Versatile trench isolation technology for the fabrication of microactuators

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Abstract

A trench isolation technology employs trenches refilled with dielectric material to create, in a single layer, electrical isolation between mechanically joined components. This paper explores further use of this technology for MEMS fabrication, particularly the fabrication of electrostatic microactuators. Adding extra features to a two-mask trench isolation process new design opportunities, like isolation structures and isolation bumps, are created. The isolation structures can be employed as flexible or rigid connections between movable or fixed components or can serve to prevent the short-circuiting by maintaining the end distance between movable electrodes. The isolation bumps reduce stiction during release and operation, prevent short-circuiting due to an out-of-plane displacement and can serve as etch holes at the same time. The trench isolation technology is used to improve fabrication process of an actuator consisting of a large number of elastic electrodes connected in parallel and in series and to develop a novel low volume, large force (> 1 mN) and nanometer resolution electrostatic actuator for low displacement applications.

Keywords: Trench isolation; Electrostatic microactuators

1. Introduction

Complex electromechanical micro-devices often require electrical isolation between mechanically interconnected structures implemented within a minimum number of layers and processing steps. A departure from the conventional in IC-fabrication widely used approach of stacking of multiple dielectric and conductive layers connected by vertical conduction paths is employment of (DRIE) etching of (deep) trenches and the successive refill with dielectric (silicon oxide, silicon nitride) or poor conducting (undoped poly-silicon) materials. The trench isolation approach was successfully
employed for different fabrication processes such as SOI micromachining [1–3], bulk micromachining [4] and thin film molding process [5]. An SOI based trench isolation technology [1,2] allows insulation and interconnection of high-aspect ratio microstructures. This process, initially developed for the fabrication of fully integrated, high-aspect ratio inertial sensors with improved sensitivity, is also highly suitable for other types of MEMS devices [3].

This paper explores further use of a trench isolation technology for MEMS fabrication with emphasis on fabrication of electrostatic microactuators. Starting with a two-mask trench isolation process (Fig. 1) suggested by Brosnihan [2] new design features are added while the fabrication process stays virtually unchanged. These additions make the trench isolation technology an even more attractive technology platform for MEMS fabrication allowing large freedom of design. As a demonstration of the capabilities of the technology, an electrostatic micro-actuator consisting of a large number of elastic electrodes connected in parallel and in series, to produce large forces and large displacement [6–8] was successfully fabricated and operated. Furthermore, a novel electrostatic actuator for low displacement and large force applications is presented proving the large innovation potential of the trench isolation technology.

2. Trench isolation technology

The fabrication steps of a basic trench isolation process is shown in Fig. 1. The starting material for this two-mask process is a doped (poly)silicon device layer on the top of the sacrificial silicon oxide layer (step 1). Use of a silicon-on-insulator (SOI) wafer allows for high aspect ratios, truly valuable in some applications. However, it is worth mentioning that one is not limited to SOI micromachining. The trench isolation process can also be employed as a part of a complex surface micromachining sequence. Isolation trenches are etched by (deep) reactive ion etching, (D)RIE, in the device layer and subsequently refilled with a low stress silicon nitride (step 2). The trenches must have a perfectly vertical or a slightly negative taper profile in order to remove in the final (D)RIE step (step 4) all (poly)silicon from sidewalls of the refilled trench to insure reliable electrical isolation [2]. Silicon nitride is used as a refill material because of favorable electrical insulating properties, highly conformal deposition and high etch selectivity to the sacrificial silicon oxide layer. The thickness of
silicon nitride layer $t_i$ depends on the width of trenches. The minimum width is defined by the photo-lithographic resolution and the maximum obtainable aspect ratio of the (D)RIE process depending on the thickness of the device layer. To avoid excessive deposition time and high intrinsic stress of the silicon nitride the maximum allowable width of the trenches should be limited to 5 μm [9]. A maskless RIE using CHF$_3$ plasma removes the silicon nitride layer from the top of the device layer (step 3). The process leaves a flat surface profile, which allows further processing including the integration of electronic circuits. A second (D)RIE step (step 4) defines mechanical structures, taking into account a possible mask misalignment $m$ (top view). The final processing step is the release of the structures by dissolving the sacrificial oxide layer using the HF or BHF etch solution (step 5). This two-mask fabrication process allows fabrication of released structures mechanically connected and electrically separated by a refilled isolation trench. A large fracture strength and high electrical resistance were measured by Brosnihan [2] between test components connected by a refilled trench.

