Pressureless Direct Bonding of Au Metallized Substrate with Si Chips by Micro-Ag Particles

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Abstract*: The aim of this work is to develop and investigate bare Si chips assembly to Au plated substrates. In this research thermal interface material paste based on mixture of micro-Ag particles and pressureless sintering at 175 °C was studied. Joints obtained in the experiments had adhesion of 10 MPa and thermal resistance as low as 0.25 K/W. Novelty of this work is application of micro-Ag paste at low temperature process and without pressure applied on the chip. Those parameters are usually shown as limitation of Ag paste applications. Additionally, after ageing for 500 h at 125 °C and thermal cycles (-20 °C ÷ 100 °C) investigated joints maintained their mechanical and thermal properties.*

1. Introduction

There is a growing demand for high power electronics based on available GaAs, GaN or SiC semiconductors capable of continuous operation at temperatures exceeding 200 °C [1–3]. This demands necessary changes in chip-to-substrate assembly technologies and research on alternative assembly substrates. At such high continuous operation temperatures, SAC solders and laminate substrates cannot be used. The limitation of continuous operation for SAC solders is a temperature around 150 °C and not the best thermal conductivity: lower than 50 W/mK. In terms of substrates, ceramic substrates with Cu, Ag, Au or Ni mounting metallizations are being investigated. These requirements have led to a growing interest in other assembly techniques such as Ag paste-based sintering or SLID (Solid Liquid InterDiffusion) technology in the last decade [4–7]. Ag paste-based sintering technology is gaining importance. By properly adjusting the temperature and sintering time as well as the contact pressure, joints with very good adhesion, thermal conductivity and reliability can be obtained. The classical sintering process can be carried out at temperatures ranging from 200 °C to 300 °C at pressures ranging from 10 MPa up to 40 MPa. The parameters of the bonding process depend on the size and shape of the Ag powder grains in the paste, additives to prevent clumping and the solvents used [8]. The pastes in which the powder particles are a few to several micrometers in size are processed at temperatures above 250 °C and at pressures higher than 10 MPa. Pastes based on Ag nanopowders are processed at temperatures around 200 °C at low pressures. Using nanopowders, it is possible to obtain a bonding material with resistivity of about 2.4 μΩcm and thermal conductivity in the range of 100-250 W/mK [8, 9]. However, it should be noted that pastes based on nanopowders are very expensive, agglomerate easily, have high shrinkage and are difficult in industrial application. Hence the interest in Ag pastes based on Ag powders of micrometer or submicrometer sizes. They are much cheaper and can be processed at temperatures around 250 °C obtaining good mechanical, thermal and electrical parameters. It should be emphasized that Ag paste sintering technology is limited to joining to metallization of Au, Ag, Ni or with some limitations to Cu [10]. Paper [10] describes the use of sintering technology for Au/Au, Ag/Ag and Ni/Ni monometallic joints processed at 250 °C for 60 min under pressure, 0.4 MPa made with micrometer-sized Ag flake pastes. Applying low pressure during sintering, adhesion exceeding 30 MPa was achieved. Another solution is reaching for pastes based on mixtures of powders. An example is the work [11], where a paste consisting of a mixture of Ag powders of micrometre and submicrometre sizes in the ratio 1:1 was used. During sintering, the temperature of 350 °C was applied, resulting in Au, Ag and Ni metallization joints with satisfactory adhesion and after long-term aging of 1000 h at 250 °C. However, it should be kept in mind that the connections made with Ag pastes should not only be characterized by good adhesion but also by low thermal resistance of the connection. The thermal resistance values quoted in the articles are difficult to compare. The values obtained depend not only on the thermal resistance of the paste itself but also on the thermal resistance of the paste-metallization interface on the surfaces to be joined and on the measurement methods used. In papers [9, 12] values ranging from 0.45 to 0.55 K/W are given.

It turns out that the thickness of the bonding layer is also an important factor ensuring good performance of sintering joints. It has been shown in [11, 13] that in order to obtain a compromise between good adhesion and good thermal conductivity it is necessary to use connections of thickness ranging from 30 μm to 60 μm. In joints that are too thin, a tendency for Ag atoms to migrate along the substrate and form alloys with Au metallization is observed, leading to an increase in porosity, cracks, and possible delamination. On the other hand, connections that are too thick are a lengthening of the path for heat flow and a deterioration of the thermal resistance of the junction.

