of components.

If a new bonding wire fails to meet any one of the above requirements, it cannot be used for LSIs, but none of the past Cu or Ag wires was qualified for commercial application owing to different technical problems.

3. Problems of Cu Bonding Wires and Development of New Cu Wire

Copper bonding wires developed in the past had the following four major problems: (1) short service life due to oxidation; (2) poor bonding properties; (3) use of hydrogen gas for the ball formation; and (4) lack of long-term reliability under high-temperature conditions. All past Cu wires were developed as bare wires, but it was difficult to solve any of the above problems without protective coating.[2] On the other hand, some wire properties were feared to deteriorate with surface coating, and for this reason, coated Cu wires have been considered difficult to commercialize.

In order to satisfy the demanding requirements for wires for LSI use, Nippon Steel & Sumitomo Metal's development team of a new Cu wire considered it was necessary to develop it as coated wire. The team embarked upon the development of overall material technology from material design including material selection, surface treatment, and the structure of the coating layers to the suitability for users' commercial packaging work in quantity and long-term reliability.

From among the noble metals of high oxidation resistance, Pd was selected as the material of the surface coating for the Cu wire in consideration of the wire melting under arc discharge and bonding properties, etc.; high melting point, high electric resistivity and other specific properties of Pd were viewed as promising for solving the problems unique to the insulating coating. However, poor sphericity of the molten metal ball, internal gas bubbles, flaking of coating layers and many other problems occurred when a Pd coating layer was simply formed on the Cu wire surface.

Through material study and design in consideration of the mechanism causing each of the problems, the structure of the Pd coating layer most suitable for stabilizing the arc discharge, increasing the adhesion of the coating layer, and solving other related problems was identified. Based on this, the thickness of the Pd coating was set at roughly 0.1 μm, its structure was selected, the best use of the diffusion layer at the Cu/Pd interface was designed, and based on these, the coating structure was defined specifically. Then, stable manufacture of the coated Cu wire was enabled by the establishment of a method for forming a thin and homogeneous coating layer. Thus, Pd-coated Cu bonding wire (trade name EX1), the first of its kind in the world to satisfy the properties required for the packaging of LSIs, has been developed and commercially applied.[3–7]

4. Characteristics of High-functionality Coated Cu Wire, EX1

Solving the four problems described earlier, which was impossible with bare Cu wire, EX1 coated Cu bonding wire exhibits advantages comparable to those of Au wire. The advantages include (1) good oxidizing resistance and consequent longer service life, (2) high bonding properties, (3) elimination of hydrogen gas for the ball formation and (4) improved bonding reliability in hot and humid environments.[2)] The characteristics of EX1 are explained below.

4.1 Improvement of oxidizing resistance and bonding properties

The reason why bare Cu wire has only a short service life is that the wire surface is oxidized and the bonding properties are lowered. **Figure 3** shows the relationship between the storage period (days) of bare Cu wire in normal atmosphere before bonding work and the breaking force (g) at the pulling test (equivalent to the wire bonding strength).[4)] The bond strength of bare Cu wire is low even when it is used without substantial storage, and moreover, oxidation of its surface is advanced during exposure in normal atmosphere for a week or so, which inevitably leads to bonding defects such as low strength and peeling off of the joint.

With EX1, in contrast, the bond strength is high without substantial storage before bonding, and in addition, the bond strength does not lower even after a long storage time: in fact, good bonding properties were obtained even after storage for 60 days or longer. This is because the optimum thickness and structure of the Pd coating layer effectively suppresses oxidation of the Cu wire. Thanks to this protective effect of the coating, the bond strength at the bond interface and the package service life of packages using EX1 have proved to be markedly better than those with bare Cu wire. Furthermore, EX1 has demonstrated excellent oxidation resistance at an accelerated aging test in a heated and humidified environment.

4.2 Hydrogen elimination from ball forming atmosphere

To prevent the molten metal ball from oxidizing, it is necessary with bare Cu wire to blow a special gas (N_2 + 5%H_2) onto the wire tip, where the arc discharge is focused,[4, 5)] which incurs an additional cost and jeopardizes working safety. Thus, stable ball formation in an economical and safe pure N_2 atmosphere was eagerly sought.

Figure 4 compares a ball of bare Cu wire with another of EX1 formed in a pure N_2 atmosphere. The ball of bare Cu is off-centered with respect to the wire in this atmosphere, and the bonding is not viable. This is because the arc extends along the surface of the Cu wire, which we suspected was helped by the copper oxide forming on the wire surface. With bare Cu wire, therefore, the addition of H_2 described earlier is required to suppress the arc extension and consequent off-centering of the ball.

