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Monolithic integration of waveguide structures with surface-micromachined polysilicon actuators

J. H. Smith, R. F. Carson*, C. T. Sullivan**, and G. McClellan**

Sandia National Laboratories
Integrated Micromechanics, Microsensors, and CMOS Technology Department
Albuquerque, NM 87185-1080

*Advanced Devices and Applications Department
**Compound Semiconductor Technology Department

ABSTRACT

The integration of optical components with polysilicon surface micromechanical actuation mechanisms shows significant promise for signal switching, fiber alignment, and optical sensing applications. Monolithically integrating the manufacturing process for waveguide structures with the processing of polysilicon actuators allows actuated waveguides to take advantage of the economy of silicon manufacturing. The optical and stress properties of the oxides and nitrides considered for the waveguide design along with design, fabrication, and testing details for the polysilicon actuators are presented.

Keywords: Microelectromechanical systems, MEMS, actuators, waveguides

2. INTRODUCTION

The integration of optical components with micromechanical actuation mechanisms shows significant promise for signal switching, fiber alignment, and optical sensing applications. Monolithically integrating the manufacturing process for waveguide structures with the processing of polysilicon actuators allows actuated waveguides to take advantage of the economy of silicon manufacturing. The interest in integration of micromechanical devices with other structures such as microelectronics is illustrated in a recent overview by Howe[1] and by the commercial success of Analog Device's integrated accelerometer[2]. Recent examples of the application of micromechanical devices to optics can also be found in the literature[3-6]. The eventual goal of this work is to couple recent advancements in actuation mechanisms such as the Sandia Microengine[7,8] to optical waveguides in order to perform optical alignment and switching functions.

There are three principal concerns for integration. First, the stress of the composite structure must be low enough to prevent warping of the underlying polysilicon actuator. Second, the waveguide structure must withstand the micromachining release process. Finally, the waveguide must have acceptable optical properties.

The optical and stress properties of a variety of oxides and nitrides deposited by low pressure chemical vapor deposition have been evaluated in order to optimize the selection of materials and thicknesses for the waveguide design. The waveguide structure itself was designed so that any oxides were completely encapsulated by either nitrides or polymers to prevent etching of these oxides during the sacrificial oxide etch which releases the actuator elements.

The actuated waveguide structures have been fabricated and released. On the initial design, the stress in the polysilicon/waveguide composite was sufficiently low so that curvature of waveguides on cantilever supports was not observed for cantilever lengths below 200 μm.

3. ACTUATORS

Micromechanical actuators have not seen the wide-spread industrial use that micromechanical sensors have achieved. Two principal stumbling blocks to their widespread application have been low force/torque and difficulty in coupling tools to actuators. In the case of actuators with rotary output, researchers at Sandia[7,8] have developed a three-level polysilicon micromachining process which greatly enhances the ability to manufacture devices with higher torque and with the facility for coupling to tools. Figure 1 illustrates a bearing formed between two layers of mechanical poly in this three level, eight mask process. This process has been applied to the microengine shown in Figure 2. Here, two comb-drive actuators[9] drive a set of linkages to a rotary gear. This gear can be rotated by applying sinusoidal driving forces 90^{o} out of phase with each other to each of the comb-drive actuators. The small gear then drives a larger 1.6 mm diameter gear which carries optical elements, in this case a simple shutter. Operation of the small gears at rotational speeds in excess of 300,000 revolutions per minute and an operational lifetime of $3.2x10^{9}$ revolutions have been demonstrated. A rotational speed of 4800 rpm for the 1.6 mm gear has been obtained.

Actuators such as this microengine will be used to position or switch optical waveguides. Ideally, these waveguides will be built as part of the same manufacturing process as the micromechanical components. To date, the work has centered on the evaluation of waveguide materials. Data on these waveguide materials and their behavior when integrated with polysilicon actuators are given below.

4. MECHANICAL AND OPTICAL DIELECTRIC FILM PROPERTIES

Both silicon dioxide and silicon nitride dielectric films are commonly used in the fabrication of conventional microelectronic circuits. Their widespread use in fabrication facilities and their compatibility with conventional IC processes make them a particularly attractive set of materials for use as integrated waveguides. Unfortunately, these films are not always ideal mechanical candidates because of their relatively large built-in stresses.

Silicon dioxide glasses typically have a compressive residual stress after deposition while silicon nitride films are usually quite tensile. If a single film is to be deposited on a flexible micromechanical support structure, excessive stress may cause the micromechanical support to bow. The micromechanical support must be stiffened or the net stress in the deposited waveguide must be reduced to prevent this bow. An additional approach not considered here would be to compensate both the stress and the stress gradient in a waveguide by using multiple layers of materials with opposing stresses.