Increasing complexity of semiconductor structures (e.g. GaN-on-Si), difficulties in applying pressure in production equipment and miniaturization force to search for pressureless joining methods. So far in such cases electrically conductive adhesives have been used, e.g. H20E adhesive from Epotek Technology. The catalog thermal conductivity of this adhesive is 29 W/mK, less than that of solders. The Ag powder content is responsible for the good electrical and thermal performance of this type of adhesives and the resin content for the adhesive properties. This kind of problems was analyzed in the paper [14]. The possibility of using Ag pastes (of grain size several micrometers) for mutual bonding of bare surfaces was investigated: Si/Si, GaN/GaN and SiC/SiC, thus for forming the connection between Ag contained in the paste and the bare surface of the chip. The junctions were formed at 250 °C for 60 minutes, without pressure. The authors suggest that the preparation of the Ag powder and the presence of oxygen on the bonded surfaces were responsible for the good bonding properties. In recent years, research is being undertaken on a new generation of Ag pastes based on a mixture of Ag powders and resins [3, 9, 15]. It is expected that the increased Ag content will be responsible for good thermal and electrical parameters of this type of pastes and the partial sintering of Ag and the presence of resins will be responsible for sufficient adhesive properties. Pastes of this type are referred to as semi-sintering type and the bonding mechanism as sintering/curing [16].

The purpose of this paper is to present a technology for bonding Si chips without metallization to Cu substrates with NiAu mounting metallization using a paste based on Ag powders. Sintering mechanism between Ag paste and Au metallization on the substrate should be responsible for joint formation and a sintering/curing mechanism for making the bond between Ag paste and bare Si chip. Our first work on the use of Ag pastes to assemble Au metallized Si chips was presented in [7]. In that paper the suitability of Ag paste sintering technology in micrometer sizes using 350 °C bonding temperatures at 10 MPa pressures and SLID technology for Sn metallized substrates was analyzed. Looking for solutions for pressureless technologies, TIM AT2M paste was prepared at AMEPOX. The paste consists of a mixture of Ag particles of spherical shape (size several tens of micrometers) and flake shaped particles of size from 1 μm to 3 μm with a small addition of resins. Preliminary results of thermal parameters and adhesion studies for joints made with these pastes between NiAu metallized substrates and Si chips with and without TiAu metallization and were presented in [15]. The joints were formed by sintering at 160 °C & 30 min + 230 °C & 60 min. Joints with adhesion exceeding 10 MPa and with thermal resistance of 0.3 K/W (without pressure) and 0.1 K/W (with 2.4 MPa pressure) were obtained. Based on these results, it was decided to refine the bonding technology of bare Si chips to NiAu metallized substrates for TIM AT2M paste and to explore the bonding formation mechanisms between Ag paste and Au metallized substrate and Si chip surface without metallization.

2. Experimental details

Two types of samples were prepared: for testing adhesion and for testing thermal parameters of the joint. The samples for adhesion testing were prepared in the following way. Cu substrate of 10 x 25 x 0.93 mm geometry covered with Ni (3 μm) and Au (1 μm) metallization on one side was used as a substrate. Si chips of 3 x 3 x 0.52 mm without metallization were mounted to the substrate via TIM AT2M paste. Pin transfer method was used for paste deposition on Cu substrate with NiAu metallization. The Si chip was then pressed into the paste on the substrate with light pressure and placed on the hot plate and joined without pressure. In Fig.1 finished sample for adhesion testing are presented. The adhesion was determined by shear test according to IPC-TM-650 standard.

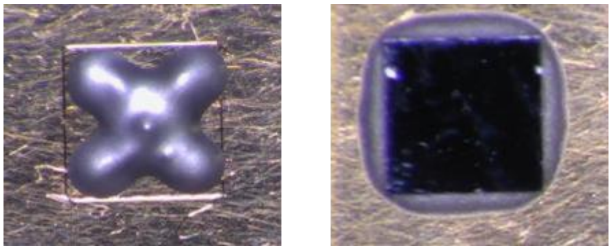

Fig. 1. Deposited paste (left) and chip placed into paste, chip size 3x3x0.52 mm

The sample for thermal testing consisted of two substrates, one of 10 x 10 x 0.93 mm with Ni (3 μm) Au (1 μm) metallization and the other substrate was a Si chip of 10 x 10 x 0.52 mm. Both substrates were bonded with TIM AT2M paste. First, TIM AT2M paste was applied to one of the substrates on Au metallization by syringe dispensing method and then the second Si substrate with the same dimensions was positioned on it and both parts were joined on the hot plate with no pressure or 0.6 MPa pressure applied.