3. Technology features

3.1. Molded isolating structures

The basic trench isolation process, given in Fig. 1, employed to mechanically interconnect two distinct electrical regions can also be used to create other isolation structures without additional processing steps. (Poly)silicon molds refilled with silicon nitride, shown in Fig. 2a, are fully exposed to the etch plasma during the structural etching step (step 4). The etch rate of silicon nitride is significantly lower than the etch rate of (poly)silicon resulting in a complete removal of (poly)silicon around the molded structures. After the release freestanding isolating structures made of silicon nitride are realized. The height of the freestanding isolating structure $h_i$ depends on the thickness of the (poly)silicon layer $t_d$ and the selectivity of the (D)RIE process and is given by:

![Fig. 2. (a) Process outline for molded isolation structure. (b) Silicon nitride bars embedded in doped polysilicon components forming a rigid truss.](image-url)
\[ h_i = t_d \left( 1 - \frac{v_i}{v_d} \right) \]  

(1)

where \( v_i \) and \( v_d \) are etching rates of the silicon nitride and the (poly)silicon, respectively. The thickness of freestanding isolating structures depends on the width of trenches used for molding (see Fig. 2a). A mold narrower than a double thickness of the deposited isolation layer \( (2t_i) \) creates a structure with the thickness equal to the width of the mold. Otherwise, the thickness of molded structures is equal to the thickness of the isolation layer \( t_i \). Isolation structures can serve as flexible or rigid connections between movable or fixed conductive components. A framework composed of silicon nitride bars embedded in doped polysilicon components forming a rigid truss is shown in Fig. 2b. The application is not limited to the connection of distinct conductive components. Different mechanical, electrical and thermal properties between silicon nitride and (poly)silicon can be used to create new opportunities in MEMS design. In the subsequent section isolating structures are used to maintain a minimum gap between movable electrodes.

3.2. In-plane isolation: stoppers

In-plane movable components driven by electrostatic forces often require electrical insulation to prevent short circuiting caused by accidental or intentional physical contact. Silicon nitride sidewalls acting as insulating layers between movable components can be obtained by deposition of a thin silicon nitride layer prior to the release step (step 5 in the trench isolation process scheme) and subsequent directional etching step. However, a silicon nitride layer covering a large electrode surface can give rise to charge accumulation leading to device malfunctioning or complete device failure. A considerable reduction of charge accumulation can be achieved by replacing continuous isolation layers by a set of properly spaced, small area isolating stoppers [10].

The molded isolating structures, presented in the previous section, can be used for short-circuit protection. A schematic view of isolation structures employed as stoppers in a gap closing actuator with two movable electrodes is shown in Fig. 3a. The distance between the isolating stoppers \( g \), defined in the first photolithography mask, is smaller than the separation between the movable electrodes \( g' \), defined in the second mask. Accordingly, contact only occurs between the isolating stoppers while the electrodes stay always at a distance equal or larger than \( g' - g \). Proper designed isolating stoppers maintain the end distance between electrodes regardless of a possible mask misalignment. The minimum controllable end-distance between the electrodes depends on the quality

Fig. 3. (a) A schematic view of isolating stoppers. (b) Polysilicon electrodes with isolating stoppers made of silicon nitride. The isolating stoppers prevent the shortening between the movable electrodes regardless of the present mask misalignment (\( \approx 1 \, \mu m \)).
of the photolithography process, etching profile and the footing effect. A SEM photograph of two movable polysilicon electrodes with isolating stoppers is shown in Fig. 3b.

3.3. Out-of-plane isolation: bumps

By applying a short isotropic etch of the sacrificial silicon oxide prior to the deposition of isolation layer (step 2), small dents are created below the device layer. During successive conformal deposition of silicon nitride these dents are refilled producing isolating bumps (Fig. 4a). By reduction of contact area these bumps can prevent stiction of components during release or during operation. Conducting parts exhibiting out-of-plane motion can employ the isolating bumps to prevent short-circuiting. The silicon nitride coating at the bottom of a hole larger than double the thickness of the deposited silicon nitride layer ($>2t_i$) is removed during a maskless RIE step (step 3) resulting in a hollow bump allowing sacrificial etching to take place through the bump, thus serving additionally as an etching hole. A SEM picture of a released plate with hollow bumps is shown in Fig. 4b.

