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Ag-based Thermal Interface Materials for GaN-on-Si Assembly Chips in Power Applications

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Abstract*: The paper aims to develop an assembly technique for the connection of bare Si or TiAu metallized Si chips to NiAu plated Cu surface. The thermal interface material (TIM) based on Ag paste was used for this purpose. It was found that Ag-based TIM allows creating sound joints between NiAu plated Cu and both types of Si chips. The analysis of the joints showed that the adhesion is in the range of 10 MPa and thermal resistance is less than 0.3 K/W. Therefore, the fabricated joints fulfil the mechanical and thermal requirements for this type of assemblies.*

1. Introduction

The assembly of bare Si surface or Si with Au bottom metallization (as in GaN-on-Si chip system) to Au plated Cu base plate using so-called TIM (Thermal Interface Material) layer is still challenging. The majority of TIMs are based on the Ag-sintered layer [1,2]. Using Ag-based TIM instead of Sn-based solders has many advantages, in particular: a) the thermal conductivity of Ag-sintered based pastes (above 100 W m^{-1} K^{-1}) are significantly better than solders (range 40-60 $Wm^{-1}K^{-1}$) and b) the joined layer is usually twice time thinner [1-3]. Properties of TIMs strongly depend on microstructural parameters such as the presence of voids and TIM layer thickness. Usually, we can expect that the thinner layer is better thermal properties will be. However, in a recent study [4] authors have shown that the bond line thickness should be in the range between 20 µm and 50 µm. Such thickness range is optimal from both mechanical and thermal properties point of view. Layer thinner than 20 µm is characterized by higher principal stresses and strains within the structure which may cause its adhesive or cohesive failure. For joints with a thickness higher than 50 µm its thermal resistance is above the acceptable limit.

In the present study, the authors concentrate on a design of the TIM layer suitable to provide a good connection between bare Si or Si metallized with TiAu to Cu substrate plated with NiAu. This study aims to find a universal TIM which may meet the thermal and mechanical requirements for GaN-on-Si assemblies.

2. Experimental Details

For all experiments, Si chips with a geometry of 3 x 3 x 0.52 mm were used. Part of Si chips was metallized at the bottom with Ti (100 nm) Au (300nm) bilayer. Cu substrates with a geometry of 10 x 25 x 0.93 mm were metallized with Ni(3 µm)Au(1 µm) bilayer. For joints fabrication, TIM AT2M paste from AMEPOX MICROELECTRONICS, Poland, was used. The paste consists of a mixture of Ag spheres (with the size of tens of micrometres), Ag flakes (micrometre size) and a resin. The pin transfer method was used for the paste deposition on Cu substrates. Si chips were pressed into the wet Ag-based paste with a pressure of 0.6MPa. Next, the sintering process was performed in the air. The following sintering procedure was applied: heating rate 5K/min, two steps sintering: 30min&160°C + 60min&230°C. The pressure sintering process was conducted using hot plates where the structure was heated from the bottom and the top and the applied pressure was 2.4 MPa. For pressure-less sintering, the sample was placed on a hot plate and the sample was heated from the bottom.

Two main properties of TIM joints were investigated: adhesion and thermal properties. For adhesion measurements, shear tests were performed, using the IPC-TM-650 standard. Thermal properties of the TIM layer were measured using test samples and a specific experimental stand, the description of which is presented below.

The stand consists of two long Cu bars (10 mm x 10 mm cross-section) where the sample is being inserted between the bars. The heat flows from the heated top bar to a water-cooled bottom bar. Knowing the heat flow along Cu bars and the temperature gradient between them it is possible to calculate the total thermal resistance of the stand. Subsequently, Cu foil with a cross-section of 10 mm x 10 mm and thickness of 0.93 mm was inserted between the bars to serve as a test sample which allowed the determination of thermal resistance of the stand and Cu foil. In the next step, the thermal resistance of Cu foil was extracted from the sum of stand and sample resistance and the internal stand thermal resistance was calculated as 1.95 K/W. So, in the next step will be possible to insert in the stand test sample (Cu foils one side NiAu coved and joined by investigated TIM material). The thermal resistance of the test sample in the stand was measured and after extracting the value 1.95 K/W the test sample thermal resistance was obtained. So, the sample thermal resistance consists of the following thermal resistances: two Cu foils one side finish NiAu, two interfaces between Au metallization and investigated TIM materials as well as TIM materials itself.