Measurements of thermal resistance were made in a two-step procedure. First, a reference Cu sample size of 10 x 10 x 0.93 mm was placed between two long Cu cuboids of 10 x 10 mm cross-section in a specially constructed test stand. By accurately measuring the temperature distribution along the Cu cuboids and knowing the geometry of the placement of the temperature sensors, the thermal resistance of the test bench with the reference sample was determined. Knowing the thermal resistance of the reference sample, the thermal resistance of the test bench was calculated. Then the test sample was placed in the test stand and again the thermal resistance of the test bench with the test sample was determined. After subtracting the thermal resistance from the measured value, the thermal resistance of the test sample was determined. The thermal resistance of the sample measured in this way consists of: the thermal resistance of the Cu substrate with NiAu metallization + the thermal resistance of the interface metallization Au-paste TIM AT2M + the thermal resistance of the TIM AT2M paste + the thermal resistance of the interface paste TIM AT2M - bare Si + the thermal resistance of the Si substrate. The value of this total resistance was reported as the test result in the following section.

2.1. TIM AT2M: Optimization of sintering procedure

TIM AT2M paste consists of a mixture of Ag spheres (several tens of micrometers in size, Fig.2) and Ag flakes (several micrometers in size, Fig.3) and small addition of resin. The paste is manufactured by Amepox Microelectronics Ltd, Poland.

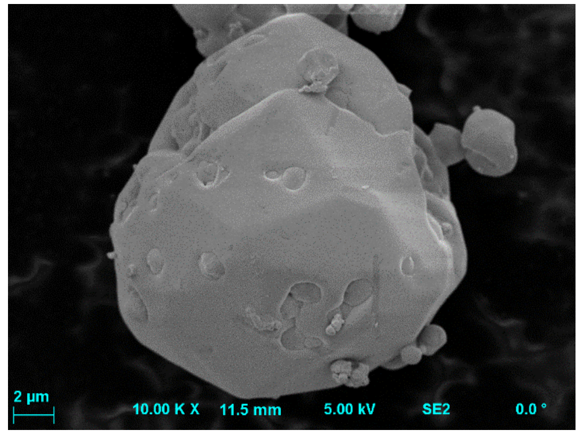

Fig. 2. SEM image of Ag particle – sphere shape

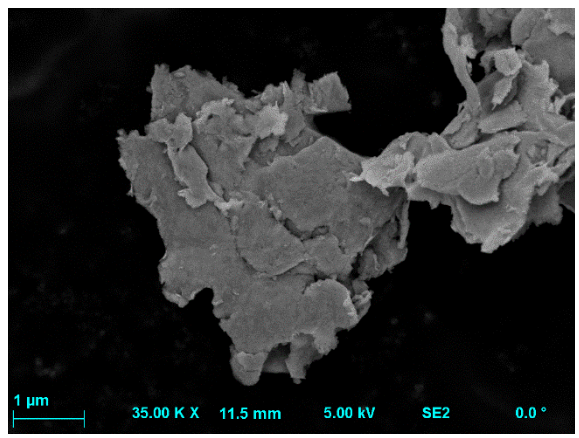

Fig. 3. SEM image of Ag particle – flake shape

It was decided to perform a procedure to optimize the sintering of TIM AT2M paste for bonding Si chips without metallization to substrates with NiAu metallization to achieve adhesion above 10 MPa and obtaining a bonding layer in the range of 30 μm to 60 μm. The orthogonal table L9(3^4) was used and the effects of the following factors on the adhesion and bonding layer thickness were investigated: factor A - sintering/bonding temperature from 175 °C to 230 °C, bonding time from 15 min to 60 min, pressure during pressing the chip into the wet paste from 0.1 to 0.6 MPa and the use of drying or not before sintering. The actual sintering/joining process was carried out pressureless. Each experiment was repeated twice for the given conditions and adhesion and bonding layer thickness were determined, Fig.4. It was found that adhesion better than 10 MPa and bonding layer thickness in the range of 30 µm to 40 µm were obtained for each experiment.

