Fabrication and Measurement of Low-Stress Polyimide Membrane for High-Resolution Variable Optical Attenuator

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Abstract—We have fabricated low-stress polyimide membranes for use as high-resolution variable optical attenuator (VOA). Polyimide membranes are assembled with fiber collimators to perform 3-D beam spoiling that varies the optical power with 0.01-dB resolution. The measured residual stress and Young's modulus of the polyimide membrane are 3.2 MPa and 15 GPa, respectively. The 41- μm deformation of the membrane is demonstrated by the electrostatic force with 170 volts. The 0.46-dB insertion loss and >15-dB dynamic range are achieved at 1550-nm wavelength.

Index Terms—Large stroke, low stress, polyimide, variable optical attenuator (VOA).

I. INTRODUCTION

ERBIUM-doped fiber amplifiers have made long-haul wavelength-division multiplexing (WDM) transmission practical. Fiber amplifiers do permit multichannel transmission, but it is critical to maintain signal integrity for all channels after cascading a number of fiber amplifiers. Variable optical attenuator (VOA) is a device that manages signal power in fiber optic links by inducing variable loss. It is used to control the power level of optical signals between outputs of light sources and electrical-to-optical (E/O) converters. It can also be applied to test the linearity and dynamic range of photo sensors and photo detectors. Fiber variable optical attenuator (VOA) has been previously realized by means of liquid crystal, acousto-optic, and microelectromechanical systems (MEMS) devices [1]–[3]. Due to recent fast progress in micromachining fabrication, VOA made by MEMS technology shows high reliability and compact size, which make MEMS VOA promising for telecommunication applications [4]. It was proposed to implement VOA by the optical beam spoiling method [5] and 3-D beam spoiling was realized via a simple micromachined deformable mirror device that changes the focal length of a membrane [6]. The previous membrane approach, however, was made by brittle semiconductor materials. The stroke was generally limited to less than 10 μm , and the highest attenuation was restricted to less than 5 dB.

In this paper, we report a novel MEMS VOA consisting of a deformable polyimide thin film aligned with a fiber collimator in a free-space configuration. Due to the compliant structure of an organic thin film, the deformation of an organic thin film can

TABLE I
LIST OF MATERIALS INDEXES OF THIN FILMS MADE BY DIFFERENT MATERIALS

Materials	Young's Modulus E (GPa)	Failure Strength σ_f (MPa)	Materials Index M
Single Crystalline Silicon	160	6600	4.13E-02
Polysilicon	120	2500	2.08E-02
Silicon Nitride	220	5300	2.41E-02
Nickel	170	195	1.15E-03
Aluminum	75	165	2.20E-03
Polyimide	8.5	580	6.82E-02

attenuate the light intensity >15 dB with 0.01-dB resolution at the wavelength of 1550 nm. The deformation of the membrane is up to 41 μm without permanent warps, and the membrane size is 6 mm $\times$ 6 mm separated from a bottom electrode by 70 μm . First, we discuss the design principle of the device. In Sections II and III, we describe fabrication processes and experimental measurements. Finally, we summarize the paper in Section IV.

II. MATERIAL SELECTION AND FABRICATION

Microfabricated VOA by using deformable membrane was demonstrated earlier [6]. The attenuation range, however, was limited by small strokes due to material properties. In principle, the maximum displacement of an actuator is determined by failure strength of the material (yield and fracture strength for ductile and brittle materials, respectively). In order to compare different materials, a materials index M is defined as [7]

$$M = \frac{\sigma_f}{E}$$

where σ_f is the failure strength and E is Young's modulus. Materials of large values of M are good candidates for high stroke actuators. Mechanical properties of popular materials, including silicon, nitride, and aluminum, are listed in Table I. It is clear that the materials index of polyimide is the highest among listed materials and is a reasonable choice for large stroke applications.

In addition to the effects of Young's modulus and failure strength, one must also take residual stress of thin films into consideration. According to the load-deflection effect, we can obtain the relationship between pressure and deflection as [8]

$$p(h) = C_1 \frac{1}{a^2} \sigma h + C_2 (v) \frac{tE}{a^4} h^3 \quad (1)$$

where p is the applied pressure, h is the center displacement, a is one half of the membrane's edge length, t is the thickness of a membrane, E is Young's modulus, σ is the residual stress, and

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Fig. 1. Schematic drawing of fabrication process.

