Fabrication of Integrated Vertical Mirror Surfaces and Transparent Window for Packaging MEMS Devices
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Abstract—A scheme for creating metal-coated vertical mirrors in silicon, along with an integrated transparent package lid for assembling, packaging, and testing microelectromechanical systems (MEMS) devices is presented. Deep reaction ion etching (DRIE) method described here reduces the loading effect and maintains a uniform etch rate resulting in highly vertical structures. A novel self-masking lithography and liftoff process was developed to ensure that the vertical mirrors undergo uniform metallization while leaving a transparent window for optical probing. Front side of a Si wafer was shallow-etched using DRIE to define an eventual optical window. This surface was then anodically bonded to a Pyrex wafer. Backside Si was then patterned to define thin channels around the optical window. These channels were vertically etched using DRIE, after which the unattached portions of the window region were removed. Negative photoresist was spun on the remaining vertical structures and the stack was exposed from the Pyrex side using Si structures as a self-mask. Subsequent metal sputtering and liftoff results in the metallized top and mirror sidewalls while leaving a clear window. These integrated mirrors and lids are then bonded to the active MEMS mirrors. Various processes and results are illustrated with an example of packaged corner cube retroreflectors (CCR).

Index Terms—Corner cube retroreflector (CCR), microelectromechanical systems (MEMS) packaging, microoptoelectromechanical systems (MOEMS), vertical deep reaction ion etching (DRIE), vertical mirrors.

I. INTRODUCTION

VARIOUS microelectromechanical devices require an optically transparent window to obtain optical access to the parts while providing protection from the environment. These microelectromechanical systems (MEMS) devices use active mechanical and/or optical elements such as optical switches, tiltable mirrors, and various optical sensors. The active structures in these devices must be free to move and an optical access is required for MEMS devices that have mirrors and optical elements. Optical access to nonoptically active MEMS devices may also be required for inspection, observation, and performance characterization of moving elements. Hence, to package the MEMS sensors, a transparent window and electrical connections to the outside world need to be integrated into the design. Processes, which can create a package and simultaneously assist in the fabrication of the needed optical surfaces, will be beneficial toward meeting the growing need for low-cost packaging solutions. Past works have presented various methods and approaches to package an optical device with integrated window for optical access [1], [2]; however, these techniques require extra complex processes to package the three-dimensional (3-D) optical structures. The packaging scheme described here uses a Pyrex wafer as a handle wafer and as the optically transparent package lid. The cobonded Si wafer was patterned, etched, and metallized using a special process to create vertical mirrors while ensuring that the lid remains optically clear after processing.

Fabricating large area vertical surfaces that can be used as mirrors in silicon has been previously accomplished using wet anisotropic etching [3], deep reaction ion etching (DRIE) [4], or using LIGA (German acronym for lithography, electroforming, and moulding) [5] process. Anisotropic etching can produce extremely smooth surfaces [3], but has limited producible geometry because of its crystallographic-dependent etch properties. LIGA process [5] can be used to fabricate 3-D metallic or polymer microstructures or molds, but requires expensive X-ray exposure which is not common in most facilities. DRIE techniques can allow etching of extremely complex geometries, but has microloading-dependent etch characteristics. Extensive research has been done to characterize geometric effects on etch rates; large open areas and small trenches etch at different rates [4]. Highly vertical structures, 70–80 µm deep have also been realized using two-step etch processes [6]. The structure to be removed was defined by a thin encompassing trench. DRIE was performed on the sample. A significantly more uniform etch geometry was achieved as the loading effect was minimized, resulting in extremely vertical structures. The bulk of the unwanted material was then removed by conformally protecting the trenches and wafer, creating openings over unwanted areas and removing the exposed material by a second long plasma or wet etch.

One of the biggest drawbacks of using DRIE to fabricate optical structures is the sidewall roughness. The optical scattering increases with roughness. Optical MEMS sensors and actuators often require relatively large flat surfaces to interact with light but with the increase in the etch depth the roughness on the etched areas increases. High aspect ratio Si vertical micromirrors 75 µm [7] and 40 µm deep [8] with sidewall surface roughness of 30 nm have been demonstrated using dry etching and
This paper addresses the challenge of fabricating and metallizing vertical mirrors integrated with a transparent window for optical probing or visualizing embedded parts. The process circumvents the need for performing difficult photolithography over high aspect ratio features, uses simple DRIE techniques, and includes only one long etch to create highly vertical structures, and uses short anisotropic etching for smoothing surfaces. A process to metallize the vertical mirror surfaces while keeping optically clear package lid window is also described. This self-masking liftoff process can be used to package various devices.

