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A heat-resistance and high-sensitivity acoustic pressure sensor based on aluminum-polyimide diaphragm

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ABSTRACT

A fiber-optic acoustic pressure sensor based on aluminum-polyimide diaphragm is proposed in this paper. The sensing diaphragm exhibits excellent properties including heat resistance and long-term stability (4 months). Together with hybrid configuration of Mach-Zehnder and Sagnac interferometer with triple detection passive demodulation algorithm, the sensor can measure the absolute amplitude of acoustic pressure. The sensor has a high sensitivity of 110 nm/Pa with the acoustic pressure amplitude of 2.05 mPa–7.15 Pa and gives a minimum detectable pressure of 37.7 μPa/Hz$^{1/2}$ at 4 kHz. The sensor also demonstrates a flat frequency response in the range of 600 Hz–6 kHz and is expected to be used for weak acoustic pressure sensing and photo-acoustic spectroscopy.

Contents

1. Introduction

Fiber-optic microphone has many advantages in comparison to the conventional capacitive microphone including electrical insulation, immunity to electromagnetic interference, high sensitivity and so on [1]. Fiber-optic Fabry-Perot interferometers (FPIs) called diaphragm based FPIs, with a hollow-cavity covered by a deflectable diaphragm, have been studied extensively due to their high sensitivity and compact size [2–4]. In general, the deflectable diaphragms can be made of various materials, such as silica, silver and graphene. Recently, J. Ma reported an acoustic pressure sensor based on a multilayer graphene diaphragm with 100 nm in thickness and obtained the sensitivity of 1100 nm/kPa with the diaphragm diameter of 125 μm [5]. However, it is difficult to prepare and transfer large diameter graphene diaphragms to the sensor head. Moreover, optical reflectivity of the graphene diaphragms is relatively low compared to metal diaphragms. F. Xu reported an acoustic pressure sensor based on a large area nanolayer silver diaphragm with 150 nm in thickness and obtained the sensitivity of 160 nm/Pa with the diaphragm diameter of 2.4 mm [6]. For silver diaphragm, it is usually difficult to maintain the flatness of the diaphragm by the electroless plating method and the result hasn't good repeatability. In addition, the sensors can't measure the absolute amplitude of acoustic pressure.

In this paper, we demonstrate a fiber-optic acoustic pressure sensor based on aluminum-polyimide diaphragm with about 1 μm in thickness and 3.1 mm in diameter. The basic theories of hybrid configuration of Mach-Zehnder and Sagnac interferometer with triple detection passive demodulation algorithm for measuring the absolute amplitude of vibration have been described in

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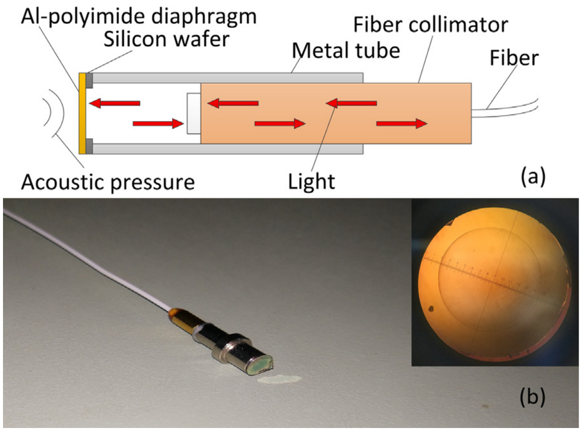

Fig. 1. (a) Schematic (b) image of the sensor head.

our previous work [7]. In this paper, the absolute amplitude of aluminum-polyimide diaphragm deflection induced by acoustic pressure will be measured. Although the sensor is similar to that of diaphragm-based fiber-end FPIs, only the reflections from the aluminum-diaphragm form useful signals. In order to ensure that no F-P fringes could be generated, we choose the type of fiber collimator consisting of the SMF whose end facet with a tilted angle of 8° and the lens surface with high quality anti-reflective coating. The schematic of the sensor head is shown in Fig. 1(a), the aluminum-polyimide diaphragm was fixed on the end of a metal tube, and light is emitted from a fiber collimator to the surface of the aluminum-diaphragm. Fig. 1(b) shows the image of the sensor head, materials of the diaphragm are aluminum and polyimide. Polyimide has many unique advantages such as high strength, high and low temperature resistance (−269 °C∼+250 °C) [8], radiation resistance and good chemical stability.

2. Fabrication process of the aluminum-polyimide diaphragm

The process for preparing the aluminum-polyimide diaphragm by silicon etch and magnetron sputtering methods as shown in Fig. 2.