ν is Poisson's ratio. C_1 and C_2 are numerical constants, which are determined by curve fitting to a load–deflection experiment. We can see that the residual stress is another effective factor in addition to Young's modulus, which determine the needed force. Therefore, if we want to get large strokes with reasonable low actuation force, we must lower the residual stress as well. The most frequently used low-stress membrane materials are single crystal silicon and silicon nitride [9]. Their residual stress are 3–7 MPa and 50–100 MPa, respectively. Young's modulus is 160 GPa for silicon and 220 GPa for silicon nitride. The numbers, however, are large to make deformable membranes with large strokes that can be actuated by electrostatic force. Ideally, we would like to have a membrane with residual stress as low as single crystal silicon, while Young's modulus is maintained one order of magnitude lower than the numbers earlier. As a result, we should look for other appropriate materials to be a membrane structure layer.

It is reported that the yield strain of an organic polymer is around 5%, which far exceeds the breaking limit of semiconductor materials, and Young's modulus is about one order of magnitude lower than that of most inorganic materials [10]. Moreover, some polymers have excellent chemical resistance during wet etching and can be coated at room temperature either by spin coating or injection printing, which require less complicated fabrication processes as compared with standard semiconductor production lines. Based on those characters, organic polymer is an ideal candidate for MEMS deformable membrane applications. We selected a low stress polymer based on biphenyldianhydride/1,4-phenylenediamine backbone chemistry to be our membrane material.

The fabrication process of low stress polyimide membrane is illustrated in Fig. 1. Starting with a 4-in (1 0 0) silicon wafer, 300-nm silicon dioxide was thermally grown on a wafer as a wet etching protection mask. A 6 mm $\times$ 6 mm square opening was patterned on thermal oxide and etched by buffer HF at the backside of the silicon wafer, as shown in Fig. 1(c). The silicon wafer was then anisotropically etched in the solution of tetramethyl ammonium hydroxide (TMAH) at 90 $^{\circ}$ C, as the

Fig. 2. (a) Picture of a fabricated polyimide membrane. (b) Schematic drawing of an assembled device.

silicon etching rate and surface roughness are sensitive to the temperature of TMAH. The etching depth of the silicon was time-controlled to left about 30- μ m silicon membranes before etching through the wafer. The 100-nm aluminum was then deposited by e-beam evaporator on the front side of the silicon wafer with a 20-nm chromium seed layer. A 2- μ m organic thin film was then spin-coated and baked at 350 $^{\circ}$ C in an oven to dry solvents out in the step of Fig. 1(f). Finally, the remaining silicon was etched by deep reactive ion etching (DRIE) and stopped at thermal oxide layer. Thermal oxide and chromium were removed by pad etchant (Pad Etch 4 from Ashland) and Cr etchant (Cr-7T). Pad etchant, which contains acetic acid, ammonium fluoride, surface tension and water, could minimize damages to metal layers. An aluminum reflection layer was undamaged after the etching process and has a good reflectivity at optical communication wavelength [11]. Fig. 2(a) shows a photograph of the fabricated device. The surface of the polymer membrane is smooth due to the tensile residual stress of the polyimide and the surface roughness is measured to be around 20 nm by a white light interferometer. The schematic drawing in Fig. 2(b) shows a polyimide membrane is assembled with a bottom electrode to generate the electrostatic force for actuating a membrane. Experimental results are discussed in Section III.

III. STRESS MEASUREMENT AND DEVICE CHARACTERIZATION

A load–deflection experiment [12] is applied to measure the residual stress and Young's modulus of a membrane. Equation (1) can be translated to (2)

$$p'(h') = C_1 \frac{t\sigma}{a^2} + C_2(\nu) \frac{tE}{a^4} h' \quad (2)$$

where $p' = p/h$ and $h' = h^2$. As a result, p' becomes a liner function that the slop is proportional to Young's modulus and the intercept is proportional to the residual stress. The measurement was done by using pneumatic force to pull down a membrane and

Fig. 3. Experimental results of residual stress and Young's modulus.

