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Piezoresistive Thin-Film Germanium Strain Gauges with Improved Sensitivity

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Miniaturized thin-film germanium strain gauges have been fabricated. Solid-source diffusion is used to incorporate a controlled amount of aluminum as p-type doping. This facilitates simple and precise control of film conductivity and results in better matching from batch to batch. Thermal sensitivity of the sensors is also minimized in this manner. Values of the temperature coefficient of resistance (TCR) less than 200 ppm/°C are achieved, while the longitudinal gauge factor is higher than 10. A new micro-soldering technique is also introduced, which provides the strong and flexible connections desired for mechanical sensors. In addition, the effect of copper-induced crystallization on the piezoresistivity of germanium films has been studied. Longitudinal gauge factors as high as 54 are obtained upon annealing a bilayer of Cu and Ge and subsequently etching away the copper germanide layer and any unreacted Cu.

1. Introduction

In spite of the high piezoresistivity of semiconductors, which makes them favorable for fabricating very sensitive strain gauges,[1,2] their widespread use has been limited mainly due to their high thermal sensitivity. The main exception is diffused silicon gauges for pressure sensors and accelerometers, in which sensor integration is the key factor. However, bulk semiconductors have some disadvantages for other applications, such as their poor flexibility, high fabrication cost, and high leakage current.[1] Thin film semiconductors are of interest for providing gauge factors comparable to those of bulk materials but

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without having such problems. Although most research in this area has been focused on polycrystalline and amorphous silicon films, Ge has been studied to a limited extent.[3–7] The main advantage of Ge over silicon is its lower crystallization temperature. Polycrystalline Ge films are obtainable at temperatures as low as 300°C, while the substrate temperature must be higher than 600°C to obtain polysilicon films. Therefore, low-cost and flexible substrates such as mica and glass can be used in the case of Ge.

In this paper, we report the fabrication procedure for miniaturized thin-film Ge strain gauges on glass. A solid-source diffusion method is used for incorporating a controlled amount of impurity in the film, which results in a better matching from run to run and is effective in lowering the thermal sensitivity of the sensors. The next section describes the fabrication process and doping method employed. Section 3 presents the results of electrical measurements and how the doping method affects the resistivity and TCR of the films. Then in section 4 the results of piezoresistance measurements are reported. In addition, we have studied the effect of copper-induced crystallization on the piezoresistivity of Ge films and the preliminary results are presented in section 5.

2. Fabrication Procedure

The sensing elements are 1000-Å-thick germanium resistors obtained by e-beam deposition at a substrate temperature of 400°C on RCA-cleaned, 150-μm-thick ordinary glass and patterned using photolithography. The substrate temperature was optimized for a reproducible polycrystalline film with good adhesion.[8] After Ge deposition, a thin layer of aluminum with a thickness ranging from 10 to 100Å is deposited onto the samples at room temperature, followed by *in situ* annealing at 400°C for 30 min. This yields a controllable amount of impurity in the film. Aluminum thickness is monitored during deposition using a QCM and confirmed with EDX analysis.

The physical structure of the films has been studied using SEM and XRD analyses. Figure 1 shows SEM micrographs of samples deposited at different temperatures. Samples deposited at room temperature and 200°C have amorphous structures as shown in Figs. 1(a) and 1(b), whereas samples grown at 400°C are polycrystalline with an average grain size of 0.1–0.2 μm (Fig. 1(c)). SEM also indicates that the samples grown at 600°C have a discontinuous polycrystalline structure (Fig. 1(d)).

The XRD spectra of the samples are shown in Fig. 2. The spectra were obtained using Cu k_α radiation. Again, samples deposited at room temperature show no crystallization, while Ge(111), (220) and (311) peaks are observable in samples grown at 400°C.