II. CCR APPLICATION

MEMS optical CCRs have been developed over the past decade to allow transmission of data from sensors to a base station or network via a probing laser beam [9], [10]. A CCR has three mutually orthogonal flat mirrors forming a concave corner. A MEMS CCR consists of an active mirror surface and two orthogonal static mirrors. If the light comes from a quadrant of hemisphere defined by the concave side of the CCR, the light entering the CCR is reflected back parallel to the source.

Tilting and realigning one or more mirrors, the CCR can intermittently reflect light away from the direction of the interrogating light source. Modulating the mirror(s) in synchrony...
with information, one can impart this information onto a probing laser beam using very little power. CCRs have, therefore, been proposed for use in free-space communication links. Initial designs to assemble CCR used large surface micromachined passive mirrors, which were lifted or actuated into place [9]. These suffer from mirror curvature due to the asymmetric film stresses, or require manual assembly or large amounts of chip space for the lifting actuators. Other devices [10] have used single-crystal silicon-on-insulator wafers to produce very flat mirror surfaces, though manual assembly of the two passive mirrors was needed to create the three mirror surfaces. Though much progress has been reported, designs reported to date do not directly address the need for packaging windows for the devices and do not lend themselves to economical mass production.

III. PROCESSES

The fabrication method described in this paper consists of three main parts. The first part focuses on fabrication of highly vertical through-wafer mirrors by performing DRIE on a 4" double side polished (DSP) Si wafer which was anodically bonded to a Pyrex cover wafer. The features were designed such that through-wafer deep vertical mirrors along with an encapsulating frame can be later bonded to active torsion mirrors [11], while permitting electrical and optical access to the packaged mirrors. The second part describes the polishing, lithography, and metallization of these vertical mirrors while keeping a clear package lid for optical probing. The third part describes assembly of a CCR by metal thermocompression bonding of the vertical mirrors and active torsion mirrors chip. The optical device was then tested and a thin layer of parylene was coated on to the packaged CCR to get a sealed package.

A. Fabrication of Vertical Mirrors and Lid Frame

The masks for fabricating the vertical mirrors were designed such that the vertical mirrors and the encapsulating package frame are defined simultaneously. To avoid the aforementioned loading effects in the DRIE, which limits etch uniformity and results in nonvertical structures, a two-step DRIE process was devised with uniform etch trench width as illustrated in Fig. 1. The process consists of an initial deposition of a thin layer of 100-nm low-pressure chemical vapor deposition (LPCVD) nitride on a 4" DSP (100) Si wafer in a Tystar LPCVD furnace (mini Tytan 4600, at 840 °C, 200 mTorr) as shown in Fig. 1(a). This was followed by an indentation patterning on the front side
of the wafer to define open areas of the package window as in Fig. 1(b). The nitride film was etched using reactive ion etching (RIE) tool using CHF$_3$ and O$_2$ plasma, and is followed by a very short silicon DRIE, using photoresist as the mask. This creates a few microns (10–15 μm) indentation into the surface of the wafer, as illustrated in Fig. 1(c). Next, the resist was stripped off the wafer and then the indented side (front side of Si wafer) was anodically bonded in vacuum to a DSP Pyrex 7740 glass wafer (EVG 501 bonder, 1 kV, 400 °C, 10 min), creating a bond everywhere except where the indentation exists, as shown in Fig. 1(d). Higher voltage was used during anodic bonding to ensure anodic bonding via the thin Si$_3$N$_4$ layer. Next, the backside of the Si wafer was coated with 1000-Å-thick Al layer through sputtering, as shown in Fig. 1(e). The Al acts as an etch mask for DRIE with high etch selectivity, while the underlying Si$_3$N$_4$ was used as wet etching mask in further processing. The Al and the Si$_3$N$_4$ layers were patterned using photolithography with a mask that defines a uniform narrow (50 μm wide) trench opening around the fixed features. The Al layer was etched in Al etchant (type A, Transene Inc., Danvers, MA) at 50 °C for 22 s and the nitride film was RIE-etched, as shown in Fig. 1(f). The trenches were etched through the Si wafer using DRIE. Once the trench etch reaches the indentation areas, the large indented area of the Si detaches from bonded Si and falls onto the Pyrex surface, as shown in Fig. 1(g). These pieces are then removed just by inverting the wafer stack. The remaining parts still bonded to the glass wafer are the vertical mirrors with rough sidewalls and the package frame, as in Fig. 1(h).

Fig. 2 illustrates the improvement in etch profile realized using the aforementioned process over the single-etch DRIE process with the same final geometry. Fig. 2(a) shows under-cutting typically seen (12.5°) during DRIE etch near large open areas. Fig. 2(b) shows (after removal of the loose piece over the initial indentation) significantly less under-cutting (< 0.3°, even before any optimization in etch parameters) afforded by this technique.

