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Development of CMOS Compatible Bonding Material and Process for Wafer Level MEMS Packaging Application under Harsh Environment

Vivek Chidambaram+, Ho Beng Yeung and Gao Shan

Institute of Microelectronics, A*STAR (Agency for Science, Technology and Research),
11 Science Park Road, Science Park II, Singapore -117685.

Abstract. CMOS compatible metallic hermetic sealing using Al-Ge eutectic alloy for packaging MEMS devices for harsh environments has been developed. The effects of various bonding parameters on the bond quality have been extensively reported. The reliability of this eutectic joint subjected to high operating temperatures involved in deep oil well logging application has been investigated with the specific focus on shear strength and hermeticity. A new configuration for stacking Al-Ge thin films has been demonstrated in order to tackle the issue of loss of Ge prior to bonding since native Ge oxides are soluble in DI water. The impact of solid-state aging prior to Al-Ge eutectic bonding has also been investigated. It has been determined that solid-state aging prior to Al-Ge eutectic bonding is a pre-requisite in order to attain a reliable hermetic sealing. Furthermore, the changes in microstructure with respect to thermal aging at 300°C up to 500 hours have also been presented since the minimum requested continuous operating time by the energy industry is 500 hours at 300°C. No thermal degradation of the Al-Ge eutectic joint at 300°C for 500 hours was observed. This could be credited to its composite microstructure. Thus, the overall conclusion of this work is that Al-Ge eutectic bonding is a prospective candidate for this application.

Keywords: Hermeticity, eutectic, composite, solid-state aging

1. Introduction

Nowadays, the pressure to reach new natural oil and gas resources is increasing as worldwide consumption grows. Moreover, higher quality crudes such as those needed for advanced petroleum fuels and natural gas are located deeper than other crudes Therefore; energy companies are forced to drill deeper to find new reservoirs and thus, adding to the harshness of the ambient experienced by the well logging instruments. These well logging instruments can be exposed to temperatures as high as 300°C [1]. The state of the art in electronics packaging for rugged electronics for oil-well logging applications is combining several different MEMS sensors and companion sensing electronics into single package forming complex systems.

Hermetic sealing of MEMS sensors is indispensable in order to ensure their reliable operation and also to provide protection during fabrication such as dicing. Metallic hermetic sealing is now widely being used for electronics packaging due to its slow permeability rate [2]. In the present work, the focus is given on the development of the CMOS compatible metallic hermetic sealing since the sensor devices require the package to effectively isolate the chip physically from its environment by hermetic sealing of the package so that the sensor performance could be maintained reliably under harsh environment. CMOS compatible MEMS packaging is generally preferred since it facilitates the integration of MEMS devices with driving, controlling and signal processing electronics [3,4]. Al-Ge system has been chosen in this work as a potential candidate since both these metals are CMOS compatible.

+ Corresponding author. Tel.: + 65 67705430; fax: + 65 67745747
E-mail address: nachiappanvc@ime.a-star.edu.sg.

The bonding parameters that comprehend bonding temperature, bonding pressure, bonding force and sealing ring width were optimized for the Al-Ge eutectic bonding at wafer level. The optimization of bonding parameters has been executed with the objective of secluding void-free bonds. The impact of solid-state aging prior to bonding on the bond quality has been investigated in this work. The high-temperature stability of microstructures and mechanical properties of the Al-Ge eutectic joint at 300°C are extensively reported.

2. Phase Diagram Analysis for CMOS Compatible Bonding Material

CMOS compatible MEMS packaging is generally preferred since it facilitates the integration of MEMS devices with driving, controlling and signal processing electronics and thereby, improves performance, lowers manufacturing costs and allows for the individual development of the micromechanics and microelectronics technology. Most current MEMS packaging applications either use glass frit and anodic bonding or metals such as gold that are not compatible with CMOS front end processing [5]. Anodic and glass frit bonding also suffer from severe alkali-ion and particles contamination in addition to having large seal width requirements. Moreover, improved hermeticity could be achieved by metallic sealing due to its relatively lower permeability rate.

Although there are a number of binary metal eutectics in the range between 300°C to 425°C, metallization of device wafer adds significant process complicity and incompatibility with CMOS foundries. Al is the best CMOS compatible metal since it is already being used as bond pads for CMOS wafers and creates no issue of contamination in the standard CMOS clean room environment. Aluminum with germanium possesses a eutectic melting temperature at 420°C as illustrated in Fig. 1 which is quite attractive for rugged electronics since in addition to the eutectic melting point, germanium too is compatible with the CMOS process. Thus, Al-Ge could be particularly applicable to 3D integration since both the materials involved are CMOS process compatible and could also provide a conductive path upon bonding. Moreover, their eutectic melting temperature is safe for subsequent board mounting process since it is much higher than surface mounting reflow temperatures (~270°C). Among the CMOS compatible metals, aluminum-germanium eutectic possesses the least eutectic melting point i.e. 420°C when compared to the aluminum-copper eutectic (548°C) and aluminum-silicon eutectic (577°C) as illustrated in Fig. 1 [6].

