A Miniaturized Thin-Film Germanium Strain Gauge Suitable for Mass-Production

A. Khakifirooz, S. S. Mohajerzadeh, and E. Asl Soleimani
Electrical and Computer Engineering Dept.
University of Tehran
P.O. 14395-515, Tehran
Iran

Abstract : A miniaturized thin-film germanium strain gauge, suitable for batch fabrication is reported. Lithography is used to pattern individual devices. Unlike conventional techniques using shadow-masking, small geometry structures, arranged in measurement arrays can be obtained. Effect of substrate temperature on the electrical and morphological characteristics of germanium films is studied and the optimum temperature of 400°C is selected. The structure consists of two perpendicular, 1000Å thick germanium resistors on a 25µm thick mica substrate. A bi-layer Al/Cu metallization was used to allow soldering. Then a modified process is suggested which facilitates precise control of film conductivity and results in better matching from batch to batch. The fabricated sensors have a gauge factor of about 10 and good long-term stability

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1. Introduction

Semiconductor strain gauges have gauge factors at least an order of magnitude greater than their metallic counterparts [1,2]. In spite of their larger strain sensitivity, the widespread use of semiconductor strain gauges has been limited mainly due to their high temperature sensitivity [1,2]. The main exception is diffused silicon gauge for pressure sensors and accelerometers, where the sensor integration is the key. However, bulk silicon strain gauges have some disadvantages for other applications. These are bad flexibility, high fabrication price, and leakage current [1].

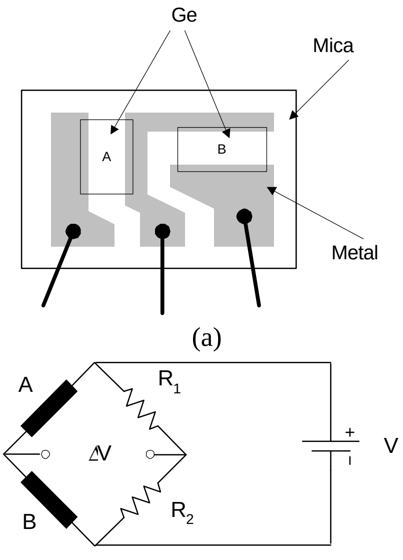
Thin-film semiconductor strain gauges are of interest for their high sensitivity while having low fabrication cost and good flexibility. They can be deposited directly on the sensing element, reducing the creep effect [1]. Semiconductor thin-films can be obtained by various methods including evaporation [3,4], sputtering and CVD [5]. However, their characteristics depend strongly on deposition conditions and method. Evaporating elemental semiconductors (Si, Ge) is fairly easy. In the case of silicon, substrate temperature must be higher than 650°C to obtain polycrystalline films. This limits the choice of substrate to materials such as oxidized silicon wafers, sapphire, or quartz. In contrast, polycrystalline germanium films can be grown at substrate temperatures as low as 300°C, allowing to use more flexible substrates such as mica or glass.

Using photolithography, sensors can be fabricated in miniaturized arbitrary shapes. Miniaturization allows batch fabrication and hence results in a lower cost. Additionally, miniaturized strain gauges can be mounted on the area where the maximum stress is applied and this reduces the length error.

In this paper the fabrication process for miniaturized germanium strain gauges is reported. Next section describes the fabrication steps and various parameters affecting the film characteristics. The main problem with evaporated semiconductor films, is the difficulty in controlling the impurity concentration. A modified process is suggested in Section 3, which facilitates precise control of film conductivity. Finally, Section 4 reports the strain sensitivity of the fabricated devices.

2. Fabrication Procedure

The main problem with semiconductor strain gauges is their high temperature sensitivity. To reduce this effect, the structure shown in Fig. 1(a) was used. This structure consists of two perpendicular Ge resistors and when connected in a Wheatstone bridge as shown in Fig. 1(b) can reduce thermal sensitivity up to 20-30 times [1].



(a)

(b)

Fig. 1 (a) Device structure (b) measurement bridge

The fabrication process used in this work is as the following: First 25µm thick mica substrates are RCA cleaned, immersed in boiling DI water for 15 min., and dried with nitrogen. Germanium is then deposited via thermal evaporation at a base pressure of 10^{-6} torr. The germanium charge is boron doped, 99.999% pure with resistivity in 5.7-6.2 Ω-cm range. The film thickness and deposition rate are 1000Å and 1Å/s respectively. After unloading the samples, germanium islands are patterned with standard photolithography. Phosphoric acid at 50°C was used to etch away unwanted Ge. The samples are dipped again in boiling water for 15 min. before stripping off the photoresist. Otherwise acid traces result in metal peel off or germanium removal during the subsequent steps.

The cleaned samples are again loaded in the vacuum chamber and 100Å aluminum is deposited at 150ºC followed by 2000Å of copper. Finally, patterning the deposited metal layer with diluted nitric acid completes the process. Fig. 2 shows the completed device.