3. Results

3.1. Adhesion measurements

A general view of a cross-section of a joint between Si chip with TiAu metallization and Cu substrate with NiAu plating is shown in Fig. 1. A lot of voids in the TIM layer is observed. Results of the adhesion measurement are presented in Tab. 1. It was found that adhesion to bare Si as well as to Si with TiAu metallization is in the range of 10 MPa or better. Good adhesion is observed despite voids presence. It can be found that the adhesion to Si with TiAu metallization is slightly better than to bare Si. In Fig. 2 and Fig. 3 it was shown the cross-section of pressure-less joints made between NiAu plated Cu substrate and bare Si and Si with TiAu metallization, respectively.

The nature of a connection between bare Si and TIM AT2M paste is adhesion type, Fig. 2. Detailed analysis in point 2 shows the only presence of Ag (99.4 wgt%) and resin, which indicates that no intermetallic compound between Si and Ag is observed. The black area in joints is representative by resin.

In the case of the bare Si chip, most probably only resin is responsible for adhesion.

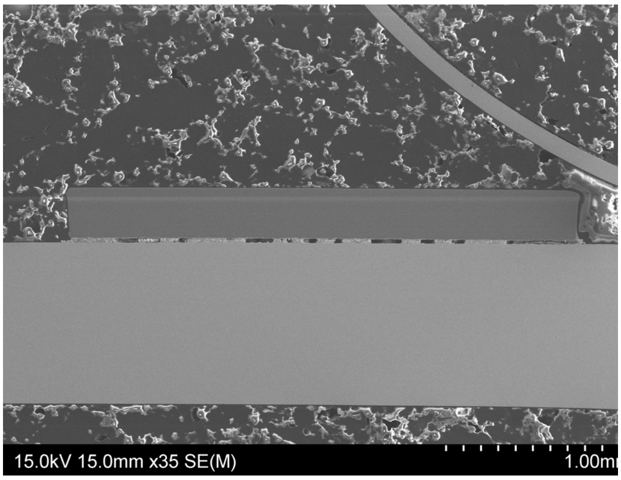

Fig.1 Cross-section of an adhesive joint between NiAu plated Cu substrate and Si chip with TiAu metallization fabricated using a pressureless sintering process

Table 1. Results of adhesion measurements of joints made using TIM AT2M paste

Metallization of		Pressure	Thick	Adhesion
Cu Substrate	Chip		[µm]	[MPa]
NiAu	TiAu	No	30	12.1±3.3
		2.4 MPa	15	13.7±5.2
	Bare Si	No	22	10.6±3.2
		2.4 MPa	15	9.0±1.4

Figure 3 illustrates the cross-section through a pressure-less joint between NiAu plated Cu substrate and Si chip with TiAu metallization. Interface analysis between TIM AT2M paste and Si chip with TiAu