The performed experiments allowed us to propose a universal method of assembly of bare Si chips to NiAu metallized substrates as follows: sintering/bonding temperature 175 °C, time 30 min, pressure 0.1 MPa while pressing Si chips into paste at room temperature. Verification experiments were performed and for the above-mentioned bonding parameters for sintering/bonding joints: Cu substrate with NiAu and bare Si, for N=6 the adhesion was determined as 12.7 ± 1.4 MPa

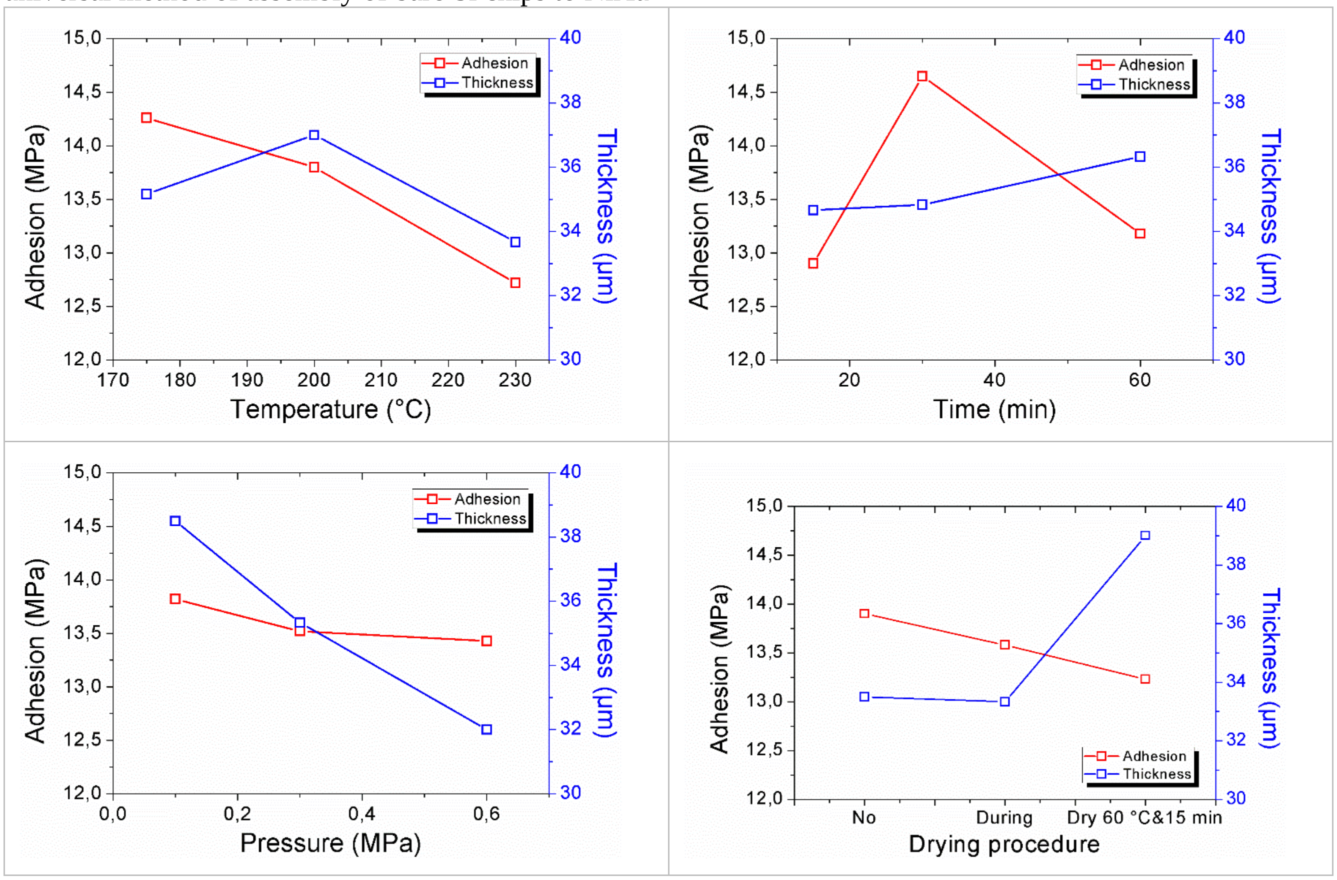

Fig. 4. Adhesion and joint thickness dependence on joining temperature, time, applied pressure and drying procedure