Fig. 3(a) shows the bonded mirrors and the package frame, which are to be bonded to the active MEMS parts, shown in Fig. 3(b), using thermocompression bonding which will be described in Section III-C. These vertical mirrors were designed in a cross pattern, slightly narrower than the corresponding cross on the active MEMS die. The design also included a package frame area corresponding to the lid seal area on the active die.

Smooth sidewall morphology was required in the mirrors to minimize the scattering loss. The mirrors obtained by DRIE suffer from scalloping effect and are not immediately suitable for optical applications. Also Teflon-like polymer (polymerized CF$_2$) gets deposited on the etched surfaces during DRIE, which prohibits any postprocessing on the mirrors. The average sidewall roughness of the DRIE structures measured using a Veeco optical profiler was approximately 150 nm. This roughness was plasma-cleaned in a Tepla M4L plasma etcher at the radio-frequency (RF) power of 400 W and 400 sccm of O$_2$ flow for 1 h. This etch removes the Teflon polymer from the surface of the sidewalls and decreases the roughness of the etched surface from approximately 150 to 90 nm. To further decrease the roughness of the mirror surfaces, a KOH+IPA polishing was performed using Si$_3$N$_4$ as the top masking layer after stripping of the Al. Standard KOH solution in H$_2$O has etch rates for different crystal planes in the order of (110) > (100) > (111). However, with the addition of IPA in the solution, the etch rates in the (110) plane is decreased by about 90% while only reducing it by 20% in (100) plane, hence the etch rate of different crystal planes in KOH+IPA solution is in the order of (100) > (110) > (111) [12]. The lithography as shown in Fig. 1(b) had been performed such that the DRIE etch mask was parallel to the (110) direction of the (100) wafer. Therefore, after DRIE, the vertical structures were very near the (110) plane. The isotropic etching using KOH+IPA solution resulted in exposing the slow etching (110) planes, hence resulting in smoother surface on our cross-shaped structures. This reduces the mirror roughness to 39 nm, as shown in Fig. 4. At this roughness level, the average scattering loss from these mirrors was approximately 24% when used with a 632.8-nm laser, at an incident angle of 45°. This scattering loss was further reduced to 17% with an infrared (IR) laser of 780-nm IR diode laser again at an incident angle of 45° [7].
B. Vertical Mirror Metallization and Transparent Package Lid Window

In order to increase the optical reflectivity of the Si vertical mirrors, they needed to be coated with metal. The glass lid shown in Fig. 3 should act as the transparent window for the probing beam in the packaged optical devices. Metal needs to be coated on the top of the package frame (to allow thermocompression bonding to surface micromachined parts on a separate chip) and to the sides of the vertical mirrors to make them more reflective, while allowing a clear window on the glass lid. To achieve this task, a self-masked photolithography step followed by sputtering and liftoff was developed. The metallization and liftoff process is shown in Fig. 5.

Futurrex negative photoresist NR9 1000PY was spun into the cavity created by prior etches (back side of Si), at 3000 r/min, and soft baked at 150 °C for 60 s. The resist was flood-exposed from the Pyrex side (front side of Si) of the bonded structure.
in EVG 620 mask aligner. The photoresist in the windowed area was thus exposed, while the brief exposure and vertical geometry prohibits the exposure of resist on the sidewalls and package frame surfaces. The resist was hard-baked on a hot plate at 100 °C for 60 s and developed in Futurrex RD6 developer. The resist remains only on the exposed window after developing. Cr–Au layers were then sputtered onto the chip. Lift-off in acetone was performed to remove the resist and metal from the window region. This leaves the sidewalls and top surface metallized for high optical reflectivity and Au–Au bonding to active parts, respectively. Fig. 5 illustrates the process to metallize the vertical mirrors and liftoff the gold from the package window. A thin coating of 500 nm has been shown to be sufficient for Au–Au thermocompression bonding [13], but, in our experiments, 1-μm-thick Au coating with 100-nm Cr layer was used since it was noticed that the thermocompression bonding of small features (50 μm) was stronger with thicker Au layer, as was also described in [14].

Due to the topography of the etched structures, nonuniform coverage of photoresist was obtained after spinning. When this photoresist was exposed from the back side using conventional lithography (Futurrex NR9 PY1000, 3000-r/min, 198-mJ/cm² exposure dose and 10-s developing), Au was lifted off from large portion of the mirrors. It was concluded that with normal exposure and developing time the photoresist on the sidewalls was not fully removed during development due to the topography of the structure and spun photoresist which resulted in the nonuniform metal coverage after liftoff.