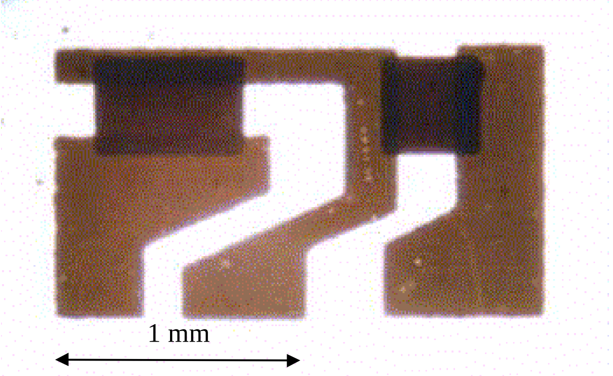


Fig 2. A completed device

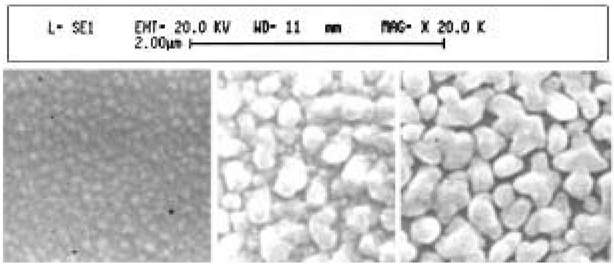
2.1 Wire Bonding

Conventional gold wire bonds, used in microelectronics are too weak to withstand mechanical stresses during the measurement. Silver-pasted wires used for strain gauges [1] need extra equipment to fix the wires during the curing step. We used a micro-soldering bonding, which is stronger and more flexible, instead. To make soldering possible a bi-layer metallization is required: a copper layer for soldering and an aluminum layer for better adhesion to germanium. Before slicing the individual gauges and wiring, samples are held at 400 °C for an hour, for better adhesion and enhanced electrical connection.

2.2 Effect of Substrate Temperature

Substrate temperature has a great impact on the physical and electrical characteristics of semiconductor thin-films. Germanium deposition was performed at various temperatures in the range of 200-600°C. The substrate temperature is provided using an already calibrated radiation heater, capable of heating up to 1000°C.

Germanium films should have good adhesion to substrate to allow the photolithography process and to resist mechanical deformations during measurement. Scotch tape tests showed that films grown at temperatures below 300°C have poor adhesion and peel off easily. Films deposited at temperature above 600°C have better adhesion, but they are still too weak for photolithography. The best adhesion is obtained at temperatures in the 400-500°C range.



(a) (b) (c)

Fig. 3 SEM micrograph of Ge films deposited at different substrate temperatures (a) 200°C (b) 400°C (c) 600°C. To reveal the crystalline structure in (b) this sample was dipped in ammonia solution.

Fig. 3 shows how the substrate temperature affects the crystalline structure of germanium films. Films deposited at 200°C have microcrystalline or amorphous structure (Fig. 3(a)) and their sheet resistance is beyond 100MΩ/□. Samples deposited at 400°C are polycrystalline (Fig. 3(b)) with sheet resistances about 25kΩ/□. As these samples have a smooth and continuous surface, they dipped in a diluted ammonia solution for 2 min. to reveal the crystalline structure. Increasing the substrate temperature to 600°C results in a discontinuous polycrystalline structure (Fig. 3(c)) with a hazy surface. Consequently the sheet resistance is more than 100MΩ/□. Table 1 summarizes these observations. According to these results, substrate temperature was chosen to be 400°C during germanium deposition.

Table 1. Effect of substrate temperature on Ge film

Substrate temperature	200°C	400°C	600°C
Adhesion	poor	good	moderate
Crystalline structure	amorphous μcrystalline	polycrystalline	discontinuous poly
Sheet resistance	very high	25 kΩ/□	very high

2.3 Effect of Tungsten Contamination

The main contamination source in thermal evaporation is tungsten sublimation from the evaporating filaments. This greatly affects the electrical characteristics of deposited germanium films. As the amount of tungsten impurity included in the film differs from run to run, a shield is necessary on the filaments. Without this shield, the sheet resistance of deposited germanium films decreases from 20-30 kΩ/□ to 1-2 kΩ/□. XRD analysis showed considerable tungsten traces in these samples.

3. Modified Fabrication Process

The main problem with semiconductor thin-films prepared with thermal evaporation is the uncontrollable impurity concentration. Boron nitride crucibles may be used to introduce a constant impurity level equal to boron solid solubility in germanium. But the impurity concentration cannot be set arbitrary. We examined a simple approach to add a predetermined amount of aluminum to the deposited germanium film.

After germanium deposition, substrate temperature is lowered and an aluminum layer with desired thickness is deposited. Then substrate temperature is raised again to 400°C allowing aluminum atoms to diffuse in germanium film. As the aluminum thickness can be controlled within 1Å, the process is well controllable and reproducible. To prevent any aluminum re-evaporation, which may result in undetermined impurity level, a third layer was used.

