Development and Applications of MEMS Process Tools

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ABSTRACT

This paper presents our recently-developed process tools including atomic layer deposition (ALD) systems for multiple materials, a vacuum wafer bonder, a vacuum flip chip bonder for hermetic chip-scale packaging and a remote-type hot-wire atomic hydrogen source for metal reduction and polymer etching. In addition, examples of micro electro mechanical systems (MEMS) which have been created using the above tools are briefly introduced. The process tools are commercially available with customization, if necessary, via our partner company.

1. INTRODUCTION

The fabrication of micro electro mechanical systems (MEMS) is based on semiconductor process technology, but also needs MEMS-specific process technologies such as deep etching, conformal deposition on three-dimensional microstructures and hermetic wafer bonding. For new types of MEMS, new process tools are often required, and also new process tools open new device technology.

Our laboratory is equipped with many lab-made process tools, which have been developed over 40 years. Available tools include oxidation/diffusion furnaces, atmospheric pressure chemical vapor deposition (APCVD) systems [1], plasma-enhanced CVD systems [2], hot-wire reactors, atomic layer deposition (ALD) systems, a sputtering system, reactive ion etchers (RIE) [3], an O_2 plasma asher, a XeF_2 etcher [4], a resist spray coater, a vacuum wafer bonder, a vacuum flip chip bonder and a laser dicer [5][6]. Although some tools are now common, they were pioneering when they were developed, leading to new MEMS.

This paper introduces the most recently developed tools; the ALD system, the vacuum wafer bonder, the vacuum flip-chip bonder and a hot-wire atomic hydrogen source. In addition, some MEMS applications of these tools are briefly described.

2. ATOMIC LAYER DEPOSITION

2.1 ALD System

ALD is atomic/molecular-level layer-by-layer thin film deposition by providing a precursor gas and an oxidation/reduction gas alternately, for example, trimethylaluminum (TMA) and water for alumina. The main characteristics are precise thickness control and excellent conformability. The latter one is especially important for MEMS, which often have high-aspect-ratio three-dimensional structures.

Our ALD system is featured by multiple materials deposition from sublimate precursors without cross-contamination [7]. N_2 base flow from a constant pressure plenum always creates smooth up-to-downstream flow to avoid backdraft, and N_2 pulse flow with a constant volume carries and purges the precursor and oxidation/reduction gases. The precursors are stored in glass bottles with their safety considered. The glass bottle has a low thermal conductivity and a small heat capacity, and the residual precursor vapor in the lines can be almost completely disused back into the bottle by cooling the bottle after deposition. The collected precursor is recrystallized or liquidized, which can be easily confirmed because the glass bottle is transparent. This is useful for avoiding the accumulation of the residual precursor and/or its reactant in the valves and line as well as to save an expensive precursor (e.g. Pt precursor).

The ALD system has the line heating system which is sectioned into many areas. The temperature of the line can be optimized area by area, which is important for multiple materials deposition. In addition, the reaction chamber, which is a glass tube, is also sectioned into three zones using a baffle and a furnace heater. This defines where a film is deposited. Figure 1 (a) shows the ALD system. Based on it, Technofine (Sendai, Japan) has commercialized an ALD system shown in Fig. 1 (b).

2.2 In-plane PZT Actuator

Figure 2 shows an in-plane piezoelectric actuator using trench-refilled lead zirconate titanate (PZT) composite [8]. In general, a piezoelectric thin film actuator shows out-of-plane motion, while in-plane motion is generally realized by an electrostatic comb type actuator. However, the electrostatic actuator occupies a large foot print for comb electrodes. The

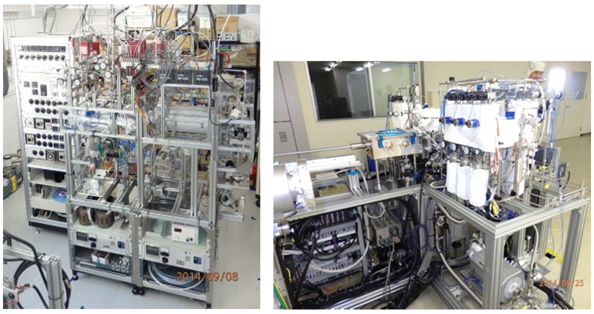
(a) Lab-made system (b) Commercial system