(a) Depositing a layer of metal consisting of the chromium with 20 nm thick and aluminum with 200 nm on the surface of silicon wafer by magnetron sputtering method. (b) Coating photoresist on the metal layer surface, then transferring the pattern printed on the film to the surface of the metal layer under the exposure of UV light. (c) Etching away the metal layer which is not to be protected with cured photoresist by Ion Beam Etching (IBE) method. (d) Depositing a layer of aluminum with ∼30 nm thick on another side of silicon wafer. (e) Coating a layer of polyamic acid solution with <1 μm thick by centrifugal device, and conducting the process of imidization. (f) Etching the silicon under the corrosive gas by Inductively Coupled Plasma (ICP) method. (g) Finishing etching and releasing the aluminum-polyimide diaphragm. (h) Making the sensor with fiber collimator. (i) Temperature-time curve of the process of imidization.

Above the surface of silicon wafer, the aluminum layer is base part and the polymide layer is the main part of aluminum-polyimide diaphragm. The way of preparing aluminum-polyimide diaphragm has the following advantages: (1) Compared with polymide diaphragm, aluminum can make the aluminum-polyimide diaphragm avoid the holes generating on the surface of silicon wafer for polyamic acid solution could not easily adhere to the silicon wafer. The images of the diaphragm were shown in Fig. 3. (2) Aluminum layer can make the surface of aluminum-polyimide diaphragm keep smooth and increase the reflectivity. (3) In the process of silicon etch, aluminum can protect the polyimide layer. (4) Polyimide can keep the internal stress in balance and maintain the flatness of the aluminum-polyimide diaphragm. (5) Polyimide can make the framework of the aluminum-polyimide diaphragm stable.

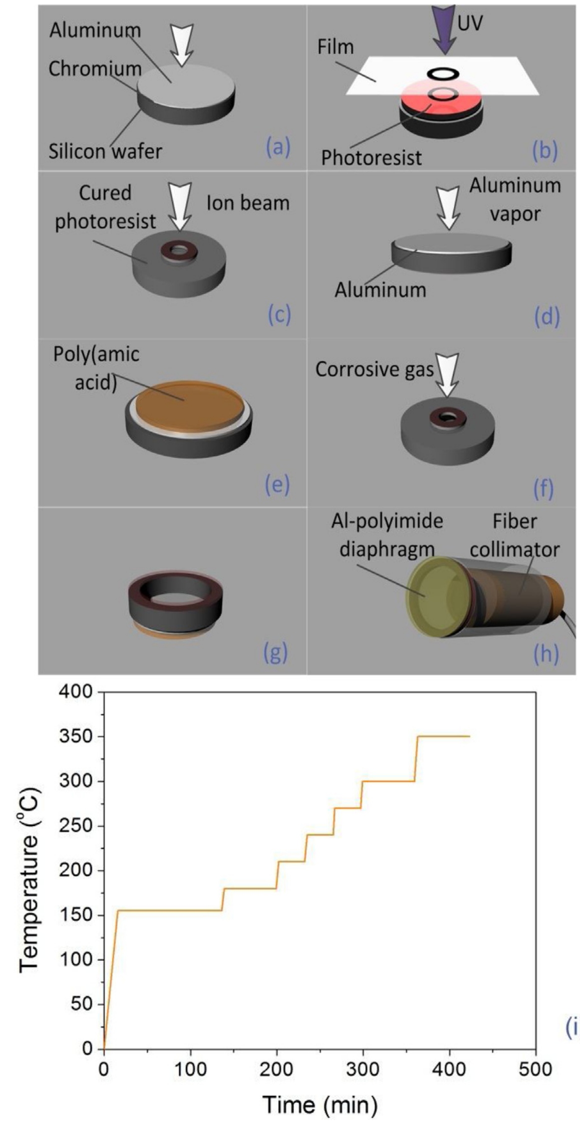

Fig. 2. Fabrication process of the aluminum-polyimide diaphragm.

3. Experiments and results

The experimental setup is shown in Fig. 4. An amplified spontaneous emission (ASE) light source (1550 nm) with power of 13 mW was adopted as a light source of the system. The sensor head was placed into an acoustic isolation box (B&K 4232), a vibration exciter (B&K 4809) and a microphone (B&K 4192) were used to calibrate the acoustic pressure applied on the aluminum-polyimide diaphragm of the sensor head. The incident light is projected onto the surface of the aluminum-polyimide diaphragm and returns back along the optical path. There are two paths which have the same optical length and could generate interference signals: 1) E-D-L-F-E, 2) E-F-L-D-E. The signals were transferred into NI-DAQ (NI-USB 6351) by photoelectric conversion and amplification. Then the signals were reconstructed by demodulation algorithm (Labview 2013) in PC.