Germanium islands are defined using a phosphoric acid solution. A 1000-Å-thick passivation oxide layer is deposited by RF sputtering and windows are opened for electrical contacts using buffered HF. A bi-layer metallization is used, consisting of 100 Å of Al followed by 1000 Å of Cu, which has good adhesion to the substrate and makes soldering possible. A new micro-soldering technique is utilized which provides the strong yet flexible connection desired for mechanical sensors to pads as small as 150 μm. Figure 3 shows a complete strain gauge, which acts as one of the active arms of a half bridge. External connections are possible through 50-μm copper wires soldered to the contact pads.

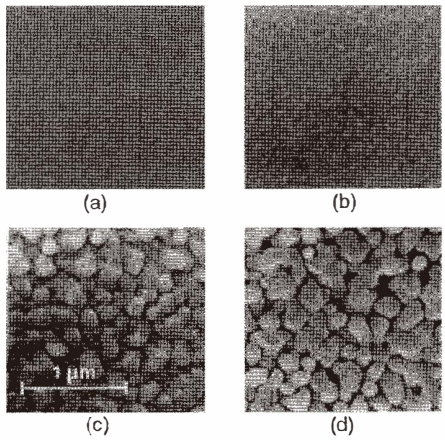

Fig. 1. SEM micrograph of the samples deposited at (a) room temperature, (b) 200°C, (c) 400°C and (d) 600°C.

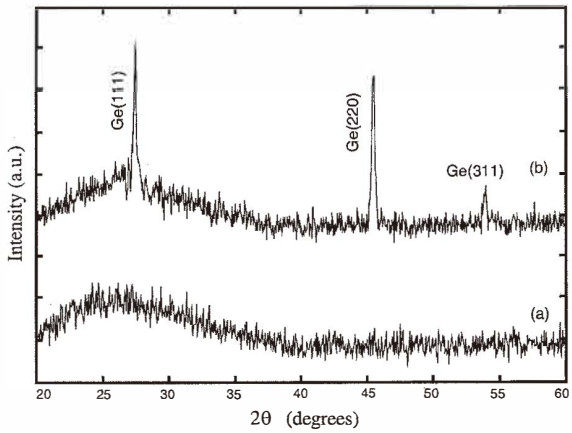

Fig. 2. XRD spectra of the samples grown at (a) room temperature (b) 400°C.

3. Electrical Measurements

The main problem associated with semiconductor strain gauges is their high temperature sensitivity. To partly alleviate this problem, a predetermined amount of impurity is added. A positive TCR is usually desired to compensate for the negative temperature coefficient of the gauge factor (TCk) in a constant-current measurement configuration.[1,2] To achieve such TCR values, a very high level of impurity is required. A simple approach is to use solid-source diffusion from a deposited Al layer, which provides such levels of

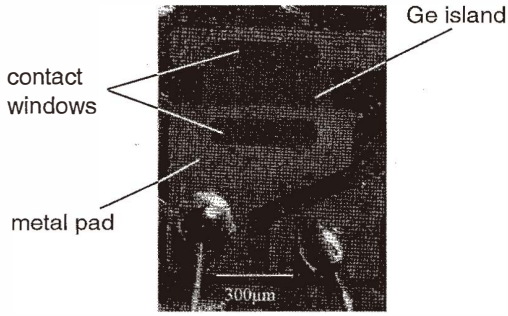

Fig. 3. A fabricated strain gauge.

impurity at relatively low temperatures.[9] Grain boundaries and other defects act as a path for the fast diffusion of Al atoms at temperatures as low as 400°C. A uniform distribution of Al is expected because of the thin Ge film used. This is confirmed by gradually etching the film and measuring the sheet resistance. Figure 4 shows the hole mobility and concentration determined from Hall measurements as a function of aluminum thicknesses. Carrier concentrations are consistent with nominal doping levels for Al thicknesses higher than 20 Å. Also, the results for undoped germanium are consistent with previously reported works.

Figure 5 shows how this added Al affects the film sheet resistance and its relative variation from run to run. As can be seen, the sheet resistance of the film varies almost linearly with the incorporated impurity for higher levels of carrier concentration (corresponding to Al thickness above 20 Å). This figure shows that the proposed solid-source diffusion is capable of making the process more reproducible. Run-to-run variation of the sheet resistance can be decreased to as low as 4%.

