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Fabrication of a metal mold with microstructures using a novel passive-alignment recombining technique

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Abstract

This study presents a novel scheme for manufacturing a large area molds with alignment microstructures electroplated from lateral joining of small area silicon plates. Conventional methods for manufacturing metal molds with nano or microstructures are extremely challenging. Semiconductor fabrication procedures that utilize photolithographic processes to generate nano-scale features easily limit wafer scale. However, a large area silicon mold with small features has been developed. However, its drawbacks were serious misalignment, tilting, and brittleness. This work presents a novel approach for fabricating a metal mold with precisely aligned microstructures. The gap, alignment precision, tilt, and height difference between the two joined plates joined laterally by passive alignment recombining techniques were all on a micro scale. Furthermore, the measurements of the metal molds and Polyvinylchloride (PVC) replicas were extremely similar. Moreover, the scalability of the technique was demonstrated using four small area silicon plates. Consequently, this approach has significant potential for bridging the technological gap between conventional precision machining and photolithography-based micromachining for metal molds exceeding typical wafer size with small features.

Keywords: Metal mold; Recombining technique; Passive-alignment; Microstructure

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1. Introduction

Large plates with microstructures are increasingly attractive in a diverse range of applications in numerous industries. The shadow mask [1, 2] is the major technology used in manufacturing cathode ray tube (CRT) televisions and organic light-emitting diode (OLED) displays that produce color images. An OLED monitor is comprised of millions of tiny red, green and blue phosphor dots that glow when struck by the electron beam that travels across the screen to create a visible image. Ensuring that the electron beam for each color strikes only the correct dots for that color is essential to generate a precise and crisp picture. The typical method is to use a thin metal plate with numerous tiny holes called a shadow mask. The deposition apertures of a shadow mask can only be as small as dozens of microns wide when using conventional precise manufacturing technology. However, if the size of deposition apertures can be effectively reduced, the resolution of OLED displays will increase.

In current microfabrication procedures, photolitho-

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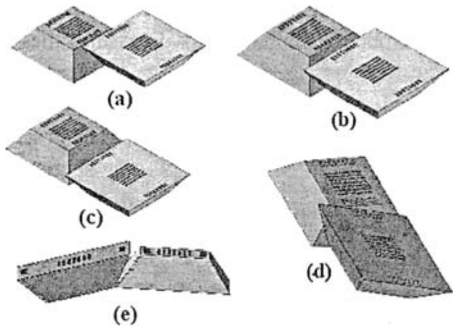

Fig. 1. Defects of joined silicon plates, (a) misalignment, (b) gap, (c) height difference, (d) rotation, (e) tilt.

graphic approaches for generating micro or nano-scale features limit wafer size. Nevertheless, conventional machining techniques for manufacturing structures less than 10 μm on a plate that is larger than the wafer size engender severe challenges when fabricating micro features. Wu [3] developed a manufacturing technology that solves the problem of manufacturing large plates exceeding wafer size with micro-scale features. This technology effectively demonstrated the feasibility of forming large silicon plates exceeding wafer size with micro-scale features. However, these plates are typically misaligned, tilted, rotated and brittle (Fig. 1).

2. Fabrication processes

The anisotropic silicon bulk-micromachining technique, laterally joined [3] and passive- alignment concepts [4, 5], and electroplating methods are key to fabricating metal molds with microstructures. The fabrication process begins with two double-sided polished silicon wafers deposited with a 1000 Å-thick silicon dioxide followed by a 1500 Å silicon nitride layer (Fig. 2). The glass layer is formed by exposing the bare silicon wafer to oxygen at temperatures of 900°C or higher for 1 hour. The silicon nitride layer is deposited by low-temperature chemical vapor deposition techniques. The films are utilized as an anisotropic etching mask layer. The silicon wafers are first cleaned in a RCA cleaning solution. The RCA cleaning technique does not attack the silicon wafer, and only organic contaminants are removed. Next, the wafer is uniformly coated with a thin light-sensitive liquid called S1813 photoresist (Shipley Co. Inc., USA). The coating is applied while the wafer is spinning. The spin condition is 3000 rpm for 30 seconds. The photoresist is approximately 1.3 μm thick. This sample is then pre-baked on a hot plate at 90 °C for 90 seconds to remove excess solvent from the photoresist. Portions of the photoresist are selected for exposure by carefully aligning a mask between an ultraviolet light source (365 nm) and the wafer. The first mask contains the patterns on joint plates. In the transparent mask areas, light passes through and exposes the photoresist, which is dissolvable to etchants when exposed to ultraviolet light. This chemical change allows the subsequent developer solution, applied for 90 seconds, to remove the exposed photoresist while leaving the unexposed portions on the wafer.

