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Flat free-standing silicon diaphragms using silicon-on-insulator wafers

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Abstract

Flat, free-standing silicon diaphragms for use as tunable micromirrors were demonstrated. Silicon-on-insulator (SOI) wafers were employed to realize single-crystal mirrors, which are nearly free from residual strain. Using a wet chemical etch and a release process, free-standing structures were fabricated. A surface bowing approximately 10 nm was measured, indicating the lack of residual strain in the diaphragm. This value is much less than typically observed in polysilicon structures with diaphragms formed by chemical vapor deposition. Electrostatic actuation of the free-standing diaphragm was demonstrated and observed as a shift in the optical transmission spectrum of the Fabry–Perot cavity formed by the membrane and the substrate surface. A displacement of the membrane of approximately 200 nm was inferred from the wavelength shift of the transmission peak at an applied DC bias of 25 V.

Keywords: Silicon-on-insulator; Micromirrors; Fabry–Perot filters; Optical MEMS

1. Introduction

Fabrication of free-standing diaphragms and micromirrors is of prime importance in the development of optical MEMS devices, including tunable filters [1], microcavity emitters [2], wavelength-sensitive detectors [3], and deformable mirrors [4]. Surface-micromachining techniques are commonly employed to build such structures, which in their most basic form involve the chemical vapor deposition (CVD) of a sacrificial layer (commonly SiO_2) followed by a polysilicon layer. After patterning of the polysilicon, the sacrificial layer is removed using a selective etch, leaving a suspended silicon structure [5]. Deposited polysilicon films typically exhibit large residual stresses, which are in part due to high deposition temperatures required in the CVD process. When such films are released, the intrinsic stress causes the structure to buckle and deform to relieve the stress. This diaphragm bowing is detrimental in optical applications that require very flat surfaces, including mirrors for high finesse resonators [1].

In this publication we report on a fabrication process for Si membranes to be used for tunable microcavities. The membrane is formed by selectively patterning the Si device layer of a silicon-on-insulator (SOI) wafer, underetching the oxide, and subsequent release of the Si membrane. The advent of SOI wafers, used for Si VLSI circuits with reduced device capacitance, has provided means of achieving thin film single-crystal silicon that is nearly free from intrinsic stress.

2. Fabrication

The commercially available SOI material used in this study was fabricated using the Smart-Cut™ process [6]. This technology has the capability of providing a large range of SOI layers and oxide thicknesses, which is an important consideration in the design of a MEMS device. All of the diaphragms reported in this work were fabricated from (100) SOI wafers with a 1.5-μm-thick silicon layer on top of a 3.0-μm SiO_2 layer. A schematic of the diaphragm geometry is shown in Fig. 1. The square-shaped diaphragm is suspended by four arms. Typical dimensions of the diaphragm are 100 μm^2 for the mirror and 100×10 μm for the arms.

The fabrication process begins with cleaving the SOI substrates into approximately 1-cm^2 pieces for test purposes. Ohmic contacts to both the top SOI layer and to the substrate were deposited by thermal evaporation of an 800 Å thick aluminum layer, followed by an anneal at 450°C

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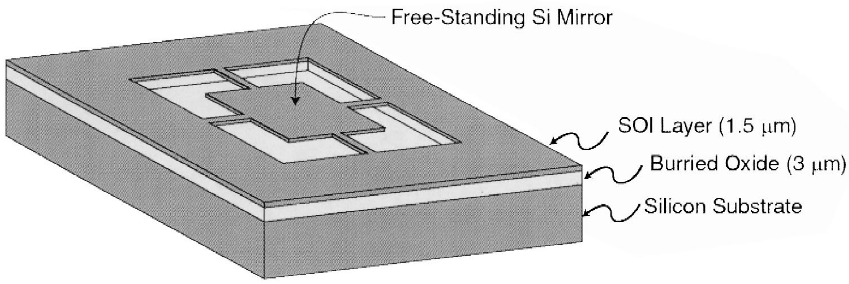

Fig. 1. Schematic of SOI silicon micromirror.

for 2 min in a nitrogen ambient. The contacts were coated with crystal wax to protect them from the remainder of the processing steps. The diaphragms were then patterned using conventional photolithography techniques, followed by e-beam deposition and lift-off of an 800 Å Ti etch mask. The SOI layer was etched through to the oxide using a 2 M KOH aqueous solution containing 5% isopropyl alcohol at 60°C for 6 min. This etch defined the boundaries of the mirror and support arms. Underetching of the oxide layer was performed in a concentrated 24 M hydrofluoric acid (HF) solution, which had the added benefit of concurrently removing the Ti mask. Etching times of between 5 and 10 min were employed for a 100-μm^2 membrane.