Fig. 1 Atomic layer deposition systems

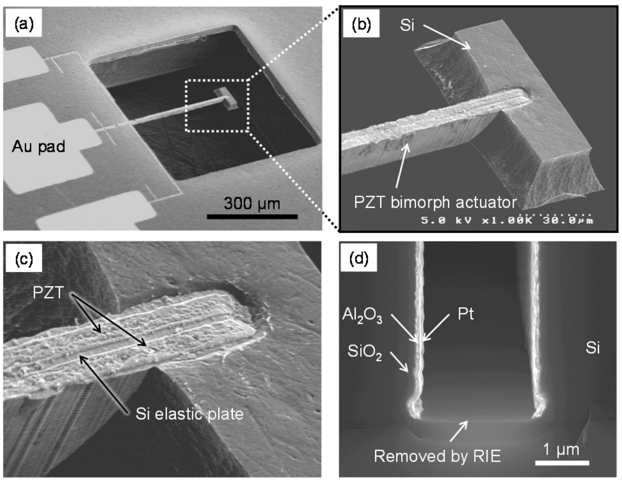

Fig. 2 In-plane PZT actuator

trench-refilled PZT composite was made in deep-reactive-ion-etched trenches with an aspect ratio of 10. The sidewalls of the trench were covered with Pt/Al_2O_3, which was formed by ALD (Fig. 2 (d)). After the bottom Pt/Al_2O_3 was removed by RIE, the trench was refilled with PZT sol including PZT nanopowders.

3. BONDING AND INTEGRATION

3.1 Vacuum Wafer Bonder

MEMS must be hermetically packaged except for a few exceptions (e.g. microphone). The most popular packaging method is bonding a lid wafer with a device wafer. Conventionally, flit glass bonding has been used, because it can overpass electrical lines to external bonding pads and is tolerant to surface roughness and particle contaminant. However, flit glass bonding width is as large as a few hundred µm, which is no more negligible compared with continuously-decreasing die size. Recently, metal-based bonding is replacing flit glass bonding. It needs bonding width smaller than 100 µm, and also can establish electrical interconnection simultaneously with hermetic sealing.

Figure 3 shows the vacuum wafer bonder which we have developed with Technofine (Sendai, Japan). It is equipped with an infrared camera alignment system, a formic acid pretreatment chamber and a bonding chamber, all of which are connected in vacuum. The bonding chamber has a multi-piston pressuring mechanism (91 pistons in 6 inch diameter) for uniform loading, which has a larger impact on metal-based bonding than anodic bonding and flit glass bonding. The wafer alignment accuracy is about 1 µm using the contrast-enhanced image of alignment marks. We have applied this wafer bonder for Cu-Sn solid-liquid phase bonding [9], Au-Au bonding [10], Cu-Cu bonding etc.

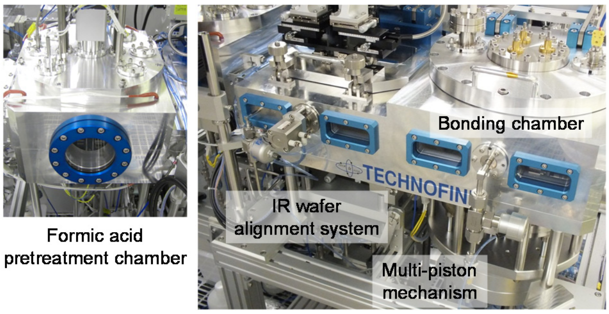

Fig. 3 Vacuum wafer bonder

3.2 Integrated Tactile Sensor

Figure 4 shows an integrated bus-network tactile sensor for robot application [11]. A CMOS LSI wafer and a special low temperature cofired ceramic (LTCC) via wafer [12] are bonded and interconnected by Au-Au bonding. The Au bump and sealing ring electroplated on the LSI are planarized by fly cutting with a single crystal diamond bit. Au-Au bonding is done at 180–350ºC after Ar plasma activation. The diaphragm is fabricated in the CMOS LSI wafer after bonding. The CMOS LSI enables high-speed digital bus communication, and many sensors can share a single bus line. This configuration is convenient to significantly reduce a number of wires in a limited space of a robot.