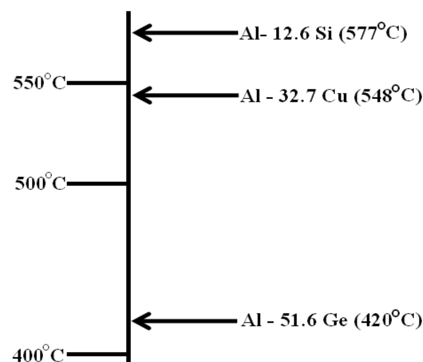

Fig.1. Various possible C-MOS compatible binary eutectic alloys.

3. Experimental Procedure

8" wafers were used for present wafer bonding process and it was prepared with a feature of sealing ring structure on both the substrate and the cap wafers. The width of the sealing ring used in this work is 100 µm. In the Al/Ge system, aluminum readily forms a tenacious oxide that is difficult to remove where as germanium oxide can be stripped off in a dilute HF. Moreover, native germanium oxide (GeO_2) is soluble in water when compared to native aluminum oxide (Al_2O_3). Thus, germanium was stacked above aluminum on both the substrate and cap wafers. The sequence of stacking is as follows Al 0.75µm/Ge 0.43µm/Al/0.25µm/Ge0.16µm. The thicknesses of the stacking layers are chosen in order to maintain the eutectic composition. 0.5µm thick silicon dioxide was deposited on both the cap and the substrate wafers

using the Novellus equipment. The patterning of the sealing ring was done by lithography using 7 µm negative photoresist as a masking material and subsequent lift-off after evaporation. Aluminum and germanium films were deposited sequentially onto the wafers using Innotec ES26C E-beam evaporator in a single pump down. The wafers were cleaned by de-ionized water (DI) rinse and spin dry prior to being introduced into the chamber in order to get rid of the surface contaminants as it would impede the quality of the eutectic bonding.

The bonding between the substrate and the cap wafer were conducted in a vacuum atmosphere using wafer bonder (EVG 520) with a bonding force of 10 KN. The bonding pressure was calculated to be around 15.7 MPa. The bonding was executed with and without solid-state aging prior to bonding at 475°C for various times ranging from 30 minutes to 90 minutes. The impact of solid-state aging prior to bonding at 400°C for times ranging from 30 to 90 minutes on the bond quality has also been investigated. After bonding, the bonded wafers were investigated for voids using C-mode Scanning Acoustic Microscopy (C-SAM) with a 230MHZ transducer and a spatial resolution of 5-10µm. Following which, the bonded wafers were diced into 16 mm× 16 mm dies with a dicing speed of 4mm/s using the Disco saw equipment.

The samples subjected to different bonding conditions were mounted and cross-sectioned for scanning electron microscopy. Energy dispersive X-ray analysis was used to study the composition of various phases. The bonded dies were also subjected to thermal aging at 300°C for 100, 300 and 500 hours. The aged samples were again mounted and cross-sectioned and the microstructure characterization was executed using the SEM-EDX analysis. The mechanical property of the bonded joint at various bonding and aging conditions were evaluated using the shear tests. 5 samples were evaluated for each bonding and aging conditions. The shear test was conducted with a shear tester (BT4000Dage) using a speed of 100 µm/s. The high-temperature mechanical testing of the joint was performed by hot shear at 250°C.

4. Results and Discussion

4.1. Impact of solid-state aging prior to bonding

The Al-Ge eutectic bonding was executed with and without solid-state aging and the bond quality was evaluated by C-SAM and cross-section. It was determined that without solid-state aging prior to bonding, hermetic Al-Ge eutectic seal could not be achieved as illustrated in Fig. 2a. The leekage of water during C-SAM analysis confirms the lack of hermeticity of Al-Ge eutectic joint. This is also affirmed by the cross-section of the Al-Ge eutectic joint (Fig. 2b). The possible explanation could be direct eutectic bonding without solid-state aging results in the formation of mushy region i.e. solid phase dispersed on a liquid phase during bonding; as the respective melting points of Al and Ge are 660°C and 938°C and their eutectic melting point is 420°C.

