

Bonding with Al Metallurgies for 200mm MEMS Devices

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Abstract

Aluminum metallization is used frequently in MEMS device structures and offers the potential to serve as a sealing metallurgy during device packaging steps. The vast majority of MEMS devices are sealed using anodic or glass frit seal rings to create hermetic packages for the accelerometer, pressure sensor or gyroscope markets. However, metal seals would enable smaller device geometries by providing for high hermeticity levels which enable seal ring shrinkage and device geometry scaling to smaller sizes. Combined with the gradual transition from 150mm to 200mm wafer diameters MEMS fabrication costs are able to keep pace with rapidly emerging consumer markets for their traditional products.

Key words: wafer bonding, aluminum, eutectic bonding, MEMS

Introduction

There are two broad categories of metal seals utilizing aluminum based metallurgies; diffusion type bonds and eutectic bonds. The main advantage of the eutectic alloys is that the sealing ring will melt and, under controlled flow mechanics, it will accommodate surface roughness and disparities. In this way the eutectic metal bonds have similar advantages to glass frit processing. Diffusion bonding, on the other hand, requires intimate contact between the two surfaces and places limits on the surface topography that is acceptable.

The key components to control in Al based wafer bonding is the aluminum oxidation and performance of the bonder. The aluminum metallurgies are more demanding than other metal based bonds that use copper or gold. Working through these choices will enable users to implement wafer level packaging with either diffusion or eutectic reactions successfully.

Oxidation

Most noble metals experience oxidation. However aluminum spontaneously oxidizes at very low partial pressures of oxygen. In fact, using the Ellingham diagram (see figure 1) it is possible to determine that aluminum will reduce most other

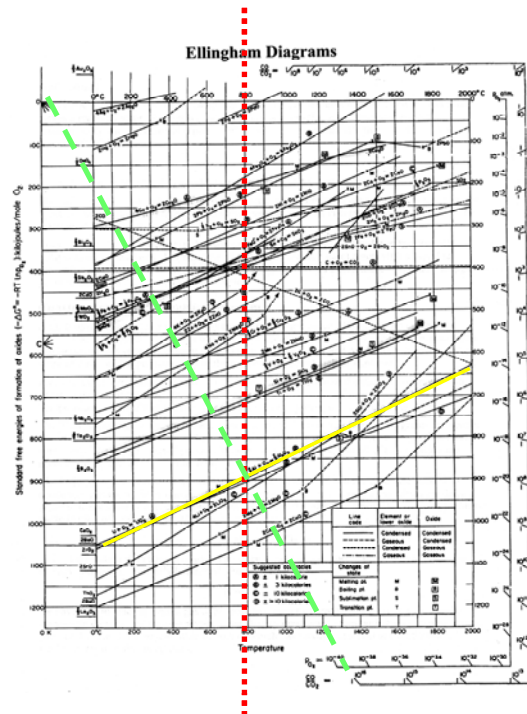


Figure 1. Ellingham diagram for the oxidation of various material. The intersection of the reaction line (yellow) with the green line gives the vacuum level required to prevent oxidation at the chosen temperature (red line).[1]

common semiconducting materials including silicon and any aluminum surface will oxidize at P_{O_2} levels of $<10^{-40}$ Torr. Considering that production wafer bonding equipment typically achieves vacuum levels of 10^{-5} Torr it is impossible to assume that the aluminum does not oxidize during bonding.

The other important feature of aluminum is that the oxide of this metal is not soluble in the matrix. The solubility limit of Al_2O_3 in aluminum is $<2 \times 10^{-8}$ wt%.[2] This is coupled with studies proving that aluminum does not diffuse through the oxide but that oxygen does diffuse through the Al_2O_3 layer to form additional thickness of oxide.[3] Thus getting two oxide free aluminum surfaces touching is simply not possible.

The situation however is not so dire. When implementing aluminum diffusion bonding the aluminum is alloyed with up to 5% Cu or 2% Zn and others. This is key to diffusion processing with aluminum interlayers. These additions were initially added to decrease the electromigration and hillock formation that is problematic in aluminum interconnects. These ternary additions assist to catalyze oxygen reduction, and improve mechanical properties.

Aluminum forms eutectics with Au, Cu, Ga, As, Ge, In, Si, Sn and Zn. In these systems the binary have less significant oxidation states. In addition the eutectic alloys melt and during the liquid formation the oxide is either dissolved in the matrix or very small precipitates.

Figure 2. SUSS MicroTec CB8 wafer bonding with WEC (wedge error compensation) to ensure parallelism between pressure plates for all bonds.

The other break through for dealing with the surface oxide is the advent of high force bonders such as the SUSS MicroTec CB8 which also comes in production clusters as a module called the CB200. This tool is shown in figure 2. Its key features that are essential for advanced bonding techniques using aluminum are the 90KN force (for diffusion bonds) and the uniform (5% variation) pressure and less than 1% thermal gradients needed for eutectic bonds. In addition the tool uses wedge error compensation to ensure parallelism between the pressure plates.