Following the oxide etch, the samples were rinsed in two successive water baths each lasting for 5 min, followed by 10-min rinses in acetone and methanol. In the drying process, stiction of the released structures to the silicon substrate was found to be a significant problem, reducing yields of suspended mirrors to under 5% when air drying alone was used. Numerous studies have been done on the problem of stiction in MEMS devices [7,8], and the technique that proved most effective in this application was found to be supercritical carbon dioxide drying. This method involves replacing the final rinse liquid (in our case methanol) with liquid CO_2 inside a pressure vessel. The temperature of the chamber was gradually increased such that the carbon dioxide entered a supercritical phase where liquid/gas interface was eliminated. The chamber was vented to atmosphere at constant temperature, making sure no CO_2 condensed on the sample. After utilization of supercritical drying in this process, the yield of released diaphragms increased to nearly 100%.

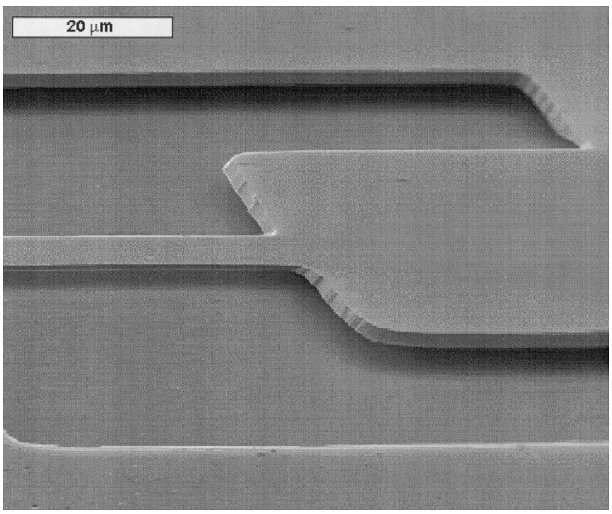

Fig. 2. SEM micrograph of free-standing single crystalline silicon micromirror.

3. Characterization

SEM micrographs of the released mirrors were taken and a typical result is shown in Fig. 2. The 1.5-μm-thick silicon mirror is clearly suspended above the silicon substrate. The exposed silicon (111) plane is also visible around the edges owing to the anisotropic nature of the KOH etch.

In order to gauge the surface flatness of the released diaphragm, measurements were made using a noncontact interferometric microscope. The peak-to-valley deformation from the surface normal was measured to be approximately 10 nm, which is comparable to the flatness of the bulk silicon substrate. A horizontal line scan across the mirror surface is shown in Fig. 3. This result is particularly important since it is common for polysilicon structures with similar geometry to exhibit strain-induced deflection

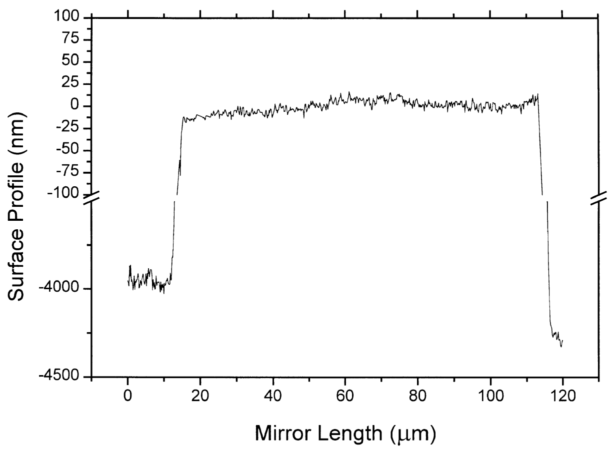

Fig. 3. Surface line profile of released SOI mirror.

of 50–100 nm [9]. In a device where flatness of the mirror is of prime importance (e.g. a high finesse etalon), SOI mirrors potentially hold significant advantages.

Actuation of the suspended structures was achieved electrostactically by applying a voltage between the SOI layer and the substrate, causing a decrease in the air gap. The deflection of the membrane is measured by optical transmittance spectra for the low finesse optical cavity formed by the membrane and the substrate. Fig. 4 shows transmittance spectra for six different applied voltages. A shift of the transmission maximum toward shorter wavelengths is observed, which is expected for an optical cavity of decreasing mirror separation.

The maximum wavelength shift for the actuated membranes is approximately 34 nm at an applied voltage of 25 V. The membrane displacement required to produce such a shift was calculated using the scattering matrix formulation [10], and was determined to be 200 nm. Note that the actuation voltage of the membrane can be reduced by changing the geometry of the membrane.