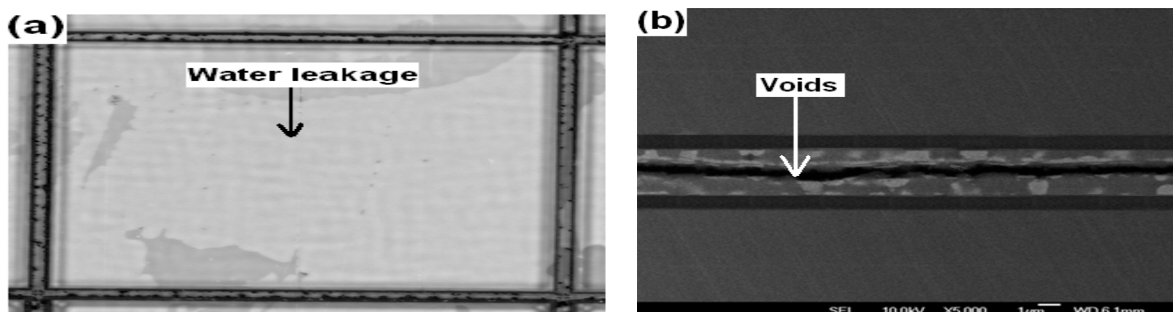

Fig. 2. Direct Al-Ge eutectic bonding without solid-state aging (a) C-SAM analysis (b) Cross-section

It was determined that to achieve a uniform concentration distribution at overall joint, a relatively longer dwelling time before melting is necessary to facilitate sufficient inter-diffusion and chemical reaction between Al and Ge and thereby, ensure a homogenous eutectic composition at the interface prior to bonding. A reliable hermetic Al-Ge joint was attained by subjecting it to solid-state aging at 400°C for 90 minutes prior to bonding at 475°C for 80 minutes. It was also determined that by increasing the bonding pressure, the

solid state aging time could be reduced. Fig. 3 exemplifies the necessity of solid-state aging prior to bonding in order to seclude a perfect hermetic sealing ring. In a wafer-level bonding due to the unevenness in the bonding force distribution, the bonding quality of the dies in the center of the wafer is slightly inferior to the rest.

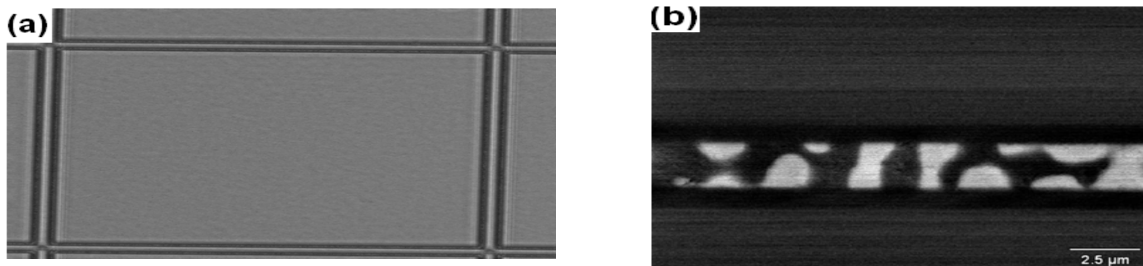

Fig. 3. Al-Ge eutectic bonding subjected to solid-state aging prior to bonding (a) C-SAM analysis (b) cross-section.

4.2. Wafer level bonding process optimization

The bonding parameters were optimized with the multiple objectives as mentioned below:

- Reduction of voids in the joint
- Thickness of the diffused zone. Higher the better
- Prevention of splashing and delamination

It was determined that a short bonding time would be sufficient to secure a hermetic Al-Ge joint provided that a high bonding pressure i.e. in the range of 20-25 MPa is employed since it ensures a good contact between the wafers and facilitates inter-diffusion during solid-state diffusion. On the contrary when a relatively low bonding force like the one employed in this work; relatively longer time for solid state diffusion and bonding is required. 100 µm sealing ring width, die size of 16×16mm and the maximum bonding force of 10 KN that can be exerted by the available EVG bonder was employed and the resultant bonding pressure is 15.7 MPa. The optimum bonding temperature was determined to be 475°C since the bonding temperature should at least 30°C − 40°C higher than the eutectic melting temperature. Secondly, very high temperatures would result in the degradation of the MEMS devices and also the CMOS process by itself is not compatible with temperatures in excess of 500°C. The optimized low pressure bonding profile in the context of Al-Ge eutectic bonding used for the microstructure characterization in this work is illustrated in Fig. 4.

