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Thin film stress sensor suitable for different substrates

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Abstract

In this paper we present a device, based on amorphous silicon technology, able to perform mechanical stress measurement with both good linearity and sensitivity. A room temperature process is performed to form a very thin film of chromium silicide on the top of an amorphous silicon layer. The chromium silicide acts as the active region of the device. From an electrical point of view, the sensor can be considered as a bridge of resistances. Two contacts of the bridge are used to apply the bias current to the sensing element, while the other two, orthogonal to the previous ones, provide an output voltage proportional to the anisotropic modification of the resistivity induced by the mechanical deformation. The device is able to measure both the bending and torsion force, depending on orientation and geometries with respect to shape and location of the contacts. In this paper, results obtained on devices fabricated on several materials (glass, metal and ceramic) will be discussed.

Keywords: Strain gauge, amorphous silicon, pressure sensor, stress sensor

1 Introduction

Mechanical stress is an important physical parameter in various areas of application, such as industrial automation, mechanics, automotive and medical engineering. In particular force and tactile sensors have been introduced in robotics since the early stage of its development, as dextrous manipulation with robotic hands [1, 2, 3] or micro devices [4]. Other interesting applications of these sensors are in medicine, in particular in exploration, diagnostic and surgery, where small dimensions of the sensor and high reliability of their measures are of primary importance [5]. On the other hand, commercially available sensors are often not suitable for these applications essentially because of the size and wiring constraints.

The common approach to stress measurement is essentially based on the use of piezoresistors connected as a Wheatstone bridge and realized in different technologies (metal or semiconductors). A mechanical stress applied to the structure induces an anisotropic modification of the resistivity and as a consequence an unbalancing of the bridge, that shows, as output signal, a voltage between two opposite metal contacts. Unfortunately, the piezoresistors approach has different limitations: large area, many connections to realize bridge circuit, resistors values mismatches, small sensitivity and high temperature drift [6].

The piezoresistive properties of crystalline silicon have long been used in the fabrication of strain gauges and other electromechanical transducers [7]. On the other hand the use of silicon thin film technology at low substrate temperature using novel substrates, like plastic, metal or ceramic, has recently received great attention due the new large area applications [8, 9].

In this paper, fabrications and characterizations on different substrates of an hydrogenated amorphous silicon (a-Si:H) based stress sensor are presented.

An important advantage of our device with respect to the existing approaches is due to the low temperature fabrication process, which is lower than 150°C for all the technological steps. Furthermore, the sensor element can be deposited directly on the stressed materials without additional packaging. This avoids the use of the adhesive resin which usually affects the device performances.

2 Device structure and operation

Fig.1 shows the basic structure of the sensor element. It consists of a n-type amorphous silicon layer and of a very thin and high conductivity chromium silicide film.

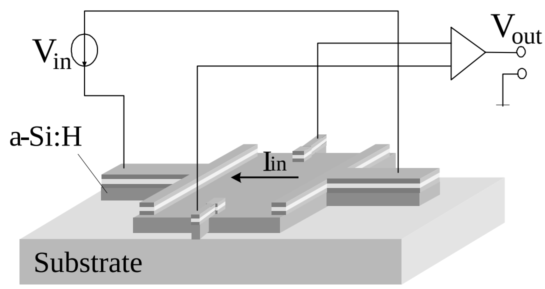

Figure 1. Structure of the stress sensor.

Amorphous silicon material has been deposited by Plasma Enhanced Chemical Vapor Deposition (PECVD) in a high vacuum deposition system, with the following recipe:

> gas flow of pure silane 40 sccm; silane diluted phosphine 10 sccm; pressure 300 mTorr; power density 25 mW/cm^2; deposition temperature 150 °C; thickness 500 nm.

A three-layer chromium-aluminum-chromium (15/300/15 nm) was vacuum evaporated and patterned by photolithographic process and chemical etching, in order to form the metal contacts of the bridge. Thicker chromium layer induces mechanical stress with the underlying silicon and then to avoid this problem a thick aluminium layer is used as conductive electrode. The top chromium has been used to avoid some technological problems in our lithography process.

A reactive ion etching (RIE) has been performed in O_2 (10sccm) / CF_4 (100 sccm) gas mixture, to define the active area of the sensor (300 x 300 μm^2).

At the interface between the amorphous silicon and chromium, a very thin chromium silicide layer is formed. This layer is not chemically removed by the wet etching and acts as active material between the metal contacts. In fact, the resistance value measured between two contacts of the bridge is around 7.5 kΩ. This value is about two order of magnitude lower than the resistance expected for the n-doped layer [10]. The resistance decrease is ascribed to the formation of a layer of chromium silicide [11] at the interface with the n-type film. After 15 s dry etching process, the silicide layer is removed and the conductivity of the layer becomes the typical one of an a-Si:H n-doped layer (2.5x10^{-2} Ω^{-1}cm^{-1}).