Starting from the above understanding, the development study of the Cu wire continued to focus attention on the mechanism by which the behavior of the arc was governed by the condition of the wire surface, but stable ball formation was not obtained by simply coating the wire surface with a Pd layer. Then, through further improvement in the surface composition and structure of the Pd layer, a method for effectively concentrating the arc discharge onto the wire tip was finally established, thus enabling stable formation of a metal ball with good sphericity aligned to the wire tip as shown in Fig. 4 in a pure nitrogen atmosphere. Such design technology of a coating layer only a few nanometers in thickness to control metal melting and solidification under arc discharge has facilitated the wide practical use of EX1. It also served as a base technology for the later development of small-ball bonding for even thinner wires and optimization of multi-layer coating for successor wire products, which will be explained later herein.

4.3 Improvement of bond reliability

At high-temperature, high-humidity tests simulating tough use conditions of automotive LSIs and the like, problems occur often at the joints between a wire and an aluminum electrode. Since Cu oxidation is accelerated by moisture, low reliability of bare Cu wire under hot and humid test conditions[6)] was viewed as a serious obstacle for its commercial use.

Figure 5 shows the results of a high-humidity heating test of Cu

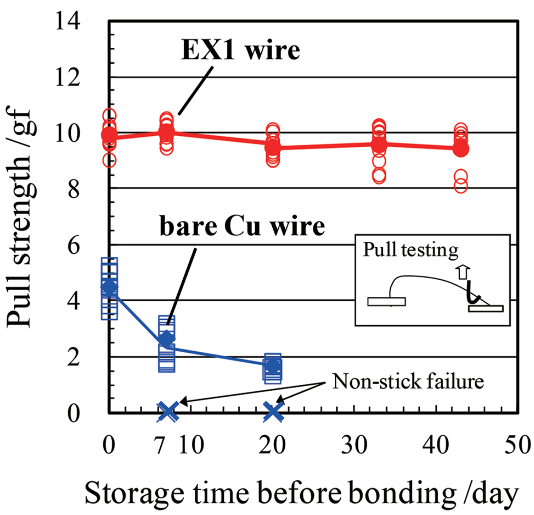


Fig. 3 Pull strength of wire bond of Cu bonding wires (diameter: 25μm, pull test of wire bonds)

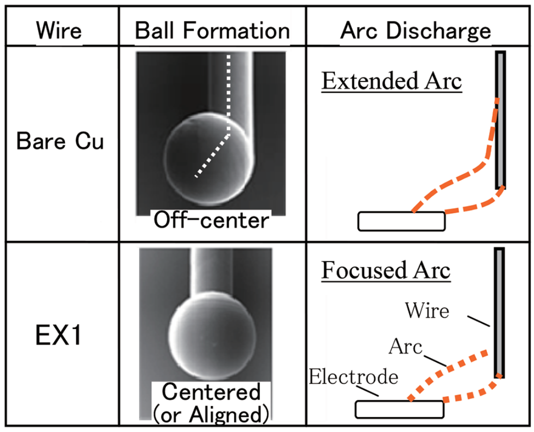


Fig. 4 Ball formation and arc discharge behavior

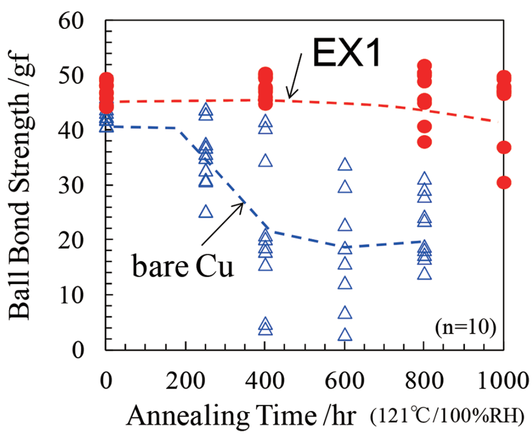
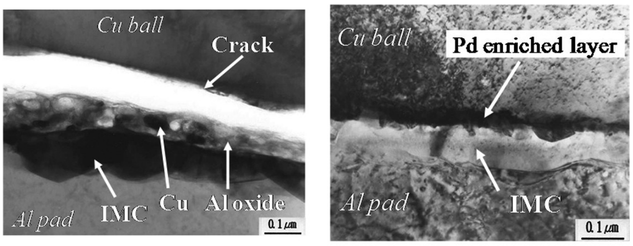


