ROOM-TEMPERATURE REACTIVE BONDING BY USING NANO SCALE MULTILAYER SYSTEMS

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ABSTRACT

This paper focuses on room-temperature reactive bonding by using nano scale multilayer systems. The exothermic reaction within the Ti/a-Si multilayer is used as an internal heat source for bonding. Herein, we used lithographical, wet etching and electro-plating procedures to generate very thin integrated reactive multilayer systems. The reaction in the very thin films generated enough heat to self-propagate and to melt tin films. High-speed camera imaging was used to characterize the reaction kinetics and the propagation of the reaction front onto substrates. Furthermore, we demonstrated a strong dependence on substrate material for adhesion after the reaction front has passed.

KEYWORDS

Ti/a-Si multilayer, Integrated multilayer systems, Reactive bonding, Exothermic reaction.

INTRODUCTION

The system integration and packaging of microelectronics and micromechanical systems (MEMS) is increasingly affected by three dimensional chip stacking [1]. Major roles therein play the fabrication of Through Silicon Vias (TSV) and wafer bonding [2]. When it comes to combining different functionalities such as electronics, mechanics or optics the integration of heterogeneous materials with different coefficients of thermal expansion (CTE) is essential. Thus, the bonding process has to fulfill several conditions. The most important requirements on the joint interface are the mechanical strength, electrical conductivity and in most cases also hermetical tightness. Typical bonding processes nowadays are silicon direct bonding, anodic bonding or adhesive bonding [3]. For most applications, however, the bonding process has to be limited regarding to temperature (<400 °C). Therefore new low temperature processes have been under investigation recently [4]. Very promising low-temperature bonding approaches with internal heat sources, such as laser bonding [5].

Reactive bonding is a new low-temperature bonding technique for the packaging of MEMS. This method uses the heat generation with the help of highly exothermic reactions in nano scale multilayer films to melt surrounding layers [6]. Such multilayer typically contains many nanometer thick layers that alternate between two elements that undergo exothermic intermixing. Once the reaction has been initiated with a small thermal pulse a large amount of heat is generated in the so called reaction zone. If the heat is generated faster than it is removed by thermal diffusion the reaction can become self-propagating. Such reactions have been observed for example in Al/Pt and Ni/Al systems [7, 8]. Especially the Ni/Al system has been researched extensively. Relatively thick (> 40 µm) and freestanding Ni/Al foils have been used for bonding of macroscopic and microscopic components. However, for bonding techniques in microelectronics and MEMS with bond frame dimensions of a few ten microns, this method is not similarly applicable. This is due to the fact of handling issues and the limited ability of patterning such foils with smaller dimensions [9].

Our approach focuses on the direct deposition and patterning of reactive multilayer films with the help of conventionally used process steps in microelectronics and Microsystems technology. These systems are called integrated reactive systems. In contrast to the Ni/Al systems, our total multilayer film thicknesses had to be smaller than 5 µm to reduce both, stress within the multilayer and costs. Fig. 1 compares the conventional method of reactive foil bonding and our method of integrated reactive systems.

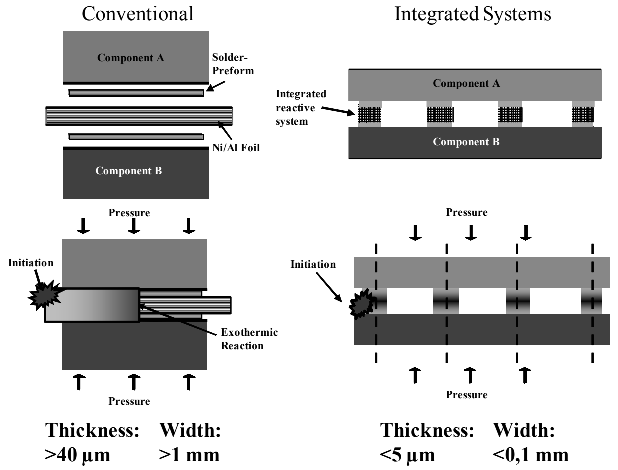

Figure 1: Comparison of reactive bonding methods: Left: conventional Ni/Al foil bonding; Right: Bonding with integrated reactive systems

EXPERIMENTAL

Deposition of Ti/a-Si multilayer

Ti/a-Si multilayer stacks were deposited by using alternating Ti DC magnetron and a-Si RF sputtering from high purity (99.999 %) Ti and Si targets. The relative Ti and a-Si layer thicknesses were maintained at a 1.46 to 1 ratio to obtain films with a 5:3 atomic ratio. The bilayer thickness (sum of individual layers of Ti and a-Si) was kept constant (75 nm), while the number of bilayers was varied to obtain total layer stack thicknesses up to 2.85 µm. The base pressure of the chamber prior to deposition was less than 1 x 10^{-7} mbar and the pressure of Ar during deposition was 150 sccm. Table 1 lists the thin-film systems investigated in this study. In this work six different types of films were deposited to investigate the influence of total thickness on the self-propagating reactions.