2.2. Investigation of joining mechanisms of TIM AT2M paste

A cross section through the sintering/bonding interface between the NiAu metallized substrate and bare Si is shown in Fig.5. Numerous small voids are present in the joint area in addition to the large voids. Fig.5 inset shows a fragment of a correctly formed junction with few small voids. In a fragment of a correctly formed bonding layer large Ag grains are visible. Those allow the formation of a short critical path for heat transfer between the bonded surfaces.

Analysis of the image of the shear surface on Cu substrate with NiAu, Fig.6 inset indicates that the damage is cohesive near the Au metallization on the substrate. In the image there are no observable voids, and an Ag layer is present on the Au metallization on the entire substrate surface. A detailed analysis of the shear surface on the substrate surface is shown in Fig.6. The analysis at every point examined showed the presence of Ag on the Au metallized substrate surface. The study showed that the bonding mechanism between the Au metallization of the substrate and the Ag paste is small range diffusion, as Ag was always found at the analysis points closest to the Au metallization. This is a typical bonding mechanism for the sintering process.

Fig.7 inset shows the bare surfaces of the Si chip after shearing. A thick layer of Ag on the surface of the entire Si chip can be clearly seen. Fig. 7 shows the surface detail on Si after shearing, small sections can be seen where Ag does not adhere to Si. The composition analysis at these points showed the presence of Ag on the bare Si fragments, which may be due to the proximity of Ag around the measurement point (the analysis volume is about 1 μm^3), the optical image does not confirm the presence of Ag. The shear surface characteristic indicates that the bond between the Ag paste and the surface of the chip without metallization is adhesive in nature. There are no traces of Ag on the exposed small areas of Si.

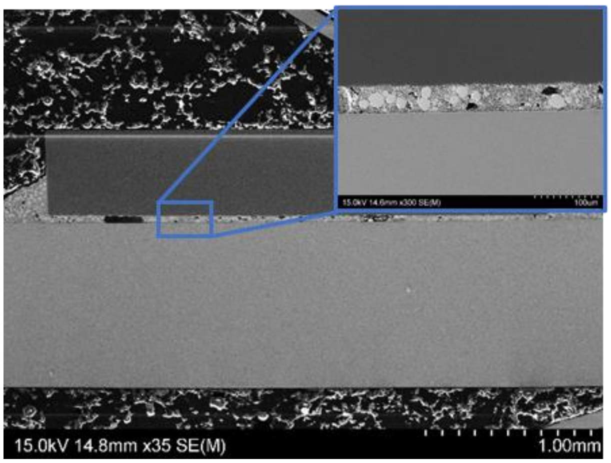

Fig. 5. SEM image of bare Si sample, detail shown in inset.

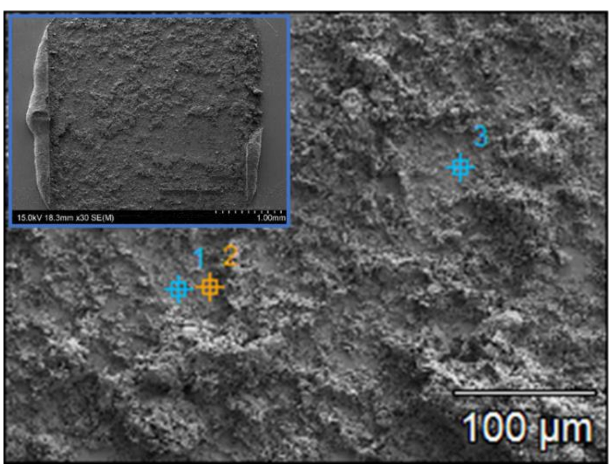

Fig. 6. SEM image of Cu substrate with NiAu metallization after chip removal, whole chip area shown in inset. EDS analysis in marked points:
1: 2.8% Cu; 83.2% Ag; 13.7% Au
2: 3.4% Cu; 11.4% Ag; 82.9% Au; 2% Ni
3: 1.7% Cu; 81.7% Ag; 11% Au; 4.6% O