The reactive ion etching (RIE) process is employed immediately after photolithography to selectively etch away unwanted silicon dioxide and silicon nitride from the wafer. This RIE process is a kind of plasma dry etching that uses SF_6 and O_2 mixing gas at a low pressure. The resist is then removed from the substrates, which are then placed in 33 % wt potassium hydroxide (KOH) solution and heated to 72 °C. Once the anisotropic bulk-micromachining has etched completely through the wafers, the slanted crystal planes of the two wafers are formed ready for lateral joint. These processes are repeated; however, the second mask is adopted, which contains the patterns of V-grooves and microstructures—the microstructures and V-grooves are manufactured separately on the processed square silicon plates. The microstructures are located above the processed square silicon plates and the V-grooves are located on the opposite side. Next, a seed layer of Ni for electroplating the Ni metal mold is deposited on the plates using an E-beam evaporator.

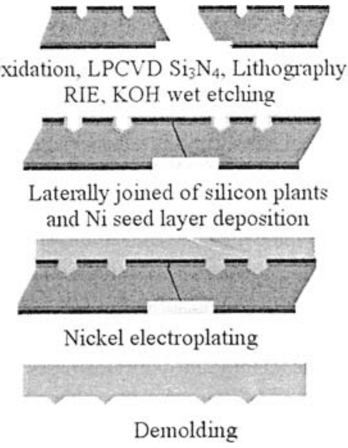

Fig. 2. Fabrication processes.

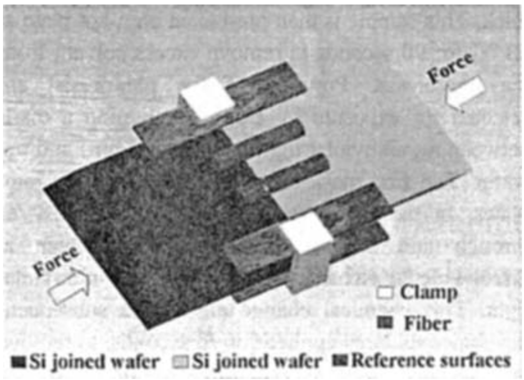

Fig. 3. Schematic of the laterally joint of silicon plates.

The most important requirement of the lateral joining technique is to maintain minimal tilting, precise alignment and seamless connection of two silicon plates of the same height. The flat surface of a polished silicon wafer is utilized as a reference plane to keep two joined silicon plates on the same horizontal plane. Optical fibers are placed into the V-grooves. Fiber diameter is 125 μm. The coupling forces are exerted by the optical fibers set in the V-groove, which minimize the tilting angle and misalignment between a pair of joined silicon plates. Fig. 3 shows two laterally joined plates clamped with flat reference surfaces around the perimeter of the laterally joined plates. External clips are utilized to generate a strong contact between joined silicon plates and reference plates. Furthermore, an external lateral force is applied to one side of the laterally joined plates to minimize the interface gap to ensure seamless joining. Once the joint plates are tightened, epoxy resin is applied to physically bond the plates together to maintain the minimum tilt and height difference, alignment, and seamless joining. Metal Ni electroplating is then applied to transfer the pattern on bonded silicon plates to a Ni metal mold. The electroplating process is performed using a common nickelsulfate electrolyte; the electroplated nickel can easily be removed from the bonded silicon plates because of its weak adhesion strength. The commercialization of microsystem product is based on low-cost, high-volume microfabrication schemes. The use of a polymer or replicated plastic microfabrication is an attractive low-cost alternative in a growing range of disposable devices. Polyvinylchloride (PVC) film is frequently used for most replication work as it has low glass transition temperature of 87 °C. The hot embossing process is a low-cost production method for replicating microstructures precisely. Replication by hot embossing consists of pressing the electroplated nickel metal mold with microstructures against a plastic sheet at a temperature exceeding the softening point of the plastic substrate. The procedure starts with a nickel metal mold held by suction. Pre-embossing contact is then applied, followed by programmed heating; pressure is thereby increased. Once patterns are replicated, relaxation and demolding are then performed to complete the hot embossing procedure. This experiment was conducted at an embossing temperature of 100°C and pressure of 30 kgf/cm^2 for approximately 3 min.