Table 1: Parameters of the Ti/a-Si multilayer films

Type	Ratio Ti:a-Si	Bilayer thickness δ [nm]	Number of bilayer N	Total thickness t [µm]
A	5:3	75	6	0.45
B			12	0.90
C			24	1.8
D			30	2.25
E			35	2.63
F			38	2.85

Preparation of integrated reactive systems

Fig. 2 shows the process flow for creating the integrated reactive systems and the following reactive bonding process. Prior to depositing Ti/a-Si multilayer the Si wafer were optionally coated with an adhesion layer in order to investigate the dependence on adhesion layer of the multilayer after the reaction front has passed. We used thermal grown SiO_2 (1 µm thick) or SiO_2 (500 nm thick), LP-CVD Poly-Si (500 nm) and Ti/Au (20 nm / 300 nm) as adhesion layer. After depositing the Ti/a-Si multilayer were patterned with the help of conventionally used photo-lithography steps. Shipley AZ9260 was used as a resist. Because of the relatively high amount of individual layers we used wet etching instead of dry etching procedures to generate test structures and bond frames. The etch medium we applied was a 33% H_2O, 3% NH_4F and 64% HNO_3 mixture. After wet etching pattern plating of 500 nm Sn layer (SAT 20-1, Max Schloetter GmbH) was applied to generate the so called integrated reactive system.

Bonding procedure

The bonding partner (Cap Si substrate) was coated with a Ti/Au wetting layer by DC magnetron sputtering (purity of both targets was 99,999 %, pressure prior to deposition was 1 x 10^{-7} mbar and pressure of Ar during deposition was 150 sccm). For bonding the exothermic heat generated within the multilayer is used to melt the electro-deposited Sn layer. This layer is used as solder for diffusion into the multilayer (alloy of Ti and Sn) and into the wetting layer (alloy of Sn and Au) of the cap Si substrate. After the Sn layer deposition, a Flip-Chip bonder is used for positioning the Cap and the Si substrate with integrated systems. During the bonding process, the components were loaded by a constant mass of 1000 g to apply a defined mechanical pressure. The exothermic reaction within the Ti/a-Si multilayer was initiated by an electrical spark.

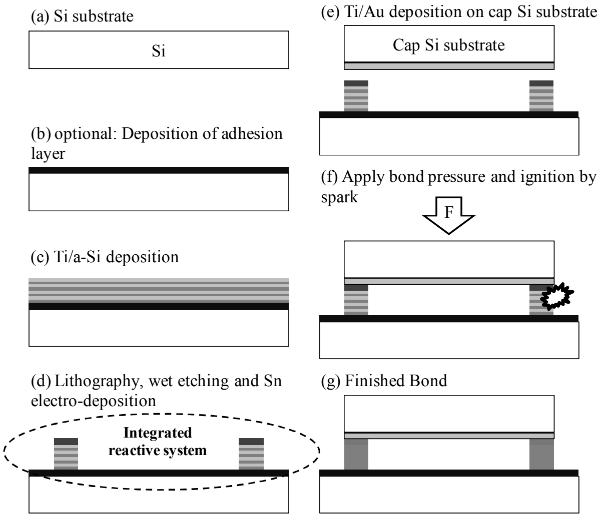

Figure 2: Process flow of the reactive bonding procedure

Analysis

The route of the reaction front was observed by using high-speed camera imaging (sample rate of 30’000 fps). The microstructure of the sputtered films and the reaction product was characterized by using SEM in combination with special preparation techniques like the FIB lift-out method. In addition to that, the bond interfaces were analyzed with the help of EDX.

RESULTS AND DISCUSSION

Integrated reactive multilayer system

Fig. 3 shows the results of the measured reaction velocities against the number of bilayer and the adhesion layer, respectively.

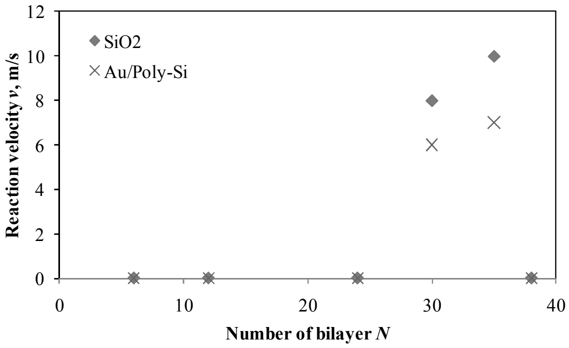

Figure 3: Reaction velocities against number of bilayer and the adhesion layer

The figure shows that no reaction can be generated in systems with a number of bilayer smaller than 35 (types A – C). This is due to the fact that more heat is dissipated in the reaction zone than it is generated, so that no self-sustaining reactions can be initiated. Reactions in type F could not be observed because the system was initiated during multilayer deposition. The reaction velocity in type E is higher than in type D. In addition to that, there was a strong dependence on the adhesion layer, so that the velocity of the reaction front is higher in systems on thermal insulating materials than on thermal conducting one. Thus, the ratio of heat dissipation into the substrate is smaller, so that more heat is generated, which drives the reaction front.