The strength of Al_2O_3 on the surface of the aluminum bond layers increase the strength of the

film by about two fold. Using the equation below, the biaxial strength of a thin film can be calculated.

$$\sigma = \frac{\sin \phi}{\cos \phi \cos \lambda} \frac{b}{2\pi(1-\nu)h} \left\{ \frac{\mu_f \mu_s}{(\mu_f + \mu_s)} \ln \left[\frac{\beta_s h}{b} \right] + \frac{\mu_f \mu_o}{(\mu_f + \mu_o)} \ln \left[\frac{\beta_o t}{b} \right] \right\}$$

- b is the Burgess Vector 6nm, ν is poisson's ratio 0.31
- h is the film thickness, t is the oxide thickness
- μ_f, μ_s, μ_o , shear moduli of the film, substrate and oxide respectively 24.8 GPa, 66.5GPa, and 178.9GPa
- β_s, β_o numerical constants for substrate and oxide = 2.6, and 17.5
- $\sin/\cos$ term=3.464 is the dislocation angle geometry term

Shown in figure 3 is the increase in strength aluminum with thin layers of oxidation as a function of aluminum film thickness for three thickness of surface oxide.

The ramification of the increased strength is that in order to create nanoscale cracks in the oxide to facilitate aluminum diffusion a very large force must be applied. In addition this large force will be necessary to achieve “compliance” in the layer so that all surface locations are in intimate contact. The benefit is that the film is able to withstand a great deal of force without detrimental effects.

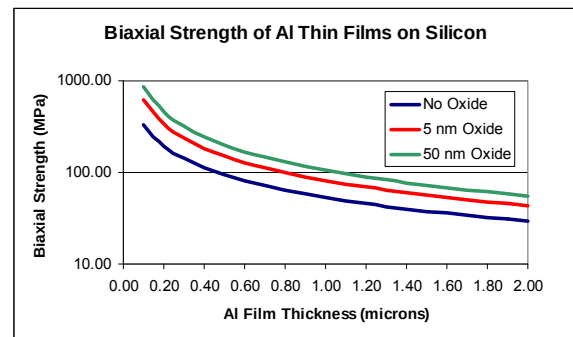


Figure 3. Biaxial strength of aluminum films with and without oxidation. Strength of the film increases by 1.9-2.6 times with 5-50nm of Al_2O_3 formation.

Aluminum Diffusion Bonding

Figure 4. shows a 200mm wafer bonded with a blanket layer of aluminum at the interface. The full coverage of metal makes this bond a good demonstrator of high force bonding. This bond was completed at 90KN on the SUSS MicroTec CB8 bonder at 440C. Although the surface oxide is can not be reduced the bonds are done in vacuum or in a forming gas atmosphere (H_2/N_2) to minimize contamination of additional layers or materials in the device. The Sonoscan[®] acoustic microscope image does not show any microvoid formation or defects at the interface. Typically the metal layers used in aluminum diffusion bonding are 2-5 μ m thick.

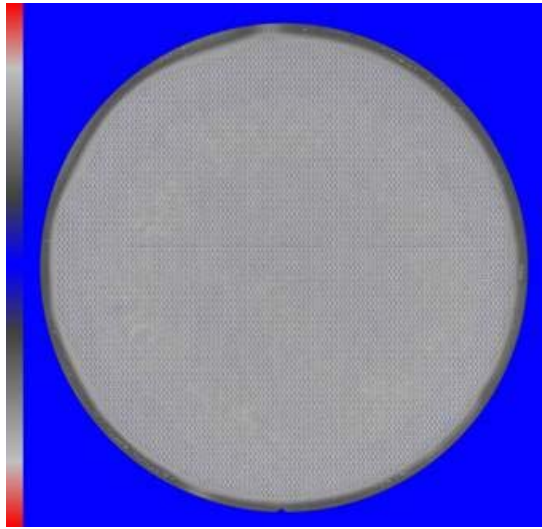


Figure 4. 200mm Wafer level bonding using blanket layer aluminum to form a diffused interface.

When patterned wafers are bonded using the aluminum diffusion bonding process the force can sometimes be reduced because the effective area is decreased. Figure 5 shows a 150mm MEMS device wafer bonded using the same conditions as described above. In most applications the sealing geometry using a metal diffusion bond will experience better hermeticity and the permeability of a metal interface is significantly less than that of glassy materials. Thus the width of the sealing rings can also be reduced to 10's of micrometers versus 100's of micrometers typical in anodic or glass frit technology.