Fig. 4. Experimental results of center displacement versus applied voltage.

experimental results are shown in Fig. 3. The length of the tested membrane is 6 mm and total thickness is $2.35 \mu\text{m}$. According to the fitting curve, we concluded that residual stress is 3.2 MPa and Young's modulus is 15 GPa. We believe that the residual stress can be lowered by optimizing substrate condition because the multilayer coefficient of thermal expansion (CTE) mismatch would alter the stress during a polymer curing step [13]. The polymer membrane is actuated by the electrostatic force. The schematic drawing in Fig. 2(b) shows the experiment setup. A bottom electrode and a membrane are separated by a $70\text{-}\mu\text{m}$ spacer. The center displacement versus applied voltage is shown in Fig. 4. The maximum deformation toward bottom electrode is about $41 \mu\text{m}$ as applying 170 V, and its equivalent radius of curvature is approximately 110 mm. This is about one order improvement over the popular deformable mirrors from OKO Technology, Holland, the membranes of which are made with silicon nitride [14]. The snap down effect of a membrane is observed when the stroke of a membrane is slightly larger than half of the gap spacing. There is no permanent damage to the membrane when it is snapped down because the yield strength of a polyimide membrane can survive such deflection.

A deformable membrane has a lot of applications, such as adaptive optics [15], and $1 \times N$ optical switches [16], etc. In this paper, we made use of fabricated membranes as high-resolution variable optical attenuators. The working principle is based on the phenomenon that the focal length of a deformable mirror is altered when a membrane is changed from a flat surface to

Fig. 5. Schematic drawing of a deformable membrane VOA.

Fig. 6. Attenuation versus applied voltage.

a concave shape. This variable focusing effect can be used to change the working distance of a self-imaging fiber collimator, as shown in Fig. 5. In this design, a single collimator lens is used as the input and output port of the VOA via an optical circulator. The total insertion loss of the device is 3.61 dB, including the circulator and the single collimator lens. The circulator shows 1.56 dB and 1.49 dB losses from port 1 to port 2 and port 2 to port 3, respectively. The single collimator lens introduces additional 0.1-dB loss. Therefore, the polyimide membrane accounts for the remaining 0.46-dB loss, which is in part caused by surface roughness of the membrane. The expanded optical beam with 2.2-mm diameter is reflected by the membrane mirror and is coupled back into the collimator. The path length for the return signal is kept equal to the working distance of the lens. The focusing characteristic of the deformable mirror is used to change this working distance for an optical beam, hence, introducing a coupling loss. Fig. 6 shows the experimental data of optical attenuation versus applied voltage. The maximum optical attenuation is around 18 dB at 170 V. Compared with a similar silicon nitride membrane design [6], the attenuation range is improved from less than 5 to about 18 dB. The average slope of attenuation is about 0.1 dB/V. In theory, fine adjustment of 0.005 dB could be achieved by utilizing a dc power supply with 50-mV resolution. However, in the lab experiment, the best resolution we observed is 0.01 dB because the minimum digit of our power meter is 0.01 dB.

To measure the response time of the membrane, an open-loop square wave was applied directly to the device. When the electrical signal was switched on, the membrane was deformed to its maximum stroke and the optical signal was dropped accordingly. The response time was 14 ms from zero attenuation to higher attenuation range, as shown in Fig. 7. Regarding the

Fig. 7. Response time of VOA.

long-term reliability, we suspect that moisture absorption and oxygen might break down the chemical links inside organic materials, as reported in other organic light emitting diode (OLED) research works [17]. As a result, appropriate hermetic packaging and surface treatment [18] are needed to ensure the reliability of a polyimide membrane.

IV. CONCLUSION

A polyimide-based deformable membrane was successfully fabricated. Its surface roughness was measured about 20 nm and the insertion loss caused by the membrane is 0.46 dB. The load-deflection experiment result shows significantly low residual stress of 3.2 MPa and Young's modulus of 15 GPa. According to these material properties, the displacement as large as 41 μm is achieved without any crack. Since the deformable range is larger, it can be potentially applied to many other optical applications.

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