3. Results and discussion

The joined silicon plates, metal mold, and polymer replicate were characterized to elucidate its feasibility of forming large plates exceeding wafer size with micro-scale features. Profiles of the interface located between the surfaces of the original master and its replicated structures were analyzed using a non-contact surface profiler (WYKO, Veeco Instruments Inc., USA). The resolution of height difference between the sampling points was 0.1 nm. An external force was applied to the outside of one silicon plate to keep the joint gap at around 31 μm (Fig. 4). Fig. 4 also presents the surface profile of two joined silicon plates with the same height, 285 nm, using the recombining mechanism (Fig. 3). This technique achieves virtually seamless joining, which cannot be obtained by conventional precision machining schemes, and yields results in the order of several microns. Such experimental results indicate that the proposed technique is feasible for lateral joining using anisotropically bulk-micromachined crystal planes on silicon wafers.

The tilting angle is 730 μrad (0.042°) between two joined silicon plates (Fig. 5). This tilting induces a height increase of 148.33 μm across an 8" wafer (8*25400*tan(0.042)) and the warp is only 0.036 % when two 8" wafers are joined (319/(2*8*25400)). The warp should be less than 0.7 % for printed circuit boards according to IPC-6012 standards, which is an industry standard for printed circuit board quality. Furthermore, the warp must be <0.15% for glass substrate, which is applied to the colors filter of flat panel displays. The experimental results show that the tilting angle can be minimized via the coupling forces of optical fibers set in the V-groove and adhering to

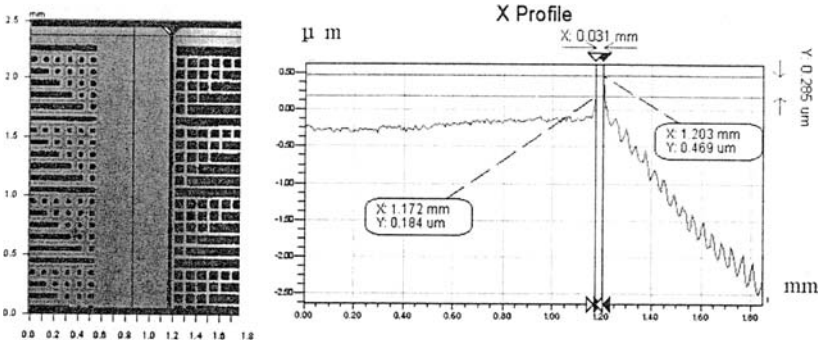

Fig. 4. Characterization of two joined silicon plates.

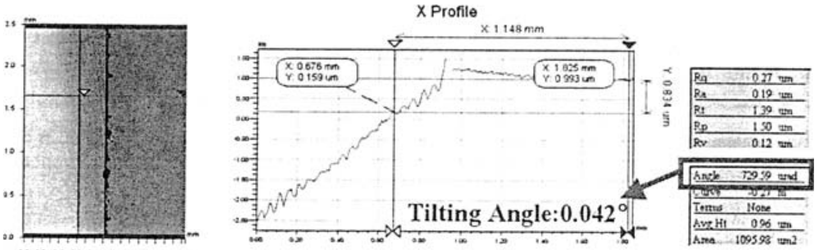

Fig. 5. Tilt angle between two joined silicon plates.

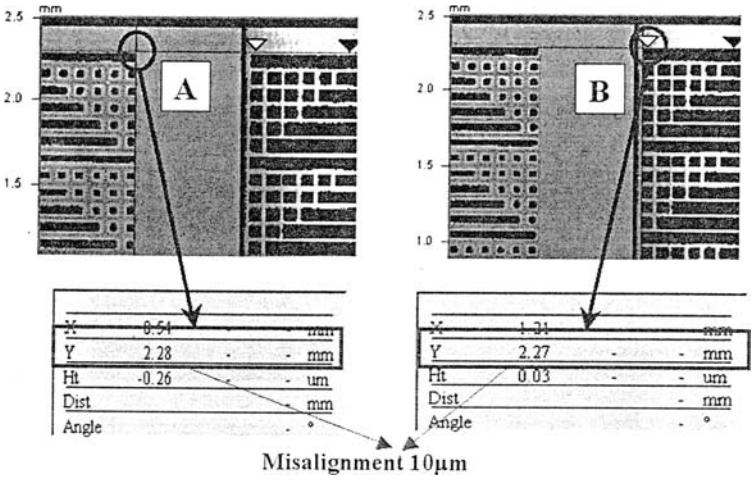

Fig. 6. Misalignment of microstructures on two joined silicon plates.