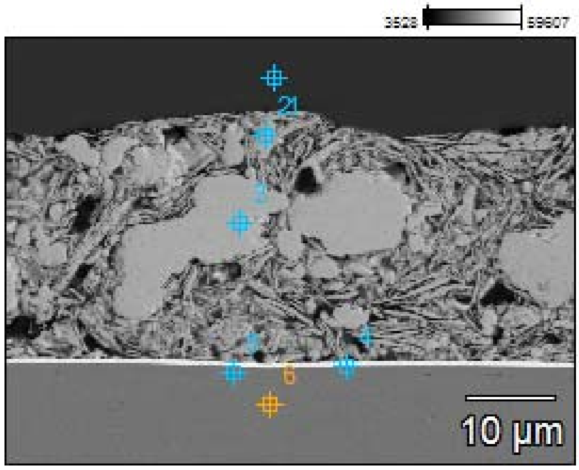

Fig. 2. Cross-section of pressure-less joint: bare Si + TIM AT2M paste + NiAu plated Cu substrate

metallization in point 2, Fig.3, shows mainly the presence of Ag and Au (2.0%O; 3.2%Si; 87%Ag and 7.8%Au) but chemical analysis in point 4 which is placed in the region of TIM AT2M /NiAu plated Cu substrate interface shows also mainly the presence of Ag and Au (1.5%Cu; 72.2%Ag and 26.2%Au). So, possibly short-range diffusion between Au and Ag occurs and this phenomenon is partially responsible for adhesion. At this point we may conclude that two factors are responsible for a good adhesion: the presence of resin in paste and surface interdiffusion between Ag paste and Au metallization on Cu substrate or Si chip.

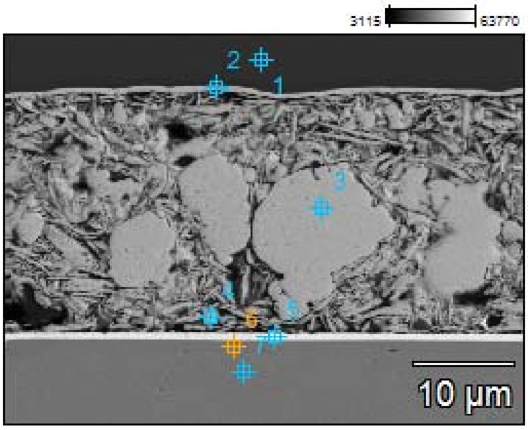

Fig. 3. Cross-section of pressure-less joint: Si with TiAu metallization + TIM AT2M paste + NiAu plated Cu

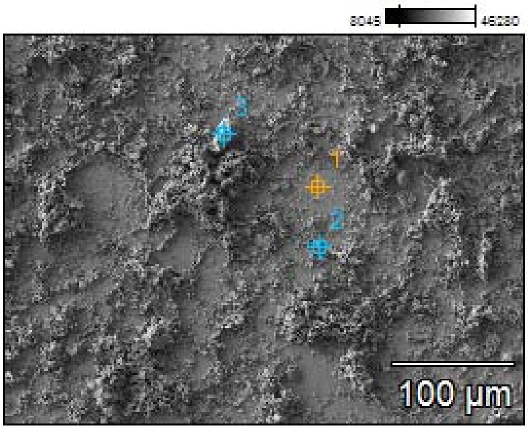

Fig. 4. Interface on NiAu plated Cu substrate after shear test, pressureless joint

Fig.4 and 5 is shown the interface on NiAu plated Cu substrate after shear tests. In Fig.4 shear interface for the pressureless joint is shown. On NiAu plated Cu substrate two different areas are observed. On the majority of surface area, Ag particles adhere to Au metallization, however on small areas pure surface of the substrate is can be seen. Analysis in point no. 1 (Fig.4, Tab.2) clearly shows that there is no connection between Au on the substrate and Ag particles. Analysis in point no. 2 shown areas where diffusion between Au from the substrate and Ag particles occurred.

For pressure joint (2.4 MPa) on a large substrate surface, the Ag particles well adhered to Au substrate metallization. Analyse in point no 1 (Fig.5, Tab.2) clear show that some surface diffusion between Ag particles and Au metallization occurs. For pressure joints, Ag particles better adhere to Au substrate metallization than for pressureless joints. The Ag grains adhere to Au metallization.