Fig. 5 Bond strength after high humidity heating (diameter: 25μm, molded with commercial epoxy resin)



(a) Bare Cu wire (b) EX1

Fig. 6 TEM observation of ball bond interfaces after high humidity annealing test

wires at 121°C and 100% relative humidity. The shear strength of a ball-bonding joint was evaluated after the following steps: wire bonding, molding with epoxy resin, heating at high humidity, and resin removal. Here, the joint strength of bare Cu wire falls markedly within a short time of 250 h or less, and in contrast, that of EX1 is maintained to nearly 1 000 h, which substantiates the far better bonding reliability of EX1.[4, 6)]

To clarify the reason for the reliability improvement, we observed sections of bonded joints after heating through a transmission electron microscope (TEM). **Figure 6** shows examples of the observed joint sections. A long crack was seen at the bonded joint of the bare Cu wire, which was deemed to have caused the decrease in bond strength. In addition, Al oxides, Cl, and other reaction products were detected near the crack. It became clear from this that the poor bond strength of the bare Cu wire was due to the corrosion resulting from the reaction of a part of the Cu-Al intermetallic compound (IMC), which formed in the bonded joint, with Cl that was included in the molding resin as an impurity.[6)] Here, moisture absorbed in the resin helped the movement of Cl ions. We have disclosed that a specific IMC phase corroded selectively, and found that Pd in the coating was effective in controlling the diffusion of Cu and Al that governed the growth of the IMC phase.

The joint of EX1, on the other hand, had a good bond interface without cracks or voids. With EX1, Pd condenses at the bond interface during heating, and by effectively using the diffusion barrier function of the Pd-condensed layer, the growth of the specific IMC phase, which is prone to easy corrosion, was suppressed, the IMC phase separated from the intruding Cl, and thus, the reliability of the bonded joint was improved.[6)] As explained above, the material of EX1 was designed such that the wire is prevented from oxidizing and the Pd coating has the function of improving the long-term reliability of the bonded joint. This differentiates EX1 from conventional bare Cu wires.

The development of EX1 verified the excellent performance of coated Cu wire, a new market of Cu wire for LSI use was formed and expanded within a short period as a result, and the change from Au wire to Cu wire was accelerated. Coated Cu wire EX1 has been commercially used to demonstrate high performance unattainable by bare Cu wires; actually, very thin EX1 wire, 20 µm or less in diameter, has been used for the most advanced ultrahigh-density packaging of multi-LSIs having many pins arranged in many tiers (see **Fig. 7**).

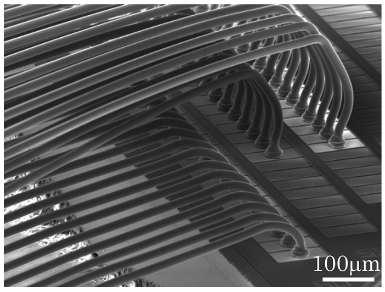


Fig. 7 EX1 for LSI package (diameter: 18µm, wire pitch: 50µm, multi-layer bonding)

5. Development of Multi-layer-coated Cu Bonding Wire Having Enhanced Bonding Properties

The most advanced techniques such as ultrahigh-density bonding and 3-dimensional packaging are employed for the most recently developed LSIs, but it is difficult to cope with these techniques even with Au wires. Thus, as the use of EX1 for this application expanded, higher and higher performance was required. To increase the use of EX1 and allow a decrease in wire diameter from 20 to 18 µm for higher density bonding, bonding with packaging materials difficult to join, etc., it is paramount that its bonding properties be enhanced, but the improvement obtainable by simply optimizing the mechanical properties of the wire and the coating layer thickness is limited. Seeking a breakthrough in the enhancement of bonding performance, we studied the structure design of the coating layer.

Eventually, a new bonding wire with multi-layered coating, which is composed of an Au-Pd alloy layer on a Pd coating, was developed, and given the trade name "EX1p". **Figure 8** schematically shows sectional structures of different types of bonding wires. While Pd coating is effective in preventing oxidation of the core and improving ball formation, it has a high hardness and a high melting point, and for this reason, it is a little slow in diffusion bonding with other materials. In this respect, the Au-Pd alloy is comparatively soft and enhances diffusion bonding, and it is possible to raise the bond strength by having an Au-Pd layer form on the wire surface.