3.3 Selective Die Transfer

Wafer-bonding-based integration is versatile and commercially used. If the sizes of dies to be integrated are largely different, however, useless parts are left on the wafer of smaller dies. To address this problem, the smaller dies are transferred with skipping one or more die(s) from a support wafer to a target wafer, as shown in Fig. 5, and the other dies left on the support wafer are later transferred to different target wafers. Interconnection between the dies is established by low temperature Au-Au bonding following Ar plasma activation. The backside of the dies on a glass support wafer is irradiated with third harmonic $Nd:VO_3$ laser for separation, and the dies are selectively transferred to the target wafer.

For demonstration, an AlN-based film bulk acoustic resonator (FBAR) with a die size of 1 mm × 1 mm and a BiCMOS-sustaining amplifier with a die size of 2 mm × 2 mm were integrated and simultaneously packaged at wafer level [13]. Four times of die transfer were

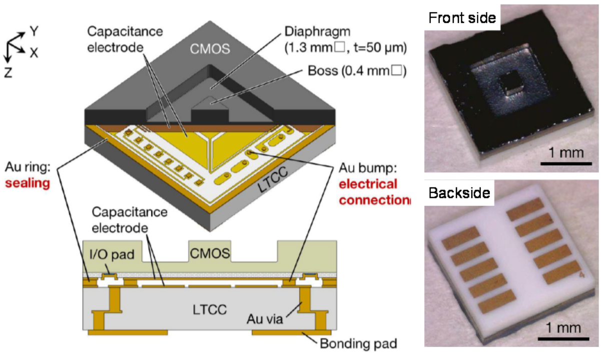

Fig. 4 Integrated bus-network tactile sensor

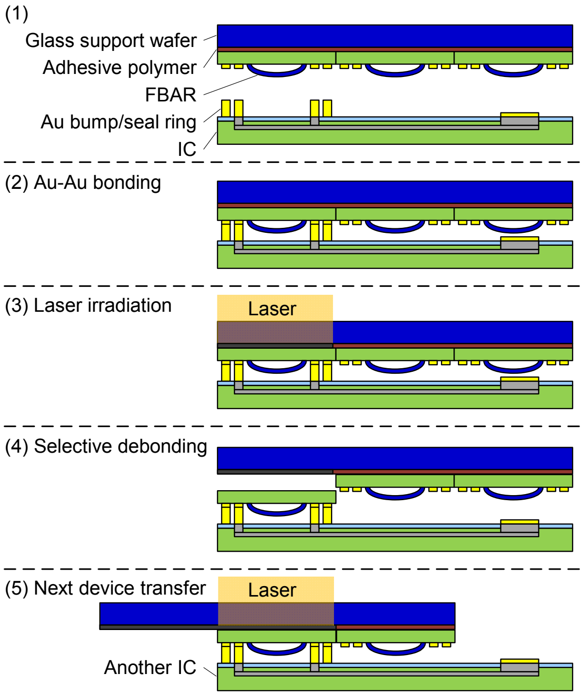

Fig. 5 Laser-assisted selective device transfer and integration

performed in total using the same FBAR wafer. The integrated device worked as a chip-size-packaged 2 GHz timing oscillator, and a phase noise of −103 dBc/Hz at 10 kHz offset and −155 dBc/Hz at 1 MHz offset was measured. A similar technology can be also applied to integration between different materials of wafer [14].

3.4 Vacuum Flip Chip Bonder

Wafer-to-wafer integration is a primary choice for mass-production. However, chip-to-wafer or chip-to-chip integration can be a choice for small-volume production as well as research and development. This is especially the case when the sizes of dies to be integrated are different as shown in Section 3.3. Chip-to-wafer and chip-to-chip integration are similar to conventional flip chip bonding. However, the largest difference is that most of MEMS should be hermetically packaged often in vacuum. Therefore, we have developed the vacuum flip chip bonder shown in Fig. 6. The mechanism is installed in a vacuum chamber. A pair of mechanical tweezers is used to pick up and flip a chip, because vacuum tweezers do not work in vacuum. The chip is bonded to a wafer or another chip by applying heat and force from the top via a heater chip.