Taking into account the etching rate of our system, the estimated thickness of the layer is only 10 nm. All the measurements presented below have been performed on samples where the silicide was not removed.

From an electrical point of view, the sensor can be considered as a simple bridge of resistances, where the resistances are due to the conductivity of the chromium silicide film. As in a Wheatstone bridge structure, two contacts of the bridge are used to apply the bias current to the sensing element, while the other two, orthogonal to the previous ones, provide an output voltage proportional to the anisotropic modification of the resistivity induced by the mechanical deformation (see figure 1). The device is able to measure both the bending and torsion force, depending on orientation and geometries with respect to size and location of the contacts. Figure 2 shows that the reciprocal orientation between the contacts direction and the applied stress (σ_x) strongly affects the measurement.

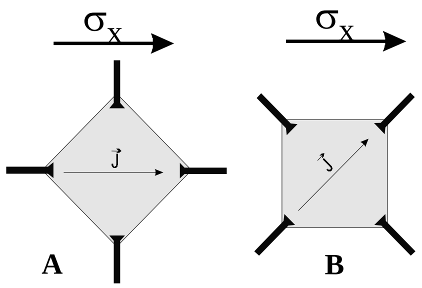

Figure 2. Possible orientation of the sensor contact with respect to the direction of applied stress σ_x. J indicates the bias current and the arrow its direction.

For the sensor A, the components of the applied strain along the direction between the electrodes of the sensor are equal. In this case a deformation of the film surface induces equal variations of the resistances of the bridge and the output voltage is zero. Sensor B is rotated of +45° with respect to sensor A and, due to rotation, the components of the applied stress are different for the different directions between the electrodes. As a consequence the sensor output will be different from zero.

3 Sensor performances

The presented sensor has been deposited on different substrates: glass, metal and ceramic. In order to generate mechanical stress, the substrates have been clamped at one side and a vertical or torque force has been applied to the other side (Figure 3).

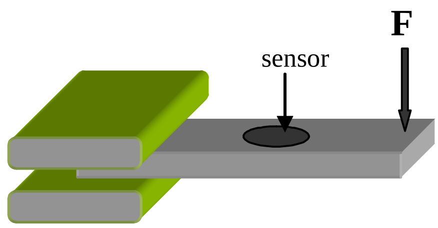

Figure 3. Experimental set-up used to induce mechanical stress in the sensor.

The output voltage has been measured by means an “ad hoc” designed circuit. The circuit includes the current supply, a section for minimizing the offset voltage due to the mismatches in the bridge resistors and a differential voltage amplifier.

3.1 Glass substrate

The sensors have been fabricated on a Corning Glass 7059. In figure 4, the output voltage of two sensors (A and B), whose orientation with respect to the applied stress is equal to the one reported in figure 2, are shown. The applied strain acts with the same intensity on the bridge resistances of sensor A and then the slope of the corresponding output voltage is much lower than the slope of the sensor B, whose bridge resistances are rotated of +45° with respect to the applied strain.

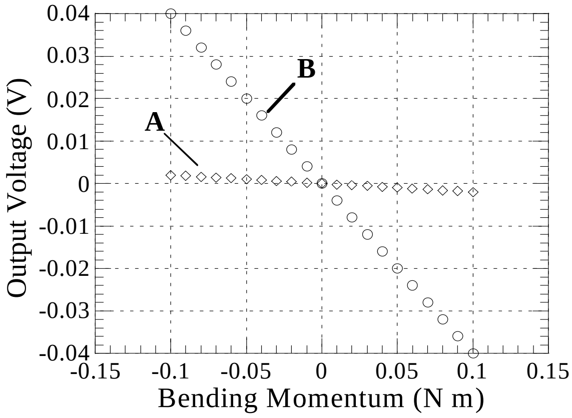

Figure 4. Response of the sensor to bending momentum. Letters refer to geometries of figure 2.

It is worth noticing that high linearity, observed in our measurements, is due to the deposition of the device directly on the substrate, since the linearity in the sensor response are usually affected by the adhesive resin used to fix the sensor element [12].

Furthermore, we observe that all the lines cross the axis origin. Due to unwanted mismatches during deposition and/or lithography processes, we measured an offset of ≈40 mV at the sensor output. This value has been cancelled out by signal conditioning and trimming procedures. In this way, the signal can be either positive or negative, depending on the bending direction.