Needs	Au alternative	High density packaging	Memory LSI	Conventional
Product	**EX1**	**EX1p**	**Ag alloy wire**	Au wire
Wire Cross-section	Cu core, Pd, (Diffusion layer)	Cu core, Pd, AuPd alloy	Ag alloy	Au
Coating	Pd	AuPd / Pd	(Ag core)	(Au core)

Fig. 8 Sectional structures of high-performance bonding wires

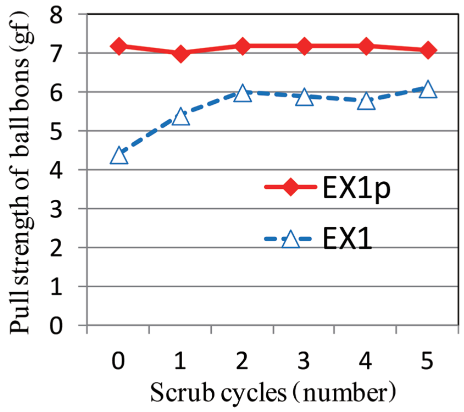


Fig. 9 High bond strength of EX1p

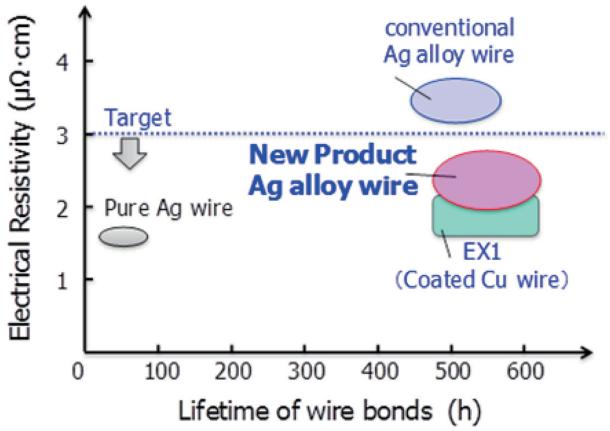


Fig. 10 Bond lifetime and electrical resistivity of Ag bonding wires

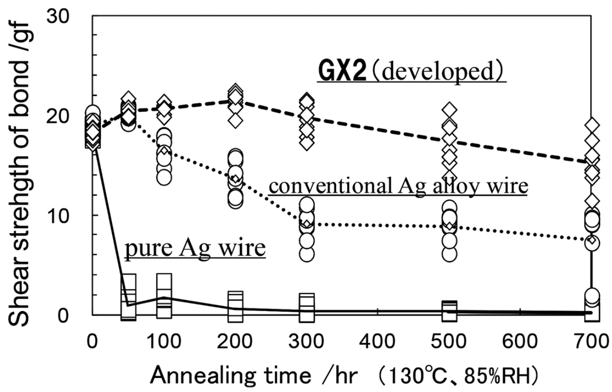


Fig. 11 Bond strength of Ag wire after high humidity test

Figure 9 shows the bond strength of coated Cu wires. The "scrub" motion of the horizontal axis means horizontal shifting of the package stage during pressure bonding; it helps wire deformation, but to shorten the bonding time, it is desirable that the number of shiftings be as small as possible. EX1p has exhibited a sufficiently high bond strength with one scrub or less per wire. Generally speaking, its bond strength is stably higher than that of EX1 thanks to the Au-Pd alloy layer, which helps the material deformation and diffusion bonding at the joint interface. EX1p is advantageous also for low-temperature bonding on resin substrates.

In order that the Pd coating effectively helps with stable formation of metal balls as described earlier, the thickness of the Au-Pd alloy coating is designed thinner than that of the Pd layer. When a molten metal ball is formed by arc discharge, if the coating consists of two or more layers, it becomes difficult to melt them efficiently, have them mixed with each other and form a ball of good sphericity. Delicate control of the thickness, composition distribution, etc. of the Au-Pd alloy and the Pd layer has produced favorable synergistic effects not obtainable singly by either of them. Then, manufacturing and heat treatment processes have been established for accurately forming the coating structure in thicknesses in the order of nanometers, and commercial production of EX1p has been made possible. Thanks to the excellent bonding properties meeting widely varied requirements, EX1p exhibits higher functionality than that of EX1 in the packaging of the most advanced semiconductors in the aspects such as use of ultra-thin wires, small-area bonding and high reliability. The excellent performance of EX1p is highly appreciated by many semiconductor makers in the world, which accelerates wider use of the coated Cu wire.

