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Metal Wafer Bonding for MEMS Devices

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Abstract. Metal films can be used as bonding layers at wafer-level in MEMS manufacturing processes for device assembly as well as just for electrical integration of different components. One has to distinguish between two categories of processes: metal thermo-compression bonding on one side, and bonding with formation of an eutectic alloy layer or an intermetallic compound. The different process principles determine also the applications area for each. From electrical interconnections to wafer-level packaging (with special emphasis on vacuum packaging) metal wafer bonding is a very important technology in MEMS manufacturing processes.

Key words: wafer bonding, MEMS, metal layers, eutectic bonding, thermo-compression bonding.

1. Introduction

Wafer bonding plays an important role in Micro-Electro-Mechanical Systems (MEMS) applications as a technique used for joining substrates. The need to address the large applications variety was the driving force for the development of different wafer bonding processes.

Among the wafer bonding processes currently used for industrial applications can be mentioned direct bonding (also known as fusion or molecular bonding - adhesion is generated by chemical bonds between the molecules on the two surfaces) [1], anodic bonding (used to bond a Si wafer to a glass wafer - bond appears due to an oxide layer grown at the interface) [2], adhesive bonding (using intermediate layers, typically polymers) [3, 4], eutectic bonding (bond occurs through an eutectic alloy layer grown at the interface) [5] or intermetallic bonding [6] and thermo-compression bonding (metal bond – bond occurs between two metal surfaces pressed together under heating) [7].

Physical, chemical, electrical, and thermodynamic properties of the given material play a crucial role in the feasibility of the bond process and must be considered already at the design stage of an application. Wafer bonding process selection is based on various criteria related to the materials used (substrates types, bonding temperature and thermal profile) as well as to the desired application (type of bond – mechanical connection, electrical or thermal conductivity of interface, optical properties and device working temperature).

This paper proposes an overview of wafer boding processes based on metal layers and introduces the process selection criteria for metal bonding.

2. Basics

Apart from direct (fusion) bonding, processes based on "bonding layers" are extensively used in MEMS manufacturing. The intermediate layers choice is made based on required processing temperatures as well as on other materials characteristics (e.g. specific outgasing or thermal/ electrical/ optical conductivity).

Wafer bonding using metal bonding layers is a technique suitable for applications requiring good thermal conductance and applications in which electrical conductivity is required (e.g. for 3D TSV – Through-Si Vias - applications).

Two different principles are governing metal bonding: alloying (eutectic alloy or intermetallic compound formation), and metal atoms diffusion by thermo-compression bonding.

From wafer bonding process and equipment perspective there are major differences between the two types of processes (Table 1).

Table 1. Main process features for eutectic and metal thermo-compression wafer bonding

Parameter	Eutectic WB	Thermo-compression WB
Temperature	Au:Sn – 300°C Au:Si – 380°C Au:Ge – 380°C Al:Ge – 440°C Au:In – 510°C	300°C – 500°C (Au-AU, Cu-Cu, Al-Al)
Temp. range	$T_{eutectic}$ + (10°C – 20°C)	100°C – 200°C (correlate with contact force)
Surface quality	Low	High
Contact force	Low	High
Atmosphere	Inert or reducing	Inert or reducing
Liquid phase	Yes	No

In some situations there is a state of confusion regarding the two types of metal bonds and this impacts mainly on further experiments design.

2.1. Eutectic wafer bonding

Eutectic alloy is formed at the bonding interface in a process which goes through a liquid phase: for this reason, eutectic bonding is less sensitive to surface flatness irregularities, scratches, as well as to particles contamination compared to the direct wafer bonding methods.

Some of the main eutectic alloys used for wafer bonding applications are listed in Table 1. For a successful eutectic bonding process it is very important that bonder assures a good temperature uniformity across the entire wafer surface and also to control very well the temperature value (avoid overshooting the set point) in order to have a reliable process.

An example of a thermal profile general shape is presented in Fig. 1.

Experimental results showed that good quality bonded interfaces are obtained when temperature is first raised to a value lower than the eutectic temperature, maintained constant to reach uniform heating of both substrates, than increased again to a temperature exceeding the eutectic point with 10–20°C (depending on specific process conditions and on substrates restrictions) followed by cooling down to a temperature below the eutectic temperature. Temperature ramp for heating/cooling processes are important and have to be selected based on substrates materials (to avoid thermal shock for dissimilar materials) as well as on device requirements (heating/cooling in vacuum or both or only single wafer in contact with heaters).