In addition to stress considerations, the fabrication sequence and the vulnerability of dielectric waveguides to chemical attack must be considered. Since silicon dioxide is used in the surface micromachining process as a sacrificial layer and is also used as a waveguide material, the waveguide oxide must be protected during the release etch from exposure to the etchant. We have chosen to overcoat a composite waveguide structure with silicon nitride to protect the silicon dioxide during the release etch. The details of this structure are given in the next section of the paper.

Several combinations of oxide and nitride films commonly available in CMOS lines were chosen for investigation into their suitability for use as waveguides. A composite structure using a nitride on top of an underlying oxide cladding layer were investigated for thin film stress. The stress in this composite structure dictates the size and stiffness of any micromechanical actuator used to position waveguides made from this film. The results of blanket film stresses extracted from wafer bow measurements are given in Figure 3. Of these film stacks, LPCVD low-stress nitride deposited at $850^{o}C$ from a 4:1 dichlorosilane:ammonia flow on LPCVD TEOS deposited at $700^{o}C$ proved to be the lowest stress. The overall stress of that system was under 10 MPa. The other oxides considered, 2% Phosphorus-doped glass (PSG) and Silane-TEOS, were both deposited at low temperature ($400^{o}C$) from a mixture of TEOS and silane (and phosphine for the PSG).

A wider selection of films was investigated for their optical properties needed to design waveguide structures; i.e., index of refraction. These films included the films mentioned previously as well as glasses doped with both boron and phosphorus (BPSG). Figure 4 gives the indices of refraction for various dielectric films measured by Variable Angle Spectroscopic Ellipsometry (VASE) at two wavelengths and prism refractometry at a single wavelength.

From these stress and index of refraction measurements, a composite waveguide structure consisting of 0.2 μm of low-stress silicon nitride on ~ 1 μm of TEOS was selected for use. Figure 5 is a photograph of bright scattering centers from one of these waveguide structures. Although the stress in these waveguide structures was low, their optical losses were >1 dB/mm as measured with a sliding prism insertion loss technique[10] due to these scattering centers and the high light leakage of the waveguide itself.

Defects present in the nitride film itself or on the surface of the oxide film before nitride deposition are suspect in causing problems with protection of the oxide films during sacrificial etches as well as causing problems by generating light scattering centers within the nitride film. Figure 6 shows a passivated waveguide structure after only a five minutes in the HF-based release etchant (1:1 HF:HCl). Pinholes in the nitride film are evident across the entire sample.

Dielectric film stacks consisting of PSG on TEOS were also measured for their waveguide properties. A loss of only 0.20 dB/cm was obtained for this film stack at 633 nm, measured using a sliding prism insertion loss technique. Although this loss is acceptable for waveguide structures, oxide-only structures are not compatible with the sacrificial technique used for fabrication of the micromechanical devices.

5. INTEGRATED MICROMECHANICAL ACTUATOR TEST DESIGN

The actuator chosen for these studies consists of a simple cantilever beam supported at one end with a waveguide at the center of the beam are shown in Figure 7. This cantilever actuator makes evaluation of the stress effects simple to interpret, yet produces a useful type of displacement of the waveguide. The actuator is deflected electrostatically by applying a bias between the cantilever and the silicon substrate. Figure 8 illustrates the complete fabrication process for these devices. A partially completed test structure with two adjoining cantilevers is shown in the SEM of Figure 9. A completed cantilever with waveguide is shown in the optical micrograph of Figure 10.

6. CONCLUSIONS / FUTURE DIRECTIONS

A nitride/oxide waveguide composite with low residual stress was identified in this work, but the optical properties of the film stack are too poor to make useful optical devices. Light scattering from defect centers within or near the nitride film were identified as one reason for the poor optical qualities of the composite. These same defects prevented the use of thin nitride films for protection of the oxide during the release etch.

An all-oxide composite structure was identified with more promising optical properties, but this structure was incompatible with the micromachine fabrication sequence (polysilicon/oxide) being used. However, conversion to the highly-tensile, stoichiometric SiN for use in a stress-compensated stack may allow use of this dielectric. The stoichiometric SiN may also have less optical scattering centers and pinholes that plagued the low-stress SiN.

The goal of this research is to obtain low-stress waveguide structures which can be fabricated on top of large micromachined actuators such as the Sandia microengine. This goal is now being pursued by using polymer waveguide structures fabricated after completion of the micromachines, but before their release. The challenge with this approach is finding polymer structures compatible with the aggressive, HF chemistry of the micromechanical release process.

