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Integration of trench isolation technology and plasma release for advanced MEMS design on standard silicon wafers

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Abstract
A new technology for the fabrication of high-aspect-ratio single-crystal silicon MEMS on standard silicon wafers is presented. A two-mask fabrication process combines vertical trench isolation with plasma release to allow formation of distinct electrical domains on movable structures in addition to an electrical isolation from the bulk of the wafer. The delicate isolation between dry released, monocrystalline, high-aspect-ratio components, accompanied with a low-cost of the starting material and a large freedom of design makes the technology an attractive platform for advanced MEMS fabrication and prototyping. Several example microstructures have been successfully fabricated using this technology.

Key Words: Trench isolation, high-aspect-ratio, MEMS, DRIE, single crystal, plasma release, bulk micromachining.

I. INTRODUCTION
Many classes of MEMS devices, both sensors and actuators, take advantages of well-established electrical and superior mechanical properties of single-crystal silicon in combination with a relatively large device thickness to improve the device performance. A widespread method for the fabrication of high-aspect-ratio, monocrystalline silicon MEMS is the use of Silicon On Insulator (SOI) wafers.

An SOI compatible trench isolation technology [1-3], which employs trenches refilled with a dielectric material to obtain electrical isolation between mechanically connected components, gives opportunities to further improve performance of MEMS [1,2] and to simplify fabrication process of existing or to design entirely new types of devices [3]. Main drawbacks of the trench isolation technology are associated with the use of SOI wafers: a relatively high cost of the wafer, a fixed device layer, a limited thickness of the buried oxide layer, the notching effect and a sacrificial oxide layer etch required to release structures.

Several methods of bulk micromachining [4-7] based on standard silicon wafers are proposed as an alternative to the SOI technology. All these methods employ Deep Reactive Ion Etching (DRIE) to pattern, a passivation layer to protect and dry isotropic etching to release structures created in the bulk material. Different techniques are used to electrostatically isolate the released structures from the bulk material: by metallization [4,5], by creating silicon islands surrounded by electrically insulating oxide [6] or by use of aluminum interconnects [7]. However, an electrical isolation between released, movable structures, which are mechanically linked, is not demonstrated using these methods.

This paper presents a novel bulk micromachining technology that combines sophisticated electrical isolation capabilities of a vertical trench isolation technology [1-3] with a plasma release process allowing a broad range of advanced MEMS designs to be realized on inexpensive standard silicon wafers.

II. TECHNOLOGY
The main fabrication steps are shown in Fig. 1.

Fig. 1. Condensed fabrication sequence: (a) trench etching, refill and top layer removal (b) structure etching (c) side-walls passivation (d) bottom removal (e) plasma release
The starting material for the two-mask fabrication process is a standard silicon wafer with an arbitrarily crystallographic orientation. To assure electrical conductivity of the substrate a highly conductive wafer can be selected or the impurity doping can be performed. Deep trenches are etched in the substrate using DRIE. The maximum depth of a trench is determined by the maximum achievable aspect ratio. A reliable electrical isolation requires a perfect vertical or slightly negative trench profile [2]. A dielectric or a poor conducting layer is deposited on the patterned surface to completely refill the trenches. A LPCVD low-stress silicon nitride solely or in combination with other materials (e.g. undoped polysilicon) is frequently used for the refill [1-3] due to good electrical insulating properties and highly conformal step coverage. The insulating layer on the top of the substrate is removed (Fig.1a) by using Chemical Mechanical Polishing (CMP) or a non-selective Reactive Ion Etching (RIE) process [1-3]. After this step the surface of the wafer remains flat and smooth and allows further processing. A small width of trenches is preferred to reduce both the deposition and the removal time of the isolation layer. A second DRIE step defines structures in the bulk material (Fig.1b). Subsequently, a thin passivation layer is uniformly deposited to protect the structures during the isotropic release step (Fig.1c). A thermal grown or deposited silicon oxide passivation layer in combination with a silicon oxide mask [4,5] or a FC-based polymer coating with a standard photoresist mask [7,8] are commonly employed. After the passivation layer on the bottom of trenches is removed (Fig.1d) a selective isotropic etch of silicon is performed in order to undercut the structures. The mask and the passivation layer are removed in the last fabrication step (Fig.1e).

III. DESIGN RULES

Analogue to the SCREAM process [4,5], a careful mask design is necessary to assure successful release and uniform thickness of MEMS components. A small structure width is favorable in order to decrease the etch time and to reduce the loss of the structure height during the plasma release step. A grid or a honeycomb design can be used for large area structures. A uniform mask design suppresses the RIE lag effect that induces variations in the structure height. The height variations caused by the RIE lag can be further amplified by a non-linear etch rate of silicon during the isotropic release step.