The transmittance peak wavelength is expected to decrease linearly with decreasing air gap thickness. Also, for small displacements of the diaphragm δ, the deflection is proportional to the square of the applied voltage, as given in the following relation

$$\delta = \frac{1}{2}\frac{e_0 V^2}{\kappa (d_0 - \delta)^2} \qquad (1)$$

where e is the electronic charge, κ is the effective spring constant of the system, and d_0 is the initial air gap distance. For small deflections such that $d_0 \gg \delta$, Eq. (1) can be simplified to the following,

$$\delta = \frac{1}{2}\frac{e_0 V^2}{\kappa d_0^2} \qquad (2)$$

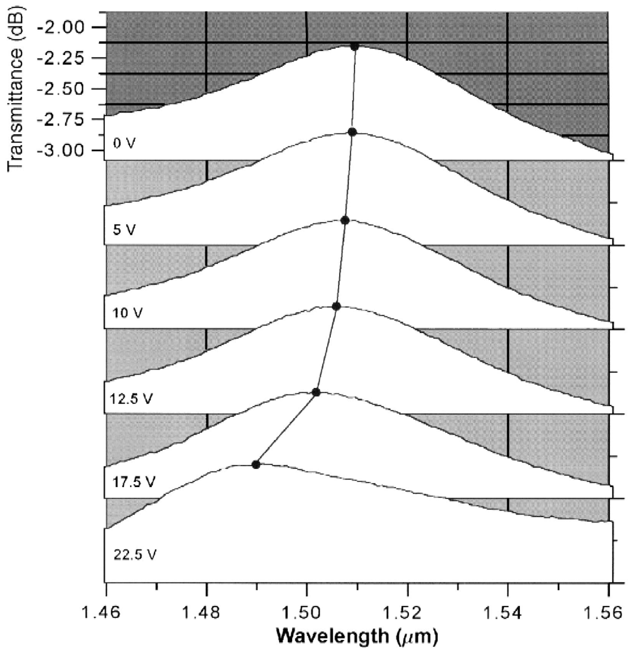

Fig. 4. Transmission spectra of the released SOI structures as a function of actuation voltage.

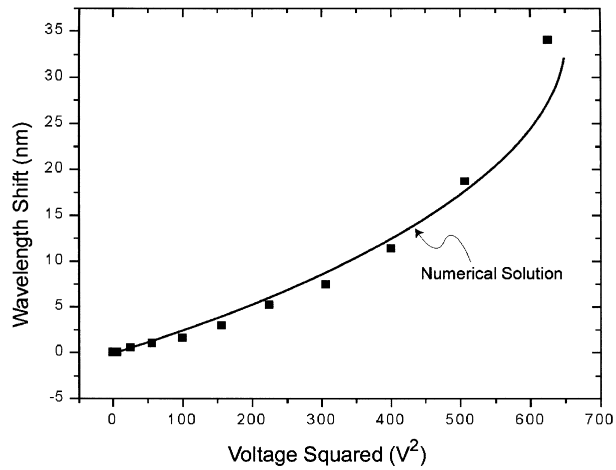

Fig. 5. Wavelength shift of the transmission maxima versus the square of actuation voltage. The line is a numerical solution to using Eq. (1).

Fig. 5 shows wavelength shift plotted versus the square of the applied voltage. Eq. (2) describes the system reasonably well for voltages below 20 V. At larger voltages, however, the linear approximation is no longer valid and a numerical solution to Eq. (1) (shown in Fig. 5) is necessary.

Applications for the SOI membrane technology described in this work include its use in a high finesse resonator after subsequent deposition of high reflectance coatings and combination with a second mirror. In the case of multilayer dielectric coatings, stresses in the deposited films may cause unwanted bowing of the mirror. However the use of a stress-free structural element (especially in the support arms) still provides advantages. When metal mirrors are appropriate, stresses in the very thin reflective coating should be negligible. We expect that such an arrangement can produce a Fabry–Perot filter whose finesse is not limited by the strain-induced curvature of the membrane, leading to a reduction in transmission linewidth.

4. Conclusions

Fabrication of silicon diaphragms based on SOI wafers was demonstrated. The flatness of the released structure was measured to be approximately 10 nm (peak-to-valley) over the entire surface of the mirror, providing a significant improvement when compared to polysilicon structures. Electrostatic actuation of the mirrors was demonstrated, and optical transmittance measurements show a vertical displacement of approximately 200 nm at an actuation voltage of 25 V.

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Biographies

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