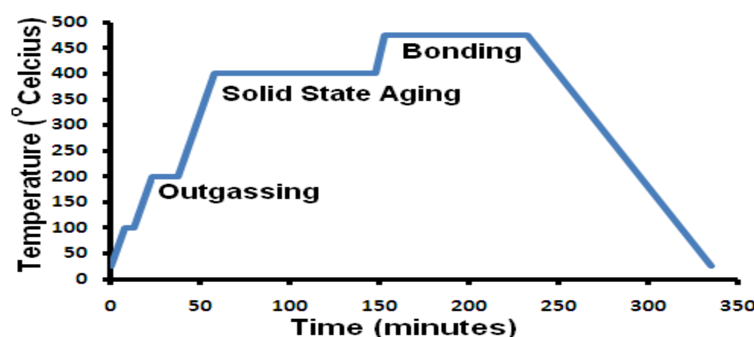

Fig. 4. Optimized low pressure bonding profile with solid-state aging prior to wafer level Al-Ge eutectic bonding.

4.3. High-temperature stability of microstructures and mechanical properties

The microstructure of Al-Ge eutectic joint possesses a composite microstructure i.e. hard (Ge) phase dispersed on the matrix (Al) phase as depicted in Fig. 5. Al is absolutely insoluble in the (Ge) phase and vice versa. Hence, these two phases remain as distinct phases in the microstructure and no intermetallic phases are formed between them. When subjected to aging at 300°C up to 500 hours, no major change in the morphology was observed in the microstructure. Slight coarsening was observed in the samples that were subjected to aging at 300°C for 500 hours.

No major variation in the shear strength before and after thermal aging was observed. This could be attributed to the stability of the microstructure at 300 °C as the homologous Temperature is only 0.83. The slight deterioration in the shear strength of the samples subjected to aging could be attributed to the coarsening of the (Ge) phase which in turn would retard the composite strengthening mechanism of the (Al) matrix by the (Ge) Phase. The hot shear testing at 250 °C confirmed the loss of strength at high-temperatures is minimal compared to other candidate alloys in this regime. Therefore, Al-Ge eutectic is a prospective candidate for this application. The average shear strength listed in Table 1 for each condition is the mean of ten values. The hot shear testing at 300°C could not be executed due to the limitations of the equipment.

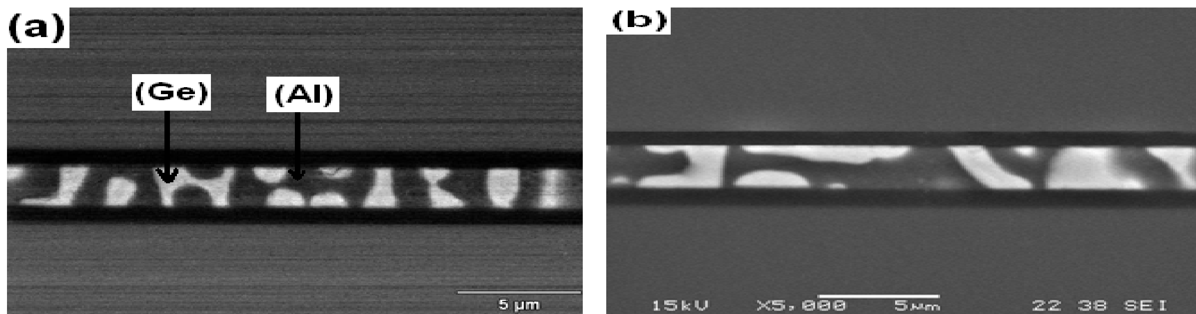

Fig. 5. SEM-SEI micrographs of the Al-Ge eutectic joint after thermal aging demonstrating the high-temperature microstructural stability (a) 300°C – 100 hours (b) 300°C – 500 hours.

Table 1: Average shear strength of Al-Ge eutectic joint subjected to various aging conditions.

Sample condition	Room shear		Hot Shear at 250°C	
	Shearing Load (Kg)	Shear Strength (MPa)	Shearing Load (Kg)	Shear Strength (MPa)
Without thermal aging	29.09	45.73	28.35	44.57
Thermally aged at 300°C for 100 hours	25.29	39.76	24.50	38.51
Thermally aged at 300°C for 300 hours	26.71	41.99	25.05	39.38
Thermally aged at 300°C for 500 hours	24.18	38.01	22.88	35.97

4. Concluding Remarks

Based on the present work's findings, it can be concluded that Al-Ge eutectic is a prospective candidate for hermetic sealing application for MEMS devices for harsh environments such as the oil well logging application. It has been determined that solid-state aging prior to this eutectic bonding is a pre-requisite in order to attain a reliable hermetic sealing

5. Acknowledgement

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