3.2 Steel substrate

When the sensor is grown on metal substrate, as in this case, it is necessary to have an isolation layer between metal and amorphous silicon layers, because the very low transverse resistivity of the doped amorphous silicon directly connects the electrodes and the substrate. For this reason, we deposited a 500 nm thick silicon nitride film using the same deposition system of the amorphous silicon film. The deposition parameters are the following:

> gas flow of pure silane 10 sccm; pure ammonia 100 sccm; pure helium 600 sccm, pressure 1000 mTorr; power density 50 mW/cm^2; deposition temperature 230 °C.

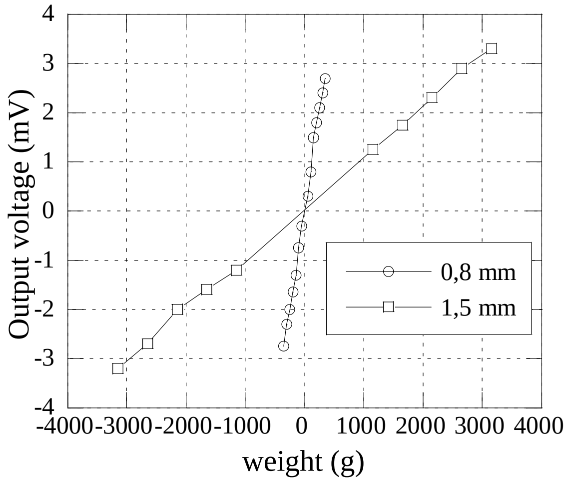

Figure 5. Measured output voltage of the sensor grown on steel substrates with different thicknesses.

Two different substrate thicknesses (0.8 mm and 1.5 mm) have been used. Results of output voltage vs applied weight on the free side of the substrate are shown in figure 5. The two devices are equal and both are oriented as sensor B in figure 2. Due to the different substrate thicknesses, equal weights determine different deformations of the two substrates. Since the sensor is sensitive to the strain, the two slopes of the sensor responses on the two substrates are different. In particular, for the structure of figure 3 the maximum bending, S, of the substrate (which occurs at the free side of the substrate) when a force F is applied, is equal to:

$$S = F\, l^3 / \, 3EI \qquad 1)$$

where E is the Young's modulus of the material (for steel is 206000 N/m^2), and I is the aspect ratio = (b* h^3)/12. l, b and h are the length (10 cm), the width (2 cm) and the thickness (0,8 and 1,5 cm) of the our substrates, respectively.

In figure 5 the output voltage of the stress sensor is reported against the weight applied to the two substrates. The slopes of the two curves are equal to 1,1 and 8 µV/g for the 1,5 and 0,8 mm substrates respectively. The ratio of the two slopes is very close to the ratio of the cube of the thicknesses as calculated from the equation 1.

3.3 Ceramic substrate

A circular ceramic membrane, with 9 mm diameter and 0.6 mm thickness, is used as substrate for the a-Si:H sensor.

The ceramic membrane has been positioned as a cap of a volume that has been emptied by a rotary vacuum pump. The membrane deformation, proportional to the pressure, has been monitored measuring the sensor output voltage.

The characterization of a multi-contact sensor, with a rectangular sensitive area of 3.5×1.5 mm^2 has been performed. The polarization current flowed along the diagonal and the output voltage has been measured between two contacts (see upper part of figure 6). In particular, the maximum gain, close to 0.05 mV/mBar is achieved in case C where the output voltage is measured through the other diagonal of the sensor structure (see lower part of figure 6).

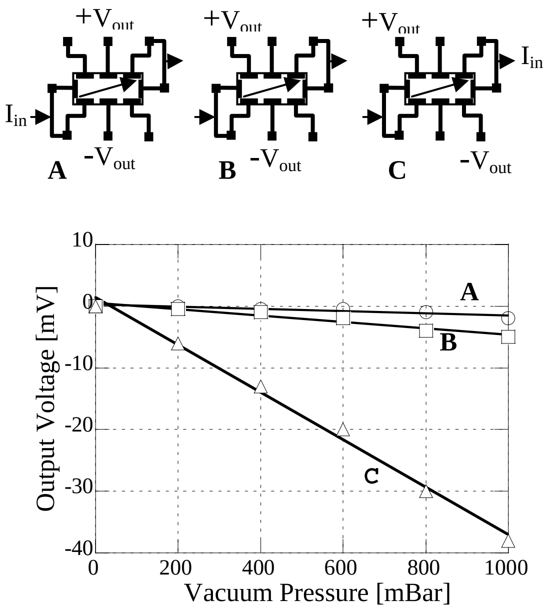

Figure 6. Structure (upper part) and response (lower part) of the device used as pressure sensor.

4 Conclusions

An hydrogenated amorphous silicon based stress sensor has been presented. The active layer is a very thin silicide chromium layer grown on a n-type a-Si:H region. The fabrication and characterization on different kind of substrate (glass, steel and ceramic) has been reported, showing the suitability of our sensor for different applications.

5 References

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