4. Fabrication results

4.1. Force arrays

By connecting a large number of driving units in parallel and in series a large force and large displacement actuator can be achieved [6–8]. Each driving unit consists of two wave-like [6] or parallel [7,8] electrodes, which can be elastically deformed by applied voltage. The driving units can be operated simultaneously giving a smooth motion [6,7] or by a selective biasing of individual units resulting in a stepping motion [8]. A successful fabrication of this type of actuators demands electrical isolation between mechanically connected components. Several fabrication methods are already proposed: electroplating of copper in combination with photoresist [6], dual-mask processing of polyimide followed by directional evaporation of a bilayer [7] and a selective chemical vapor
deposition of tungsten [8]. In this paper the trench isolation technology is used to simplify fabrication of an integrated force array. A doped, 5-µm thick polysilicon layer on top of the sacrificial silicon oxide layer is used as the starting material. The fabricated array, shown in Fig. 5a, consists of eight driving units serially connected. Each unit has two parallel electrodes 200 µm long, 2 µm thick and separated by a distance of 2 µm. The electrodes are joined together by isolating structures enabling selective biasing. Thin silicon nitride sidewalls are used to prevent short-circuiting between electrodes. The fabricated actuator was successfully operated and a maximal displacement of 4 µm was observed.

The trench isolation technology yields several advantages compared to the originally proposed fabrication processes. Besides simplicity of the fabrication process based on well-documented materials and processes, improvement on actuators performance is expected due to the attainable high-aspect ratios and possibility of integration with electronics.

4.2. Novel electrostatic actuator

Micromotors based on the inchworm motion can provide a large displacement by adding small steps in sequence. Tas [11] has proposed a promising approach for an alternative step generation. This approach employs a built-in mechanical transformation to produce a large force and nanometer resolution step within a low volume. A novel electrostatic microactuator [12], also based on the built-in mechanical transformation as suggested in Ref. [11], is fabricated using the trench isolation technology. The new actuator (see Fig. 5b) consists of parallel conducting beams which are perpendicular to the substrate and which are mechanically interconnected but electrically separated. On application of a voltage the beams deflect laterally inducing a powerful longitudinal contraction. A doped, 5-µm thick polysilicon layer on top of the sacrificial silicon oxide layer is used as a device material. A thin layer of silicon nitride on the sidewalls is used to prevent short-circuiting between two parallel beams at pull-in. A large force (>1 mN) with a controllable nanometer resolution step (<15 nm) was measured for an actuator containing 16 parallel beams, 200 µm long, 2 µm thick with 2 µm distance between. The actuator fits in a volume of $200 \times 62 \times 5 \, \mu m$ and is operated by a voltage.
of 70 V. Typical applications for the new actuator include the contraction/elongation body of an inchworm motor, vibration excitation or friction measurements [13].

5. Conclusions

New functions have been added to a trench isolation technology by rather small modifications and/or additions to the technology and by proper design while keeping the fabrication process rather simple. By employing trenches as mold, silicon nitride isolation structures are created. The isolation structures can be employed as flexible or rigid connections between movable or fixed conductive components or to prevent the short-circuiting between movable electrodes. Using isotropic etching in the sacrificial oxide layer isolation bumps are created. The isolation bumps can reduce stiction, prevent the short-circuiting due to a vertical displacement and serve simultaneously as etch holes. The trench isolation technology complemented with the above-mentioned features is a powerful platform for MEMS fabrication. Besides possibilities for simplification of fabrication and improvement of performance of existing devices, the technology allows designers to create new types of MEMS. An electrostatic actuator consisting of a large number of parallel electrodes connected in parallel and in series is successfully fabricated and operated. The trench isolation technology reduces the complexity of the originally proposed fabrication processes, allows improvement of the performance of this type of actuators by using high aspect ratio structures and/or by integration of electronics. Furthermore, a novel electrostatic microactuator has been fabricated using this technology. The novel actuator, which occupies small volume (200×62×5 μm), is able to produce a large force (>1 mN) and a controllable nanometer resolution step. Typical applications for the new actuator can include the contraction/elongation body of an inchworm motor, vibration excitation or friction measurements.

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References