3.5 Hot-Wire Atomic Hydrogen Source

For metal-based bonding except Au-Au bonding, the removal of metal surface oxide is important. The vacuum wafer bonder described in Section 3.1 has a formic acid pretreatment chamber for this purpose. However, formic acid sometime erodes or contaminates other materials. Ar plasma is also often used for the pretreatment of bonding metals as described in Sections 3.2, 3.3 and 3.4. However, metals are reoxydized in air, if they are exposed to air after the pretreatment. On the other hand, through-vacuum processing is not always available, because wafer alignment is done in air for major commercially-available wafer bonders.

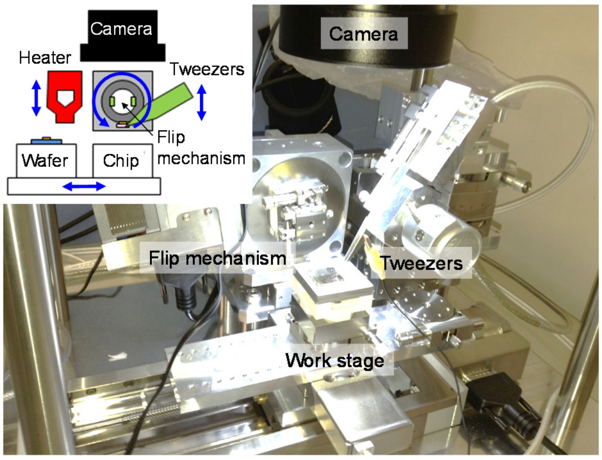

Fig. 6 Vacuum flip chip bonder

We have developed a remote-type hot-wire atomic hydrogen source shown in Fig. 7. A double-spiral W wire heated around 2000°C catalytically decomposes H_2 into atomic hydrogen, which is conveyed in a glass tube to a substrate by H_2 laminar flow. One or two orders of magnitude higher atomic hydrogen density is obtained compared with plasma decomposition. In addition, the remote-type configuration dramatically reduces the radiative heating of the substrate compared with the conventional configuration, where a W hot wire is located just above the substrate.

The remote-type hot-wire atomic hydrogen source is used for the reduction of metals. We confirmed that the reoxydation of Cu was slower after atomic hydrogen treatment than formic acid treatment. This is an optimistic result for in-air wafer alignment for the commercially-available wafer bonders. In addition, there is no sputtering damage or erosion in atomic hydrogen

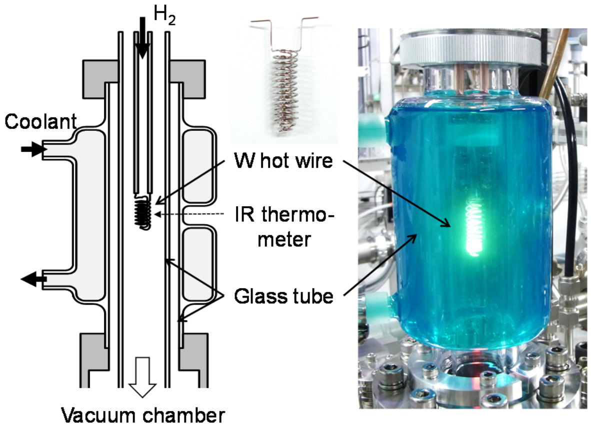

Fig. 7 Remote-type hot-wire atomic hydrogen source

treatment. We also applied the same system for the removal of polymers (e.g. SU-8 high-aspect-ratio photoresist) [15].

4. SUMMARY

This paper introduced the process tools developed in our laboratory; ALD systems, a vacuum wafer bonder, a vacuum flip chip bonder and a remote-type hot-wire atomic hydrogen source. They are commercially available via our partner company, Technofine (Sendai, Japan), with tailored modification, if necessary. The lab-made process tools are for the development of the tools themselves, but also used for the fabrication of new devices. This style of research has been continuing from Prof. Jun-ichi Nishizawa via Prof. Masayoshi Esashi, and contributing to student education as well as advanced research.

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