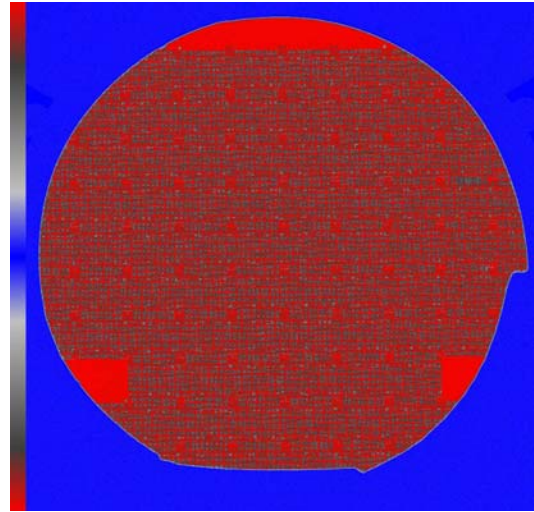


Figure 5. 150mm MEMS device wafer bonded with Al-Al diffusion techniques. Sonoscan[®] acoustic image shows no voids at the bond interface.

A typical seal width is 25 μ m and the thicknesses of most metal seals are 2-5 μ m. Most end users report higher yields resulting from a combination of a higher yielding bond process convoluted with cleaner processing (no metal or sodium contamination) and better hermeticity in the package. The scaling of the devices and reduction in seal rings allows for a higher die density on wafer and offsets any metal processing costs.

Al-Based Eutectic Systems

Table I gives the eutectic compositions and the temperatures for alloys formed with aluminum. The predominant choice among R&D activities over the past two years has been the Al-Ge eutectic for wafer level bonding applications.

Table 1. Eutectic Alloys with Aluminum

Alloy System	Eutectic Temperature	Eutectic Composition
Al-Au	525, 569, 650 °C	78, 60, 1.1 at% Au
Al-Cu	548°C	17 at% Cu
Al-Ge	420°C	28.4 at% Ge
Al-In	639°C	4.7 at% In
Al-Sn	228°C	97.6 at% Sn

Whenever an element forms a eutectic with two other elements which share a eutectic it is possible to form ternary eutectics. Thus a SiGe-Al eutectic reaction is possible and creates opportunities for Al integration schemes with SiGe as well as GaAs and several solder materials.

Eutectic alloys are unique because the metal layers actually melt and reflow at the eutectic temperature and composition. This makes these bonds ideally suited to samples in which the surface roughness or topography may exceed the limits necessary for diffusion bonding methods, roughly 5-10nm RMS. The drawback of reflow bonding methods is controlling the width of the seal rings during the melting and resolidification process.

In order to assist in reflow control it is often advisable to diffuse the two layers together under a relatively high force prior to melting. In this case a two step bonding process is used in which the first step enables the wafers to mechanically attach to one another via diffusion. As an example, you might have a wafer coated with Al-Ge alloy that is placed in contact with another wafer coated with Al-Ge alloy. During the first stage of the bonding recipe an applied force at $T \leq 400^\circ\text{C}$ ($T_e = 420^\circ\text{C}$) is used to atomically mix the metal at the interface via diffusion. This generally takes a few minutes. The second phase of the bonding recipe raises the temperature above the eutectic point while reducing the force to a few kilonewtons. The alloy will melt, reflow and the interface microvoids that might have exists from topology issues are resolved.

Because of the success of a two step process to control the seal ring geometry additional recipe variations have evolved. Another primary method used in eutectic bonding involves putting the two individual elements of the eutectic down on opposite substrates. For example, in this method aluminum would be deposited on one wafer and the Ge on the other wafer. During step one a diffusion process is used to drive the interfacial to mixing and reach the eutectic composition. If intermetallic phase formation occurs this can inhibit successful bonding. After the eutectic composition is reached the force is reduced and the melting/reflow is allowed to occur as described above.

Summary

Aluminum is an important metallization material in IC's and MEMS fabrication. Its excellent adhesion to silicon and various dielectric materials make aluminum a practical choice for inclusion in wafer to wafer bonding technologies. The control of the oxide layer is assisted by using common metallization materials that contain a few percent of ternary additions. Using high force bonding chambers, diffusion reaction can be successfully completed to achieve direct Al-Al interfaces with good contact resistance.

Whenever a compliant interface is needed the eutectic alloys such as Al-Ge are excellent choices. Both aluminum and germanium are CMOS friendly and commonly available. The reflow reaction can be controlled with uniform application of force which is adjusted depending on the reaction pathways. The self planarization of eutectic reflow processes reduces the constraints on surface roughness and waviness needed for void free interfaces.

Alignment using wafer to wafer bonding is a convolution of effects due to the alignment targets, processing temperatures and type of equipment used. Generally it can be expected that aluminum diffusion bonding can achieve $3\mu\text{m}$ or better in overlay accuracy after bonding is complete. The eutectic alloys can achieve similar results but are also dependent upon the thickness of the reflowed layer.

Metal bonding techniques are rapidly replacing traditional bonding methods including anodic and glass frit processing. The metal techniques afford superior device performance and device scaling while enabling vertical integration.

Reference

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