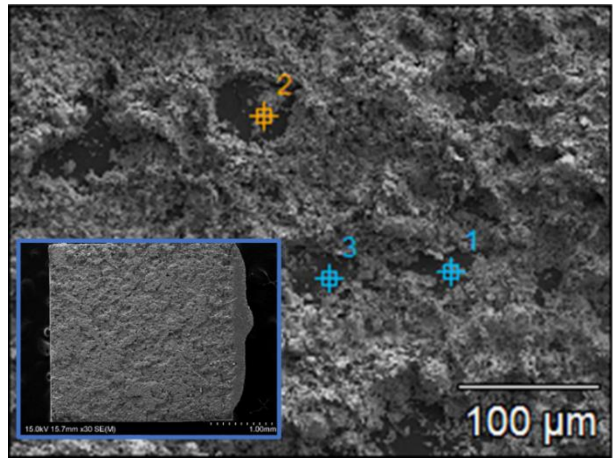

Fig. 7. SEM image of bare Si chip, chip area shown in inset. EDS analysis in marked points:
1: 2.2% Si; 97.4% Ag
2: 4.4% Si; 95.4% Ag
3: 98.6% Si; 1.4% Ag

Independently of investigating the nature of the bond between the NiAu metallized substrate and the bare Si surface, the adhesion stability was investigated in an aging test at 125 °C & 511 h and in a test of 40 temperature cycles -20 °C ÷ +100 °C. The adhesion was stable during whole ageing and temperature cycling experiment. Temperature cycling exposure is more critical for sintering/bonding joints and these issues will be investigated further.

2.2. Thermal measurements of (Au + paste + Si) joints

Independent of the adhesion tests, the thermal resistance of custom-made samples consisting of a Cu substrate with NiAu metallization bonded with TIM AT2M paste to a bare Si substrate was investigated. The same temperature-time profile as for the adhesion test samples was used. The only difference was the bonding process was performed under a low pressure of 0.6 MPa. Tab.1 shows the change in thermal resistance during measurements up to 3 h.

Table 1. Cu substrate with NiAu + TIM AT2M paste + bare Si
* 0.1 mm thick Si substrate was placed on TIM AT2M dried paste

Joint thickness	R_{th} after [K/W]				
	60 min	90 min	120 min	150 min	170 min
35 μm (Si=0.52 mm)	0.25	0.25	0.24	0.26	0.23
35 μm* (Si= 0.1 mm)	0.13	0.09	0.15	0.10	0.11

For sintering/bonding layers with thicknesses of 35 μm, a thermal resistance of 0.23 K/W was obtained and for thinner Si wafers laid on a desiccated paste, a R_{th} of about 0.10 K/W was obtained. The results of the thermal resistance measurements of the interface between the Cu substrate with NiAu metallization and the Si chip surface without metallization indicate that the TIM AT2M paste can be used as a Thermal Interface Material that dissipates heat well from Si chips without bottom metallization while maintaining good adhesion. The ability to process this paste at temperatures of 175 °C without pressure during joining indicates that it can be used in the final stages of the assembly process without thermal damage to previous joints (e.g., those made with SAC solder).

2. Conclusion

This paper analyzes the mechanisms of bonding TIM AT2M paste between Cu substrates with NiAu metallization and Si chip surface without metallization. The investigated paste consists of a mixture of spherical Ag powders several micrometers in size with Ag flake powders several micrometers in size. The paste can be processed at 175 °C without pressure during joining. Joints between 30 μm and 50 μm thick are obtained, resulting in short critical paths for heat flow and the formed joints have low thermal resistance while maintaining satisfactory adhesion. Shear tests showed that the failure is cohesive near the Au metallization on the substrate. On the other hand, the thick layer of Ag powder adheres well to the Si chip surface and this bonding is most likely adhesive in nature due to the resin in the paste. On the other hand, two phenomena small range diffusion between Au and Ag as well as the presence of resin are responsible for the bonding quality between Ag paste and Au metallization of the substrate.

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