In Fig. 4 time lapse images, which are showing the reaction propagation in a patterned Ti/a-Si multilayer (type E), are presented. Herein, an Au/Poly-Si adhesion layer was used.

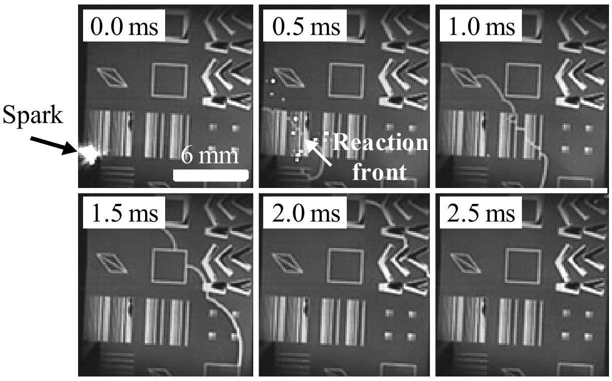

Figure 4: Time lapse images, showing reaction propagation from up left to down right. Scale bar in upper left applies to all images; timestamp is relative to the first image in the sequence

After the reaction is initiated the reaction front is propagating through the entire non reacted multilayer. These images demonstrate homogeneous propagation behavior of the reaction front. Furthermore, the reaction front is passing the smallest lateral geometries (20 µm) without any significant reduction of the velocity. Complex back tapers can be reached. In addition to that, it can be seen that the reaction front stops at interruptions (square in the middle of the pictures). These results lead to the possibility of generating very complex geometries (especially bond frames) for bonding procedures.

Fig. 5 shows a typically SEM cross-section of a patterned multilayer (type D). A typical etch rate for the used Ti/a-Si systems is approximately 0.3 µm / min. The results showed an etch mismatch between Ti and a-Si, nevertheless vertically arranged side wall can be generated.

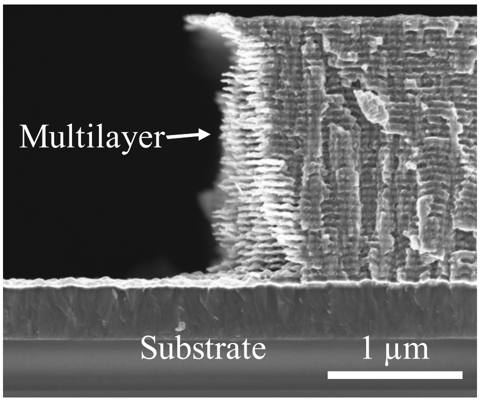

Figure 5: SEM cross-section of a patterned multilayer

Fig. 6 shows a SEM cross-section of a multilayer (type E) after the reaction front has passed. The substrate used herein was 1 µm thick thermally grown SiO_2. The figure shows that the substrate is damaged because of the high amount of energy directly induced into the substrate and the very fast heating and cooling rates.

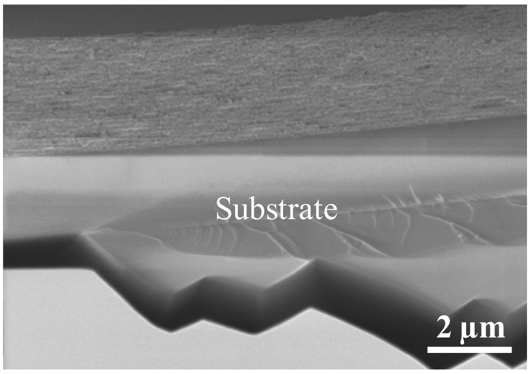

Figure 6: SEM cross-section of reacted multilayer without optimal adhesion layer

By using poly-Si and Au as adhesion layer the multilayer is not destroying the substrate. Fig. 7 shows FIB prepared SEM images of Ti/a-Si multilayer prior to and after the reaction front has passed (each type E).