The modified process is as the following: After germanium deposition, the substrate temperature is lowered to 150ºC and an ultra-thin aluminum layer is deposited. Then germanium patterns are defined using the prescribed lithography step. Samples are loaded in the vacuum system and a 1000Å thick SiO_2 layer is deposited by e-beam evaporation at a substrate temperature of 400ºC. Windows are then opened in the oxide with a diluted HF solution for metal contacts. The samples are held in vacuum at 400°C for an hour for aluminum diffusion and then metallization layers are deposited as before. The rest of the process remains unchanged.

The modified process has some advantages over the previous one. First, as the substrate temperature during metallization can be higher without the risk of undesired formation of copper germanide, the adhesion of metal pads is enhanced. A good electrical contact is now obtained as a result of copper germanide formation directly beneath the contact windows.

Second, as the impurity level is well controlled, the batch-to-batch variations in the resistor values are lower. The resistors are in the 1.4-1.5 kΩ/□ range instead of 20-30 kΩ/□. Furthermore, these samples have better temporal stability.

Finally, adding the impurity results in a lower temperature sensitivity. Fig. 4 shows that with adding 100Å of aluminum to germanium layer, TCR decreases from 4200 ppm/°C to 3100 ppm/°C. This can be further lowered as the TCR is still negative. The resistance values is high enough to ease the measurement, and devices have still reasonable gauge factors as shown in the next section.

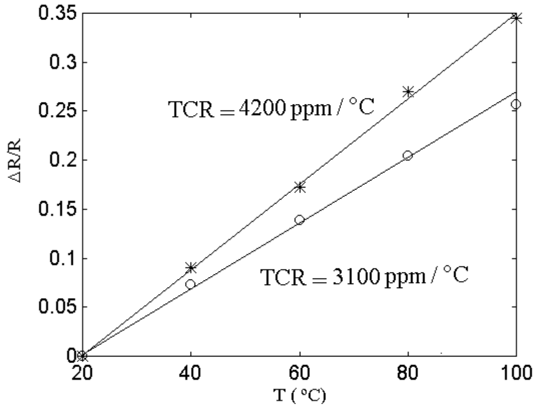


Fig. 4 Absolute value of TCR for samples (*) without and (o) with added Al. Note that in both cases TCR is negative.

4. Mechanical Measurements

Cantilever beam bending was used to measure the gauge factor of the fabricated devices. In this method the strain gauge is mounted at the fixed end of the beam and a uniaxial strain is induced in it by applying a force to the free end of the beam. It can be shown that the longitudinal strain is [6]

$$\varepsilon = \frac{3xyh}{2L^3} \qquad (1)$$

where h and L are the beam thickness and length respectively, x is the distance between the gauge and the free end of the beam and y is the beam deflection at its free end.

Fig. 5 shows the sensitivity of the fabricated devices. The obtained gauge factor of about 10 is somewhat lower than that predicted due to the deformation of epoxy bond. Sensors have good long-term stability and linearity up to 1000 microstrains.

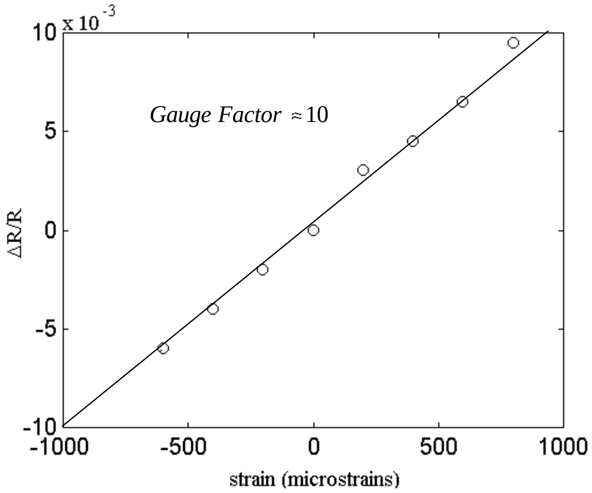


Fig. 5 Sensor characteristics

5. Conclusion

The fabrication procedure for a miniaturized thin-film germanium strain gauge was reported. The effect of deposition conditions on germanium films was studied and photolithography was used to fabricate miniaturized gauges. Using photolithography makes it fairly easy to fabricate devices with arbitrary shapes arranged in measurement bridges. Miniaturized devices are capable of being batch-fabricated, resulting in low-cost sensors. The proposed doping method in our modified process is better for adding a predetermined impurity concentration resulting in more reproducible devices. The impurity level may be increased even further to lower the temperature sensitivity. The fabricated sensors have a gauge factor of 10 and linear characteristics up to 1000 microstrains and their high electrical resistance facilitates the measurement.

More accurate measurements are underway to characterize the temperature sensitivity of the fabricated sensors and to reduce it by tailoring the impurity type and level, and using other germanium-metal alloys.

Acknoledgement:

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