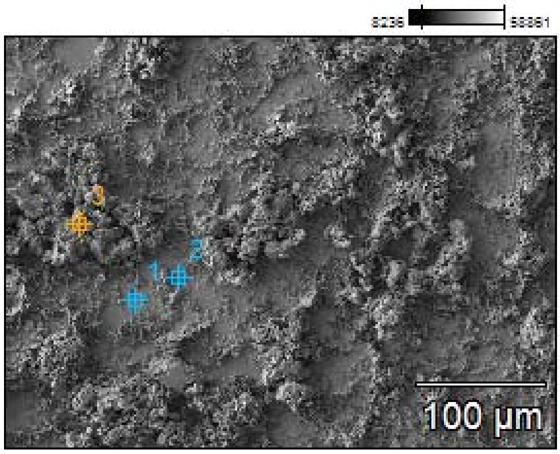

Fig. 5. Interface on Cu substrate with NiAu after shear test, pressure joint 2.4 MPa

Tab. 2. Material composition in measured points from Fig. 3 and Fig.4

Joint Type	Measured points		
	No 1	No 2	No 3
Pressureless Joint, Fig.4	2.7%Ni; 5.8%Cu; 91%Au	3.2%Cu; 93.2%Ag; 3.0%Au	99.4%Ag
Pressure joint 2.4 MPa, Fig.5	2.1%Ni; 93.7%Au; 3.7%Ag	95.5%Ag; 3.9%Au	99.6%Ag

3.2. Thermal measurements

Results of the thermal resistance measurements of samples consisting of two Cu sheets joined by TIM AT2M paste are shown in Tab.3. It was found that the thermal resistance of joints made of TIM AT2M paste is very good, below 0.3 K/W, and that by applying pressure during sintering it was possible to reduce the thermal resistance almost two times. It was caused by thickness reduction and better Ag particles connections with Au metallization on the substrate.

Tab.3. Results of thermal measurements of joints made by TIM AT2M paste

Cu foils top and bottom	Pressure	Thickness [μm]	Sample thermal resistance [K/W]
Cu with NiAu	No	36	0.28; 0.29
	2.4 MPa	14	0.10; 0.11

3.3. Thermal ageing and thermal cycling stresses

Independently of the adhesion and thermal measurements the test samples were subjected to preliminary thermal ageing: 144 hours & 125°C in air and 20 thermal cycles stresses: -20°C÷+100°C. Such stresses did not degrade the mechanical properties of the joints, Tab. 4 and Tab. 5.

Tab. 4 Adhesion changes after ageing test at 125°C

Sub./chip metallization	Press	Adhesion [MPa]	
		As received	After 125°C &144h
Cu with NiAu / Si with TiAu	No	11.5 ± 0.6	12.3 ±2.8
	2.4 MPa	10	12.7

Tab. 5 Adhesion changes after thermal cycling tests

Sub./chip metallization	Press	Adhesion after 20 cycles -20°C +100°C [MPa]
Cu with NiAu / Si with TiAu	No	9.5 ± 0.8
	2.4 MPa	7.3 ± 1.9

4. CONCLUSIONS

The adhesion and thermal properties of TIM joints created between bare Si chips as well as Si chips with TiAu metallizations manufactured by TIM AT2M paste were investigated. It was found that for good mechanical properties of joints created between bare Si and Ag-based TIM AT2M paste is probably responsible for resin content in the paste. The connection has an adhesion type nature. Opposite the connection between Au metallization on Si chip as well as on Cu substrate, the good mechanical properties are guarantee by both, resin and small range diffusion between Ag and Au. By applying pressure during sintering the role of diffusion type connection increase. Short time annealing at 125°C and thermal cycling -20°C÷+100°C do not destroy good mechanical properties.

Joints created between two Au metallized Cu sheets by TIM AT2M paste has good thermal properties, their thermal resistances are better than 0.3 K/W. By applying pressure during sintering, it is possible to reduce thermal resistance almost two times.

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