Sensors and Actuators A 160 (2010) 35–41

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

A hollow stiffening structure for low-pressure sensors

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ARTICLE INFO

Article history:
Received 15 December 2009
Received in revised form 18 February 2010
Accepted 12 March 2010
Available online 18 March 2010

Keywords:
Pressure sensor
Electrochemical etch
Hollow structure
Boss
Diaphragm
Silicon

ABSTRACT

This paper presents a novel process for producing thin-walled hollow stiffening structures on thin silicon diaphragms using an electrochemical etch-stop process. Examples of structures produced using the method are presented together with focused ion beam (FIB) analysis of critical areas within the structure. These demonstrate the integrity of the structures and show that the process is suitable for use in MEMS sensor applications. Using this process a 30 mbar full-scale differential pressure sensor has been demonstrated, and used to verify the suitability of these hollow structures for use in MEMS sensors. The novel process allows for increased sensor performance, with reduced die size. Details of the pressure sensor design and characterization are presented, showing a device with 18 mV/V full-scale output with linearity <0.4% (terminal base non-linearity).

1. Introduction

Piezoresistive silicon pressure sensors typically consist of a wheatstone bridge of piezoresistors fabricated on a square silicon diaphragm. The sensitivity of these sensors will be inversely proportional to the square of the diaphragm thickness, and directly proportional to diaphragm area [1]. To fabricate higher sensitivity devices the designer is forced to increase die size or reduce diaphragm thickness. Cost constraints often lead the designer towards reducing die size. Therefore the approach taken is generally to reduce diaphragm thickness in order to meet the required sensitivity. Silicon diaphragms for MEMS pressure sensors are typically fabricated by wet anisotropic etching of a cavity into bulk silicon, and to achieve a required diaphragm thickness requires careful timing of this etch. Even if great care is taken to continually monitor the etch in order to achieve the desired thickness, process variation from wafer to wafer, and from die to die within a wafer will ultimately dictate the minimum practicable thickness. Typically diaphragms thinner than 40 μm prove challenging for many manufacturing environments [2]. To overcome this problem there are a number of etch-stop methods that may be employed to automatically stop or limit the anisotropic etching once the required thickness has been reached. Examples of such techniques are, the use of silicon on insulator wafers [3], the boron etch-stop process [4], or an electrochemical etch-stop [5,2]. In this work the electrochemical etch-stop technique is used to form the basis of a novel process that firstly addresses the issue of increased sensitivity by allowing thinner diaphragms, but also allows for additional structuring of the diaphragms to improve other device performance characteristics such as output linearity.

As high sensor linearity is often a very attractive sensor characteristic, flat silicon diaphragms are generally modified with the addition of a lump or 'boss' structure to stiffen the centre of the diaphragm. Fig. 1 shows a micrograph of a typical pressure sensor diaphragm with a central stiffening boss, the cross-section marked on the micrograph can be seen as a schematic in Fig. 3b. These features improve linearity by limiting strain stiffening of the diaphragm, which is a significant cause of output non-linearity [6]. The addition of such stiffening bosses is often done at the expense of other device parameters such as die size. Fabricating the boss on the diaphragm generally increases die size, and the additional mass that is suspended will tend to cause increased acceleration sensitivity. This acceleration sensitivity becomes especially critical as higher sensitivity pressure sensors are fabricated. This is because the diaphragm that is supporting the boss becomes increasingly flexible, thus any inertial loads imposed on the boss will result in a greater deflection of the diaphragm and thus be seen as a more significant proportion of the sensor output.

To address these issues this work presents a novel fabrication route that allows for a wide variety of hollow structures to be fabricated on the surface of a thin silicon diaphragm. These structures may be used, in effect, as hollow bosses that have considerable stiffness relative to the diaphragm, yet due to their hollow construction add very little mass to the diaphragm (see Fig. 3c). The diaphragm and hollow bosses are produced using an electrochemical etch-

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0924-4247/$ – see front matter
doi:10.1016/j.sna.2010.03.024

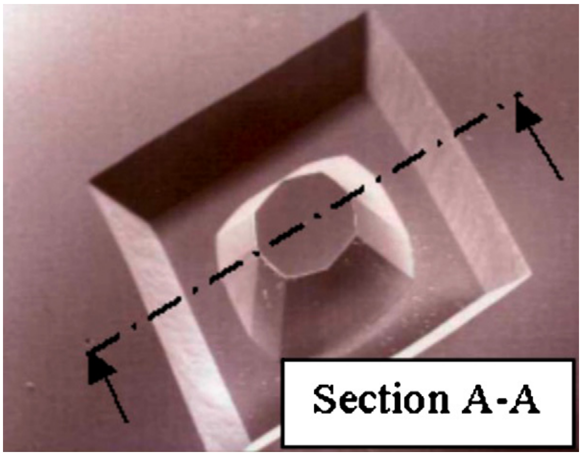

Fig. 1. Micrograph of an etched pressure sensor diaphragm with a solid lump at the centre, the diaphragm is approximately 1.5 mm square.