Unlike in the SCREAM technology, refilled trenches are employed in the proposed process. A large mechanical strength and a high electrical resistance between components connected by a refilled trench [2] assure for both mechanical integrity and electrical isolation. The refilled trenches require only a small wafer area and can be configured in many different ways depending on application. Different configurations (Fig. 2) result in: (a) an isolated material island completely embedded in the bulk material, (b) an anchor with one free side to connect some functional part or (c) a movable part with integrated electrical isolation.

![Fig.2. Refilled trenches assure electrical isolation and mechanical integrity: (a) an isolated material island, (b) an anchor (c) a movable part with integrated isolation.](image)

To achieve a reliable electrical isolation several design and fabrication parameters, shown in Fig.3, must be carefully chosen.

![Fig.3. A schematic view of a released insulated structure with design and fabrication parameters.](image)

Assuming that the release process is completely isotropic, the etch distance \( r \) has to be larger then a half width of the structure \( (r>0.5w) \) to completely undercut it. However, when the structural etch is
deeper then the isolation trench \((d_2 > d_1)\) a minimum etch distance \(r_{\text{min}}\) equal to:

\[
r_{\text{min}} = \sqrt{(d_2 - d_1)^2 + \left(\frac{w_2}{2}\right)^2}
\]

(1)

is required for an reliable electrical isolation. It is thus important to realize that a released structure does not always implicate a good electrical isolation and vice versa a good electrical isolation is not a warrant for a mobile structure. Three different situations that can arise depending on selected design and fabrication parameters are illustrated in Fig. 4. A relative deep isolation trench and a relative short release step leave the molded dielectric parts embedded in the bulk material resulting in a good electrical isolation and a very stiff suspension desirable in some application (a). However, in this case an electrical isolation on movable parts is obviously not possible. In order to achieve this a well-timed etching and release processes are necessary (b). A too short release step may result in a short-circuited movable structure (c).

![Fig. 4. Reliable isolation requires a careful control of design parameters: (a) high stiffness support (b) movable structure with integrated isolation (c) short-circuited structure.](image)

II. FABRICATION RESULTS

Diverse example microstructures (comb drive microactuator, displacement sensor, XY-stage) are successfully fabricated using the proposed technology.

The fabrication process is started on a highly conductive (100) silicon wafer. Isolating trenches with slightly negative profile, 2 \(\mu\)m wide and 30 \(\mu\)m deep, are etched by cryogenic DRIE using SF\(_6\)/O\(_2\) based plasma chemistry [9]. A layer of 50 nm chromium was used as a masking material. Deep trenches are refilled with a 1.2 \(\mu\)m thick LPCVD low-stress silicon nitride. Silicon nitride from the top of the wafer is removed by standard RIE using CHF\(_3\) plasma.

After lithography of the device layout using standard Olin 917 photo resist, the so-called BSM multi step release process [8] is applied to etch, passivate and release microstructures in a single run (see Fig. 5). The BSM process is performed in a state of the art etching machine type A 601 E of the company ALCATEL [10].

![Fig. 5. SEM micrograph of high-aspect-ratio comb fingers fabricated using BSM multi step release process.](image)

In the first process step all trenches with different exposed areas are uniformly etched at the same depth as the isolation trenches (~30 \(\mu\)m) using a No-Lag DRIE Bosch process [11]. During the second step a fluor carbon coating is uniformly deposited on the sidewalls, using C\(_4\)F\(_8\) plasma chemistry, to protect the structures during the isotropic release step. Before the release can take place the fluor carbon on the bottom of the trenches is removed by high energetic SF\(_6\) plasma. A selective isotropic SF\(_6\) etch of silicon is performed to achieve a freestanding device structure. The complete BSM multi step release process took only 15 minutes. The final height of the released structures is 28 \(\mu\)m. A gap between the freestanding structure and the bulk of the substrate is 7 \(\mu\)m.

A part of a fabricated XY-stage is shown in Fig.6. The XY-stage consists of a large movable shuttle (1430 x 1012 \(\mu\)m) suspended by folded flexures and driven by electrostatic comb actuators. The
flexures are connected to a free side of contact pads. The contact pads, electrically isolated from the bulk of the wafer by the trench isolation, enable application of a voltage on connected parts. Electrical contact was made with a standard probe set due to a high stiffness and large mechanical strength of the suspension.

Inside the large shuttle a small frame is suspended by folded flexures and driven by comb drives in a direction perpendicular to the movement of the shuttle. The trench isolation, employed on the movable shuttle, allows independent excitation of the small frame.

The XY-stage was successfully driven in both directions. A maximum displacement of 18 μm was observed for both directions.

**IV. CONCLUSIONS**

A low-cost bulk micromachining technology is presented. A two-mask process allows fabrication of single-crystal, high-aspect-ratio movable structures on standard silicon wafers. Distinct electrical domains can be defined on a movable part in addition to an electrical isolation from the bulk of the wafer. The electrical isolation is achieved using trenches refilled with a dielectric material and requires low wafer area. The delicate isolation accompanied with a low-cost of the starting material, a no time consuming dry release and a large freedom of design makes the technology an attractive platform for advanced MEMS fabrication.

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