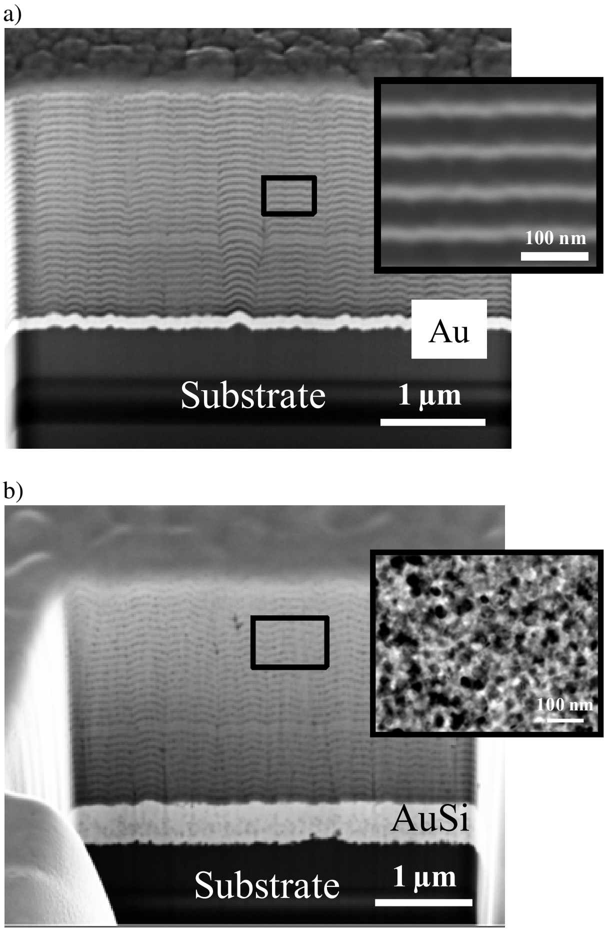

Figure 7: FIB/SEM of multilayer with optimal adhesion layer: a) as-deposited, b) reacted (insets show a high resolution image of the as-deposited and reaction product)

Fig. 7a shows a Ti/a-Si multilayer onto Au/poly-Si adhesion layer. A separated layer structure can be seen. After the reaction front has passed the Ti and a-Si are intermixing so that no individual layers can be detected (cf. Fig. 7b inset). Furthermore it can be seen, that adhesion between the reacted multilayer and the substrate is optimal. Hence, the substrate is not damaged. We assume that an AuSi alloy is generated so that the minimum reaction temperature has to be the eutectic temperature of AuSi (363 °C).

Bonding

A produced bond interface is shown in Fig. 8 (left). The thickness of the interface is approximately 3 µm. The highly explosive reaction generates a large amount of heat which is completely intermixing all the individual layers. Different phases and conglomerates can be seen. To investigate the intermixing of materials EDX-analysis (Fig. 8 (right)) was done. The white marked rectangle in Fig. 8 (left) represents the EDX-analysis area. This analysis clearly shows that all the individual layers are completely intermixed and no layered structure can be seen anymore. Ti is distributed along the whole interface. In contrast to our assumption, Sn is distributed near the poly-Si layer. Furthermore, Sn and Au and Sn and Ti created alloys. A very interesting fact is that Si cannot be detected. One reason for this might can be that an Au-Si eutectic is primary generated so that the Si fraction is below the possible detection rate of EDX.

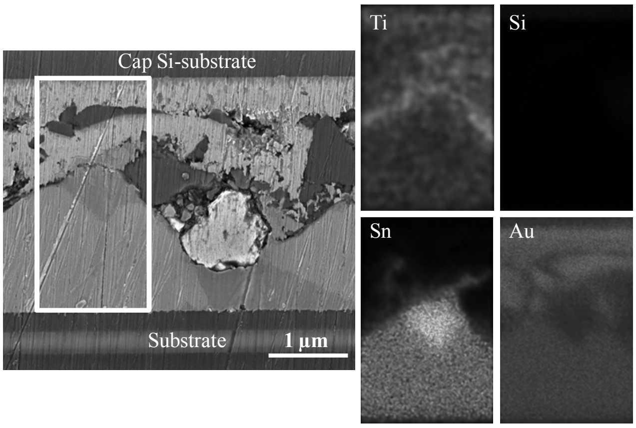

Figure 8: Bond results: Left: SEM cross-section; Right: EDX-analysis

CONCLUSION

In this work very thin Ti/a-Si-Sn-Au bond interfaces were fabricated. The interface was generated by using integrated reactive systems. We used self-propagating exothermic reactions to melt the Sn layers and so generating the bond interfaces. The reactive systems were accurately patterned by photolithographic and wet etching procedures. The reaction characteristics showed a strong dependence on the adhesion layers, so that the propagation velocity of the reaction front is higher onto thermal insulating material than onto thermal conducting materials. Without optimal adhesion layer the multilayer is peeled of the substrate after the reaction front has passed.

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