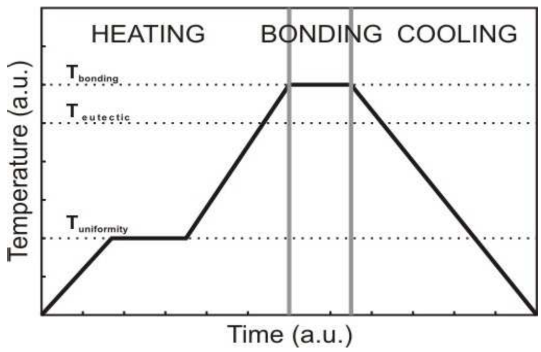

Fig. 1. General principle of eutectic wafer bonding thermal profile.

Eutectic wafer bonding does not require application of high contact force. Due to the liquid phase formed during the process, high contact force results always in metal squeezing out of the interface, resulting in poor interface layer uniformity as well as contamination of the bond tools and bond chamber. The role of the low contact force required is just to ensure good contact of the two wafers and good contact of the two heaters of the bonder with wafers' back sides.

Eutectic wafer bonding is a good candidate to high-vacuum applications as this process has a very low specific outgasing due to the use of only high purity components. The liquid melt formed during process can only enhance the high vacuum compatibility by allowing high quality sealing even on non-perfect surfaces.

2.2. Diffusion soldering

For some applications the process temperatures must be lower than the bonding temperatures of the most usual eutectic alloys (300°C–400°C). In such situations an alternative process can be used, which results in an inter-metallic compound bonding layer. In literature this process is known under different names: "diffusion soldering" [8] or Transient Liquid Phase (TLP) bonding [6, 8].

This bonding process is an advanced type of solder bond that can form high-quality hermetic seals at lower temperatures than other bonding technologies. This technique uses one thin metal layer (typically 1–10 μm thick) which during a thermal process inter-diffuses with its bonding partner forming an inter-metallic compound layer with re-melting temperature higher than the bonding temperature [8].

Among metal systems forming intermetallic compounds at temperatures below the eutectic point Cu:Sn system was reported in literature mainly for die bonding ("Chip-to-Wafer" – C2W [9, 10]) while Au:In was mainly reported for wafer-level vacuum packaging [8, 11].

Same as eutectic wafer bonding, diffusion soldering bonding is attractive for MEMS vacuum packaging as the process is completed at low temperatures (150°C–300°C), bonding layers are metals (low permeability), and they can planarize over surface defects or particles resulting from prior processes due to surface wetting by the molten metal.

2.3. Metal thermo-compression wafer bonding

In thermo-compression bonding process the two surfaces adhere to each other due to a metal bond established between two metal surfaces pressed together under heating. The bonding mechanism is enhanced by the deformation of the two surfaces in contact in order to disrupt any intervening surface films and enable metal-to-metal contact. By heating the two metal surfaces the contact force applied for the bond process can be minimized due to metal softening. High force uniformity across the bonding area enables high bonding yield.

Several metals are used for metal thermo-compression wafer bonding, as Au-Au [7], Cu-Cu [12] or Al-Al [13]. These are considered interesting for wafer bonded MEMS applications mainly due to their availability in main microelectronics applications. Their use for one or another type of applications is conditioned by the type of substrates or technology used (e.g. no Au-containing substrates can be processed in CMOS fabs).

This type of wafer bonding process is used mainly when electric interconnections between the two wafers are required. However, metal thermo-compression bonding is used also in vacuum packaging applications [13].

3. Discussion

The choice of the appropriate metal system and bond process are crucial and has to consider aspects related to substrates, device requirements and process conditions.

3.1. Materials-related criteria

The type of substrate may determine the choice process-type (eutectic/diffusion soldering or metal thermo-compression) or the choice of the metal based on factors as compatibility of bonding material with other materials or processes used for manufacturing process. Thus for example, Cu is always preferred to Au if there is a major concern of Au diffusion in a thermo-compression process.

One important challenge in metal wafer bonding is surface oxidation. As most of the metals used as bonding layers oxidize relatively easy when exposed to ambient conditions it is important to prevent this from happening. For eutectic/diffusion soldering it is possible to protect the fast-oxidizing component by deposition of very thin layer of the other component of the alloy (e.g. a thin layer of Au is evaporated on top of the Sn or In layers for Au:Sn or Au:In systems – the Au layer doesn't change the process kinetics but prevents Sn or In oxidation).

In case of metal thermo-compression bonding process the situation is different: if for Au surface oxidation is not of concern (in this case organic contamination may be a considerable issue and would require typically oxygen plasma cleaning prior to bonding), for Cu and Al oxide layer on the bonding surfaces is a major topic.