IPC standards and specifications for flat panel displays. Fig. 6 presents the accuracy of alignment between two joined plates. They coordinates of points A and B should theoretically be the same as they were created on silicon plates using photolithography processes. The misalignment error between two silicon plates can be reduced to approximately 10 μm according to the coupling force of fibers; conventional precision machining techniques cannot achieve such a small misalignment error. The ISO 10791-1 and 10791-4.2 measurement standards for machine tool performance recommend test conditions for machining centers, including accuracy and repeatability of positioning of linear axes. The straightness and position accuracy must be <15 μm and 20 μm, respectively, along the cutting direction according to these standards. Generally, the straightness is approximately 0.005" (127 μm) per linear inch (2.54 cm) under typical tolerance using the casting engineering scheme. Additionally, the cutting position error of the printed circuit board is 75 μm when using milling machines. In this study, misalignment error is smaller than those obtained using conventional methods, and adheres to ISO standards. This experimental result indicates that the passive alignment mechanism effectively solves the misalignment problem between the two joined plates.

The rotation angle between two silicon plates was calculated using trigonometry as it cannot be measured directly. Points A and C are located on the same plate (Plate I), and points B and D are located on the other plate (Plate II) (Table 1 and Fig. 7). The Y coordinate is of particular importance as it is the heights of measured points (unit, μm) (Fig. 7). The Y coordinate (Fig. 7) is recast as the Z coordinate (Table 1) such that it fits with the conventional cartesian coordinates system. The angle between the horizontal plane and plate I, which has points A and C, is 0.029° (tan0.029=((-1.296-(-2.178))/(2190-441)). The angle between the horizontal plane and plate II, which has points B and D, is 0.025° (tan0.025=((1.445-(0.681))/(2190-441)). Therefore, the rotation angle between the joined plates is 0.004°, indicating that tilt, rotation, and misalignment errors are efficiently minimized by the proposed passive alignment techniques.

Fig. 8 presents the surface topologies of the silicon plate, nickel metal mold and the replicate PVC film. The lower-left corner of Figs. 8(a), 8(b), and 8(c) show the scanning electron microscope (SEM) images of the silicon plate, nickel metal mold, and replicate PVC film, respectively. Following hot embossing of a nickel metal mold onto the PVC plastic sheet, the microstructures are accurately reproduced on the PVC plastic sheet. The widths of

Table 1. Rotation angle between two joined silicon plates.

Location	A	C	B	D
x axis, mm	0.260	0.260	1.416	1.416
y axis, mm	2.19	0.441	2.19	0.441
z axis **μm**	-1.296	-2.178	1.445	0.681
	0.029		0.025	
Rotation angle			0.004	

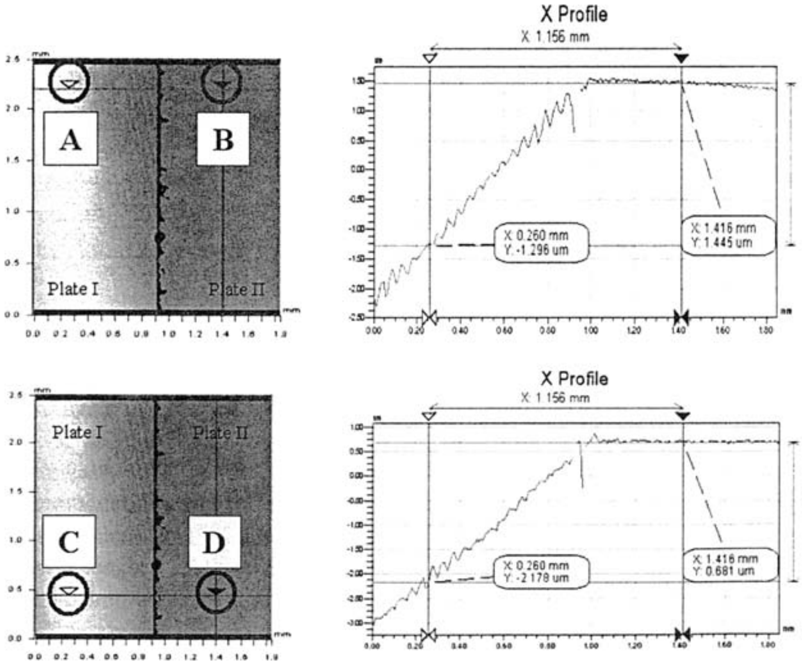

Fig. 7. Rotation angle between two joined silicon plates.