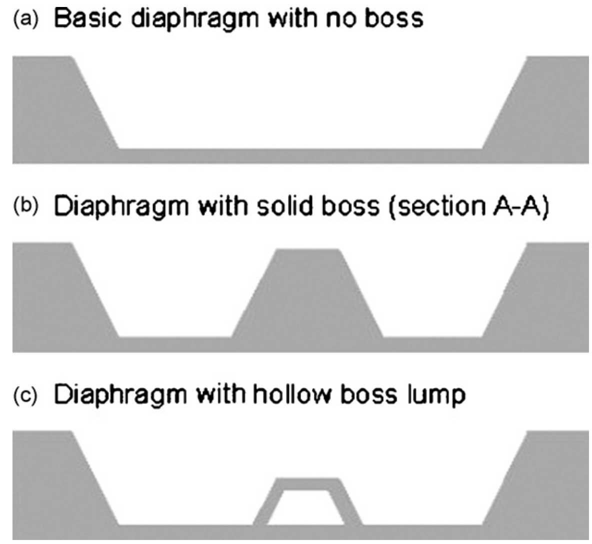

Fig. 3. Cross-sectional schematic view of a boss etched into a wafer follow (1 1 1) crystal planes.

stop technique and therefore this allows for controlled etching of thin diaphragms that are <10 μm in thickness. The combination of these features allows the advantages gained by a stiffening boss in terms of sensor linearity, without either the negative affects of inertial sensitivity, or unnecessary increase in die size that may result from traditional fabrication techniques that produce solid bosses. For example the increase in die size comes about due to the constraints imposed by standard processing methods. These typically require that the boss is patterned on the surface of a wafer then etched down following (1 1 1) crystal planes to reveal pyramid shaped bosses with sloping sidewalls of 54.7° as shown in Fig. 2. Etching bosses in this way means the designer is constrained to use bosses that may be taller or wider than required. This has the adverse affect of removing active diaphragm area and therefore leads to an increased die size, as the designer has to compensate by increasing the diaphragm area. The hollow boss process is not limited by these constraints and allows boss heights independent of wafer thickness.

In the following sections the innovative process that was developed to fabricate hollow bosses will be described, demonstrating that in principle the technique may be used to create a wide range of generic hollow structures suitable for many MEMS applications. A specific example of the technology is then given in the form of a piezoresistive pressure sensor. A description of the design and fabrication work carried out to develop test samples of a prototype pressure sensor are detailed. Finally, analysis and characterization are presented that verify the performance of the pressure sensor and validate the feasibility of the hollow structures for use as mechanical elements in MEMS sensors.

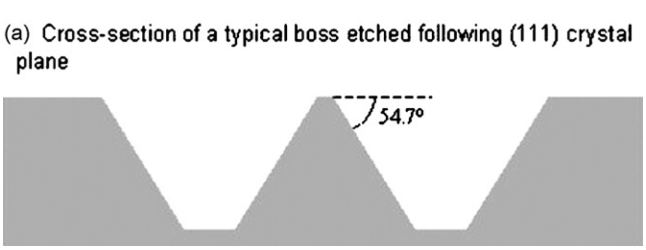

Fig. 2. Cross-sections of three types of pressure sensor diaphragm, type a is the most basic form of diaphragm that is completely flat, type b is the traditional form of diaphragm that contains a solid lump, and type c is a hollow version of the solid lump.

2. The hollow boss process

In order to create thin-walled hollow structures using wet etching in a KOH solution the hollow boss process has been developed. An overview of the process is shown in Fig. 4 and it consists of five main process steps. Firstly a p-type silicon wafer is prepared and suitably patterned for etching (step 1); then a negative of the required boss is etched into a silicon wafer (step 2); the etched feature is implanted to render a layer of n-type silicon in the p-type substrate (step 3); a second n-type layer is then fusion bonded over the previously etched and implanted features (step 4); finally the p-type substrate material is etched away using an electrochemical etch-stop process to reveal a hollow structure.

The electrochemical etch-stop, which is a key part of the process, results from the application of an anodic potential to silicon in OH-containing solution that causes the formation of silicon oxide on the silicon surface, known as passivation. The process demonstrated here utilises the difference in passivation potentials of n-type and p-type silicon to generate an automatic etch-stop process that can preserve a hollow boss structure [5,7]. A fixed voltage, between the n-type and p-type passivation potentials, allows the p-type to etch, but causes passivation on reaching the n-type layer, marked by the cessation of bubble evolution at the etch surface. Since silicon oxide etches at a rate of approximately 100th that of silicon n-type and is self-sustaining under the cell potential, the integrity of the etch-stopped layer may be preserved for many times the lifetime of a standard sacrificial oxide. The electrochemical etch-stop was set-up as shown in Fig. 5.

To calculate the correct passivation voltage, data showing the relationship between current and voltage was collected for wafers and electrodes being used, see Fig. 6. The maximum current reached on the chart shown in Fig. 6 corresponds to the passivation potential, which was 1.05 V. A power supply (indicated by PS in Fig. 5) with fixed anodic potential of at least 1.2 V was connected to an aluminum contact on the n-type layer of the silicon wafer, such that the wafer potential was always above the n-type passivation potential. The n-type surface was wax-bonded onto glass for protection of the sensing structure. A nickel plate was inserted into the solution and formed the cathode. The p-type silicon etched in normal anisotropic fashion in the aqueous KOH solution, as it was well below the p-type passivation potential. The electrochemical etch-stop ensured passivation of the hollow structure and allowed it to be fully revealed as the etch progressed.