As Cu layers are typically fabricated in a damascene process, during post CMP cleaning the Cu surface can be coated with an organic layer (e.g. tolyltriazole or benzotryazole): this organic layer will protect Cu surface from contact with air and during the bond process will evaporate leaving no residuals on the surface (evaporation temperature $\sim$250°C–300°C). For Al thermo-compression bonding the oxide layer is one of the main problems. Some groups reported results improvement by increasing the contact force during the process [13].

3.2. Process-related criteria

An important process parameter is the atmosphere composition inside the bond chamber during process: in order to prevent oxidation an inert gas may be used (nitrogen or argon). In order to be even more efficient, a forming gas or formic acid vapor gas atmosphere can be used: besides the oxidation prevention some oxide may be reduced in this case. Considerable improvement of bond results was observed if Cu wafers were first heated at 300°C in forming gas (4% hydrogen content mixed with an inert gas) for few minutes prior to bonding.

Equipment needs to be well set in order to provide good temperature uniformity across the bonding area and very uniform distribution of contact force.

The wafer bonding results can be quantified by inspecting the bonding lines integrity (e.g. by Scanning Acoustic Microscopy – SAM, Figs. 2, 3). In SAM imaging, an acoustic signal reflection is caused by a material density change along the signal pathway (acoustic impedance variation). The amplitude of the reflected signal correlates to the defect density of the interface and is represented as a grey scale image. Black in the SAM image represents well bonded area (no signal reflection) while the white area in the image indicates lower quality bonded area (reflected signal from bonded interface). In Fig. 2 is shown a SAM image of a Si wafer pair bonded with

Al-Al thermo-compression process. It can be observed that the bond is defect-free with the exception of two non-bonded lines at the major wafer flat (the wafers IDs - laser marks were not planarized during metallization) and a small area defect at the edge (left side).

Fig. 2. SAM image of a 150 mm Si-Si bonded wafer pair bonded with Al-Al thermo-compression process.

Figure 3 shows SAM image of a Si wafer pair bonded with Cu-Cu thermo-compression process. The bond is completely defect-free.

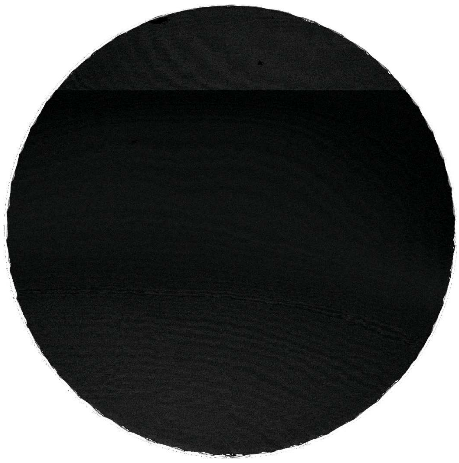

Fig. 3. SAM image of a 300 mm Si-Si bonded wafer pair bonded with Cu-Cu thermo-compression process.

Another quality investigation of the metal bonds can be performed by inspecting bonding lines integrity and material composition (e.g. by Scanning Electron Microscopy cross section analysis – using EDAX the composition variation inside the intermetallic layer can be determined).

3.3. Wafer-to-wafer alignment

Wafer bonding process is strongly influencing the alignment accuracy. Table 2 summarizes the main wafer bonding processes used for aligned wafer bonding and shows main process feature with impact on wafer-to-wafer alignment accuracy.

Table 2. Main wafer bonding process features with impact on wafer-to-wafer alignment accuracy

WB Process	Temp (°C)	Interface (process)	Accuracy (μm)
Thermo-compression	300 – 400	Solid	±0.6
Eutectic/Soldering	200 – 400	Liquid	±1.0

Among the most significant factors influencing alignment accuracy can be mentioned compression of intermediate bond layers which induces shifts (for bonding with intermediate layers as for eutectic bonding, or diffusion soldering bonding), different thermal expansion of the two substrates which induces run-out-type errors and the z-travel range of the wafers when brought in contact (e.g. given by thickness of the spacers used in the bond setup). For such bond processes typically two alignment specifications are defined: post-alignment accuracy (accuracy provided exclusively by the optical alignment equipment) and post-bonding accuracy (the final accuracy measured after bonding, when the bonded interface is already rigid).

4. Conclusions

Metal wafer bonding is an important technology for MEMS and 3D interconnects applications. Apparently simple process, this category of wafer bonding has very strict requirements in terms of substrate preparation (including here the metal bonding layers), handling through the process flow as well as the right choice of the process conditions.

Bonding surfaces require special attention as the most used metals are sensitive to oxidation. Diffusion inside the substrate may be another undesired effect which can be prevented by using diffusion barrier layers.

Metal wafer bonding is compatible with high vacuum packaging applications allowing encapsulation of vacuum levels higher than 10^{-3} mbar, required by new applications as high frequency resonators, optical switches or IR sensors.

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