6. Ag Alloy Bonding Wires for Memory Devices

As a measure for down-sizing and capacity increase of memory elements, three-dimensional packaging has been employed, whereby memory devices as thin as several tens of micrometers in thickness are stacked in many tiers. Wire bonding for memory devices is somewhat special; a wire is often double-bonded to a thin memory device, and to prevent damage to the element, it is desirable to use soft and easily deformable wires. On the other hand, low electrical resistance is required for rapid data processing. Since the core of EX1 is made of Cu, it is hard and its use for memory devices is expanding only slowly, with Au wires still being used for this application.

Ag is soft and promising as an alternative material for wires for memory devices to replace Au, but the problem with pure Ag wire is low reliability of joints with Al electrodes, and its commercial use was abandoned. Electric resistance increases when an Ag alloy contains other elements by 5 mol%, approximately, and for this reason, the use of Ag alloy wires was limited. To solve the problem and extend the service life of bonded joints, we designed an Ag alloy with additional elements in low amounts, and developed a new type of high-functionality Ag alloy wire, trade name GX2. **Figure 10** compares the bonding wires of pure Ag and Ag alloys in terms of electric resistance and bonding life. GX2 demonstrates an electric resistance equal to or lower than the target 3.0 $\mu\Omega$cm.

Figure 11 shows the change in the bond strength of joints of Ag wires with Al electrodes at high-humidity heating tests at 130°C and 85% relative humidity. Whereas the bond strength of pure Ag wire fell dramatically within as short a period as 50 h or less, that of the newly developed GX2 remained substantially unaffected for roughly 250 h, verifying the largely improved bonding life.[8)] Sectional analysis of the bonded joints confirmed that, with GX2, the corrosion reaction of an Ag-Al IMC with Cl, which occurs with pure Ag wires, was suppressed. The additional elements of the Ag alloy effectively control the material diffusion at the joint interface, and help the formation of another corrosion-resistant IMC, which grows only slowly under other, typical conditions. This effect, which has been realized through adequate design of the coating alloy, is partly common to that of the Pd coating of EX1 described earlier.

7. Conclusion

The control of the coating structure of EX1 including the optimum design of the Pd coating layer has enabled marked improvement of the wire properties related to the mutually conflicting requirements of oxidizing resistance, bonding properties and long-term reliability, which were difficult to achieve with conventional bare Cu wires. EX1 has dramatically reduced costs while retaining substantially the same high performance as that of Au wire. Of different types of Cu bonding wires, EX1 was used for the first time in the world for commercial production of the most advanced ultra-high-density LSIs.

Nippon Micrometal Corporation, a member of the Nippon Steel & Sumitomo Metal Group, produces and sells a wide variety of bonding wires including the EX1 family products, GX2 Ag-alloy wires, etc. These bonding wires are used in mass production at more than 40 plants of the world's top-ranking semiconductor companies as virtual world standard products. In appreciation of the high functionality suitable for the latest LSIs responsible for the electronic control of smartphones, tablet devices, etc., the demand for EX1 and its successor product EX1p is rapidly increasing. They are advantageous in diameter reduction because of high conductivity, and therefore, applicable more widely to the next generation ultra-high-density packages than Au wires. The replacement of Au wires with the EX1 series products will have a knock-on effect of a 99% decrease in the total consumption of the noble metal. The development of the EX1 products was so highly appreciated outside the group, too, that the Nippon Steel & Sumitomo Metal Group was awarded the 2012 Principal Award of the Ichimura Industrial Prize in Industry by the New Technology Development Foundation, the first case among steelmakers.

To establish industrial property rights for the coating structure of EX1, developed as the first of its kind in the world, more than 100 patents have been registered in and outside Japan to form a global patent protection network. As a diversification of the group activities and an example of innovative Japanese technologies, the use of these patents has been licensed to several leading bonding wire manufacturers.

Making the most of the advantages such as an electric conductivity about 20% higher than that of Au, higher heat resistance and good durability, the use of EX1p for semiconductors is expected to expand in the fields of HV, EV, and other types of next-generation automobiles, and power control devices for a low-carbon society.

The use of Au-replacing materials that the development of EX1 has cultivated is expanding further. On the other hand, the Ag alloy wire GX2 developed in pursuit of the functionality required for memory semiconductor packages is the first Ag bonding wire having both low electric resistance and high bonding reliability, and its commercial use by leading semiconductor makers is being planned. In consideration of the use of flash memories for widely varied devices from memory cards to industrial machinery, GX2 is expected to open a large market to support the rapid global growth of information processing as one of the principal electronic materials.

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