Due to the topography of the structure, a modified coating, exposure, and developing process were developed. If a photoresist spray coater is available, these changes may not be necessary. The spin speeds, exposure dose, and developing time were changed to obtain the best metal coverage on the vertical mirrors and package frame with a transparent glass lid after liftoff. The exposure dose was changed to expose the uneven coating of photoresist on the glass window from the backside without exposing the photoresist on the vertical mirrors, which were self-masked with the vertical Si structures. Too much or too little dosage results in undesirable metal coverage on the vertical mirrors or a glass lid. Due to the spreading of the ultraviolet (UV) light, the photoresist on the sidewalls gets exposed with increase in the exposure dose. This resulted in the lift-off of some metal covering the vertical mirror. Thus, it was important to control the exposure dose to minimize the spreading of light. Complete removal of photoresist from the vertical mirror was ensured by longer than normal developing time, while leaving photoresist on the glass window.

To further improve the metal coverage care was taken to get rid of any bubble formation while dispensing photoresist on the samples. A bubble was formed due to the surface tension of the photoresist, which prevents coating of the photoresist at the intersection of the cross hair and leaves an open area around it. Thus, the metal gets sputtered directly on the Pyrex and cannot be lifted off, as shown in Fig. 6(a). To overcome this problem, micropipettes were used instead of a conventional dropper, hence forcing the photoresist to coat the intersection area. 2.0 μl photoresist was dispensed at each quadrant of the cross hair. This resulted in the better photoresist coverage and minimal air bubble formation at the cross hair, resulting in the better liftoff, as shown in Fig. 6(b).
C. Assembling and Packaging of CCR

The metallized vertical mirrors were bonded to the active MEMS die using Au–Au thermocompression bonding using a flip-chip tool. This MEMS die contains torsion mirrors and electrical routing for the MEMS devices. Active torsion mirrors were fabricated using Si$_3$N$_4$ as the structural layer sandwiched between Ti–Au metal films to allow electrostatic actuation of parts and provide high reflectivity [15].

A base metal layer was used for electrical routing and wire bonding the final parts. A polyamide sacrificial layer was used, which can be released in tetramethyl ammonium hydroxide (TMAH)-based developers or O$_2$ plasma. This active parts die also contains an open area, which is slightly wider than the width of the mirror cross hair, and also an Au-coated package frame area, which is isolated from the underlying routing electrodes by an intermediate silicon nitride insulating layer.

The package lid (vertical mirrors and package frame) was then bonded to the active torsion mirror die by thermocompression bonding using a flip-chip bonder. The bonding was carried out at 320 °C for 10 min with a 40-MPa pressure applied to it. The bonded CCR with transparent package window for optical access is shown in Fig. 7.

The glass lid protects the underlying optical structures from dust and other contaminants. However, due to the conformal nonplanar feature of the package frame on the active MEMS die, the vertical structures does not completely seal the device to protect it from moisture and liquid ingress. Coating the whole assembly with a thin layer of parylene using Labcoater 1 PDS 2010 parylene deposition unit formed a better seal. Specialty coating system’s MEMS compatible A-174 silane solution in 100% IPA was used as the adhesion promoter. Coated devices were dipped in IPA for more than 2 h without any leakage. Helium leak test have not yet been completed. The devices were tested before and after parylene deposition without any noticeable difference.

IV. RESULTS AND DISCUSSIONS

These fabrication techniques allows creation of extremely vertical through-wafer surfaces in silicon, without any significant surface damage to the cobonded Pyrex lid enabling its use in diverse optical packaging schemes that require patterned and reflecting sidewalls. The sidewall angle obtained using this method was better than 89.7°. Newer ICP etch equipments may achieve 90° sidewall profile [16]. The average surface roughness on a 120 × 90-μm$^2$ area scan was measured to be 39 nm, using an optical profilometer. This roughness is 5% of the wavelength of light used, hence it is suitable for optical applications. The packaged CCRs were tested for wireless communication to a distance of approximately 10 m. The torsion mirrors were modulated with an amplitude-modulated signal of 20-V peak-to-peak. 180° out-of-phase voltage was applied to each side of the torsion mirror electrodes on the active MEMS chip. 780-nm wavelength diode laser was used to incident light on the packaged CCR and the reflected signal was measured using a photomultiplier tube. Fig. 8 shows the voltage signal applied to one side of the torsion mirrors and the data received by the photomultiplier tube. Data was transmitted at 9600 Bd with a 50-kHz carrier frequency.

A fully functional, packaged and sealed optical device has been described here. A single long DRIE method was used to etch through-wafer vertical structures and novel self-mask lithography and liftoff technique was employed to metallize
the vertical mirror and get transparent optical window for probing optical parts along with a package frame. The DRIE etch trenches can be made wider than 50 μm to decrease the etch times. Also, a photoresist sprayer coating system might give better coverage and metallization coating after liftoff.

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REFERENCES


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