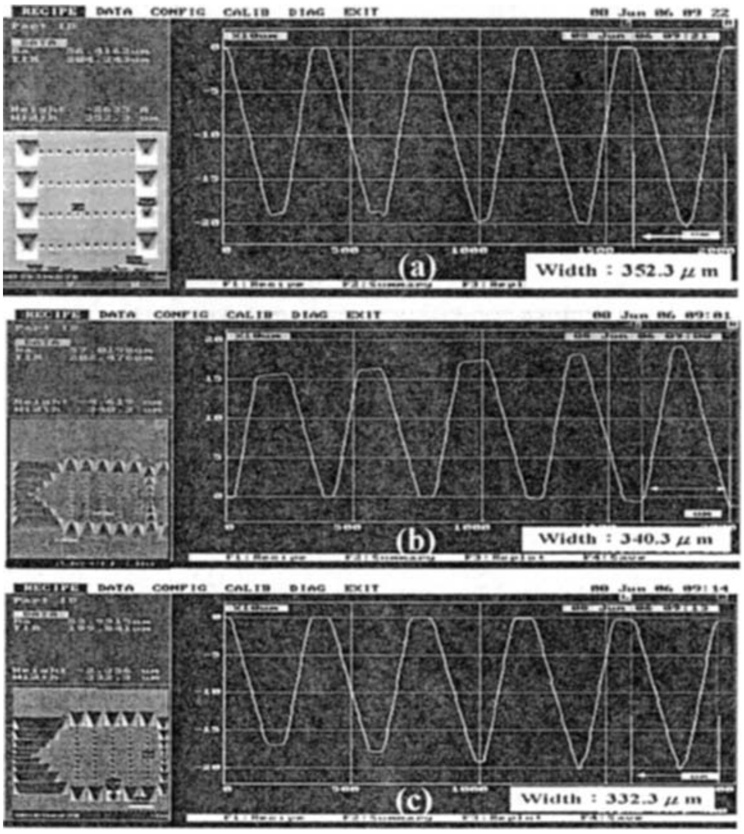

Fig. 8. Characterization of microstructures on different substrates (a) silicon plate, (b) Ni metal mold, (c) PVC film.

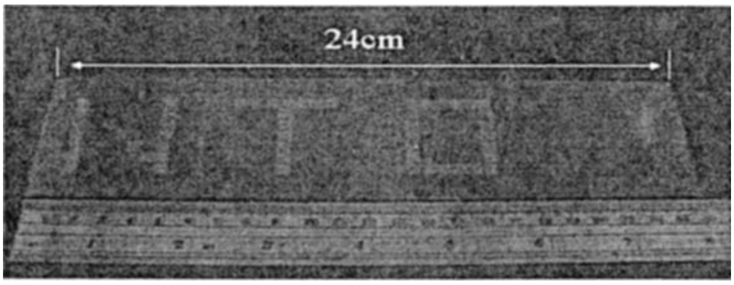

Fig. 9. Large-area silicon plate with micro scale features.

microstructures on the silicon plate, nickel metal mold, and replicate PVC film are 352 μm, 340.3 μm, and 332.3 μm, respectively. The width of the microstructure on the nickel metal mold is smaller than that on the silicon plate due to the intrinsic stress in the nickel metal mold. Owing to the PVC resultant contraction phenomenon, the widths of the microstructures on the PVC film are smaller than that of on the metal mold. Furthermore, the heights of the microstructures on the silicon plate, metal mold, and replicate PVC film are roughly 15–20 μm, indicating that the Ni metal mold is successfully electroplated from the joined silicon plates. Moreover, the microstructures on the PVC film are faithfully replicated from the Ni metal mold using hot embossing techniques.

As verified with previous experimental results shown in Figs. 4–7, a large area plate (Fig. 9) joined by the four small area plates demonstrates the wafer-joining scalability of the proposed technique. The area of the joined plate, consisting of four processed silicon plates, is 6 × 24 cm, with one side longer than that of the 8" silicon wafer. Therefore, the proposed lateral joining technique allows one side of the joined plate to be extended to 16". No 16" silicon wafer and semiconductor foundry currently exists.

4. Conclusions

This study presents a novel procedure for manufacturing a metal mold with small features. The gap, alignment, tilt angle, rotation angle, and height differences between the two joined plates joined laterally were all on the micro -scale using the proposed passive alignment techniques. The hot embossing process for the metal mold electroplated from the joined silicon plates was employed to accurately replicate the micro structures on the PVC plastic film. The joining scheme can be applied to increase mold size using small wafers. Four processed plates were used to demonstrate the scalability of metal mold. Therefore, this novel technique is a potentially low-cost approach for bridging the technological gap between conventional precision machining and semiconductor micromachining for a beyond-wafer-size metal mold with small features.

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