7. ACKNOWLEDGMENTS

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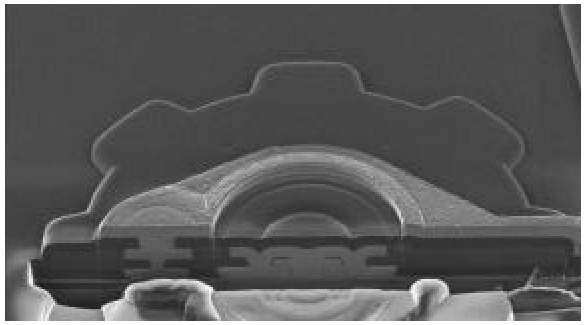

Figure 1. A focused ion-beam cross-sectional image of a gear produced with the MDL's three level polysilicon process.

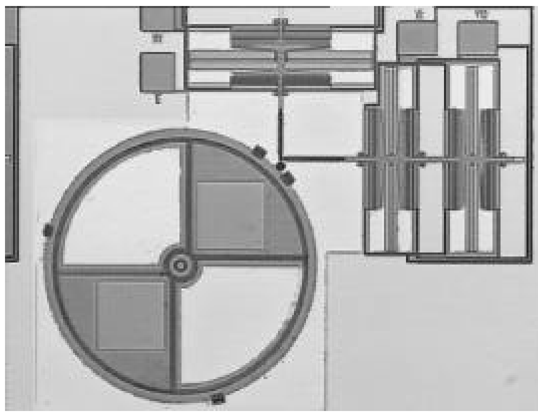

Figure 2. Two sets of linear comb-drive actuators driving the gear shown in Figure . This smaller gear drives a 1.6 mm diameter shutter in the lower left of the photo.

Film	TEOS	TEOS (silane)	2% PSG
Post-Glass Stress (MPa)	<10	135 (comp.)	130 (comp.)
Final Composite Stress (MPa)	<10	35 (tens.)	100 (comp)

Figure 3. Film stress measurements extracted from pre- and post-deposition wafer bow measurements for three composite waveguide structures. The stress in the TEOS stacks was less than the uncertainty in the stress measurement. The composite stress consists of ~ 1 μm of glass covered with 0.2 μm of low-stress silicon nitride.

Material	Thermal Oxide	TEOS	Silane-TEOS	2% PSG	1%/4% BPSG	5%/5% BPSG	PECVD Nitride
Technique (Wavelength)							
VASE (859 nm)	1.455	1.441	1.459	1.463	1.462	1.466	1.933
VASE (633 nm)	1.459	1.445	1.464	1.467	1.469	1.469	1.961
Prism Refractometer (633 nm)	1.457	1.438	1.463	1.461	NA	1.463	1.968

Figure 4. Index of refraction of dielectric materials measured at two wavelengths by two techniques (Variable Angle Spectroscopic Ellipsometry and prism refractometer technique). The measurement uncertainties for the VASE technique are +/- 0.001. The prism refractometer technique had a significantly wider uncertainty.

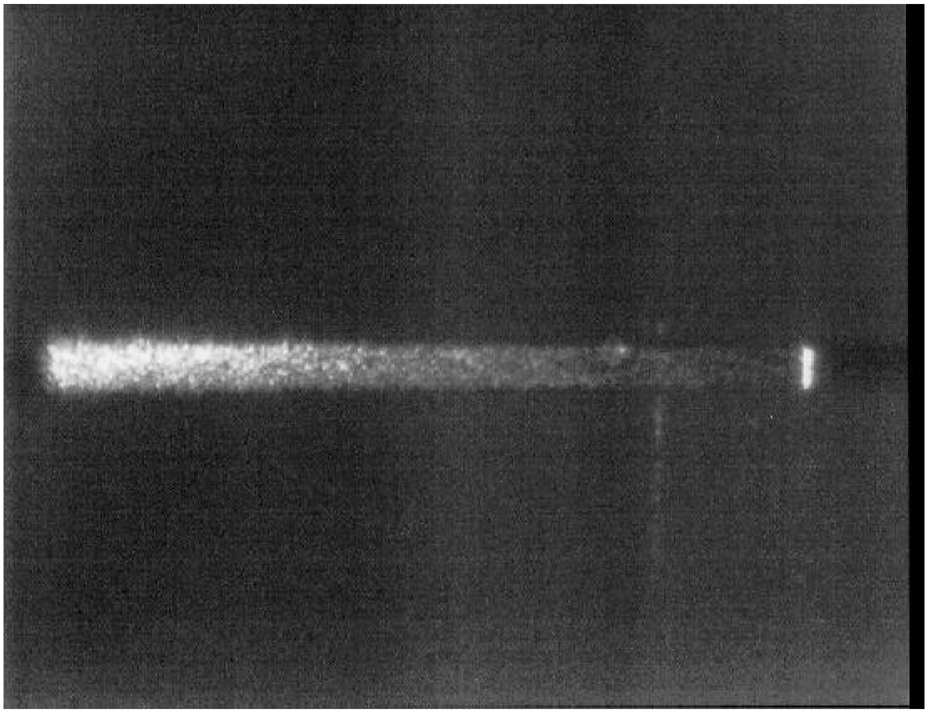

Figure 5. Optical scattering (859 nm) from a 1 mm long, nitride/oxide composite waveguide. A high density of film defects are evident from the bright scattering centers shown in the photograph.

Figure 6. Example of chemical attack of the waveguide structure during the micromechanical release etch due to pinholes in the passivating nitride film. This device is non-functional due to the large number of pinholes.

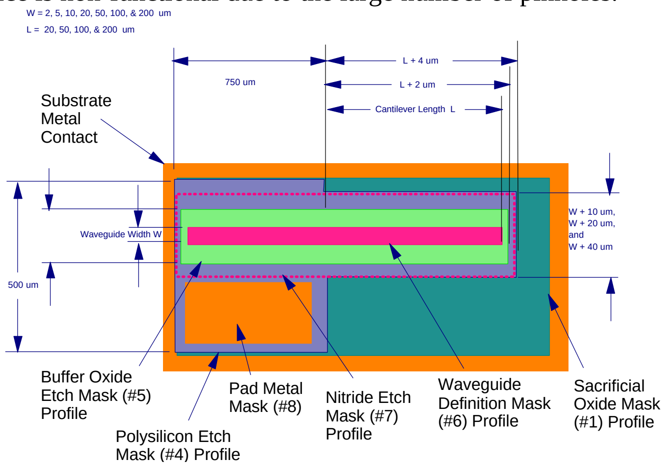

Figure 7. Layout, dimensions, and design rules of cantilevered waveguide test structures.

Figure 8. Fabrication sequence and cross section of a micromechanical device with monolithically integrated waveguide structure.

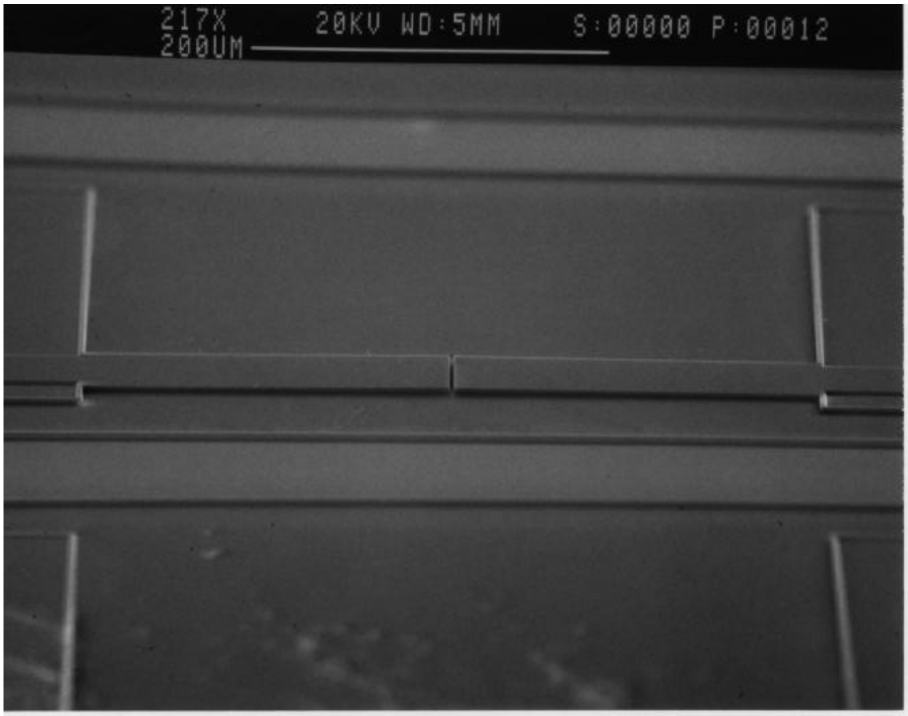

Figure 9. An SEM of two adjoining cantilevers released prior to waveguide deposition arranged to form a simple test/switching structure for waveguides.

Figure 10. An optical micrograph of a completed polysilicon cantilever with an attached, encapsulated waveguide. This structure was fabricated by increasing the thickness of the passivating nitride layer from 0.05 µm to 0.1 µm.