Depicted in Fig. 6 is the film TCR as a function of hole concentration. Measurements were performed for temperatures in the range of 25–100°C. Values of TCR as low as 200 ppm/°C are achieved by depositing 20 Å of Al and near zero values are expected for thinner films.

4. Mechanical Measurements

A cantilever beam bending method is used for mechanical measurements. Sensors were mounted on a steel bar and the applied strain, ε, was calculated from the well-known formula:

$$\varepsilon = \frac{3xyh}{2L^3}, \tag{1}$$

where x is the distance of the sensor from the free end of the beam, y is the beam deflection at its free end, and h and L are beam thickness and length, respectively. The longitudinal

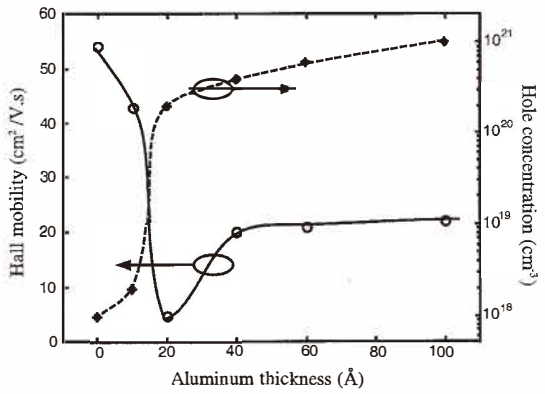

Fig. 4. Hole mobility and concentration determined from Hall measurements as a function of Al thickness.

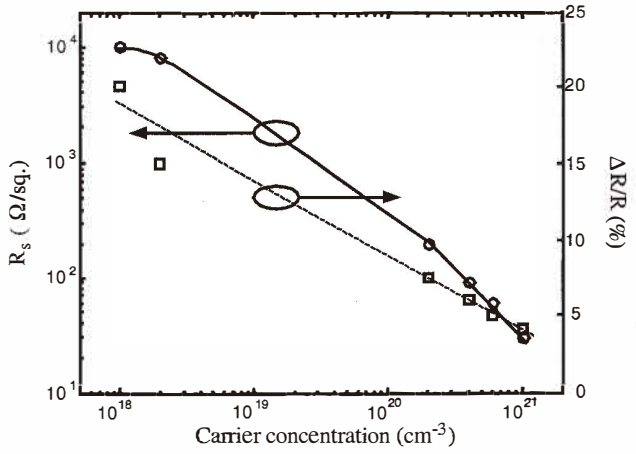

Fig. 5. Sheet resistance and its run-to-run variations as a function of the derived carrier concentration.

and transverse gauge factors, l and t, are then calculated as the ratio of the relative change of the resistance to the applied strain for resistors parallel and perpendicular to the direction of the strain, respectively.

Figure 7 shows the relative change in the resistance as a function of the applied strain for as-deposited Ge sensors. The extracted longitudinal and transverse gauge factors are 32 and 16, respectively. These values are in agreement with previous results.[1,3–7]

Measurement results for various levels of doping are shown in Fig. 8 to clarify the effect of impurity on the piezoresistivity of the film. As expected, doping greatly reduces the mechanical sensitivity. The gauge factor varies almost linearly with the logarithm of

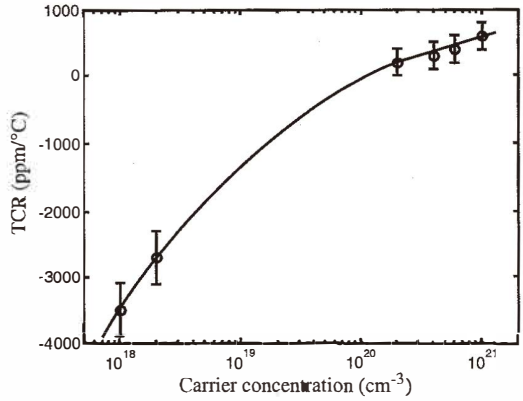

Fig. 6. TCR versus carrier concentration.

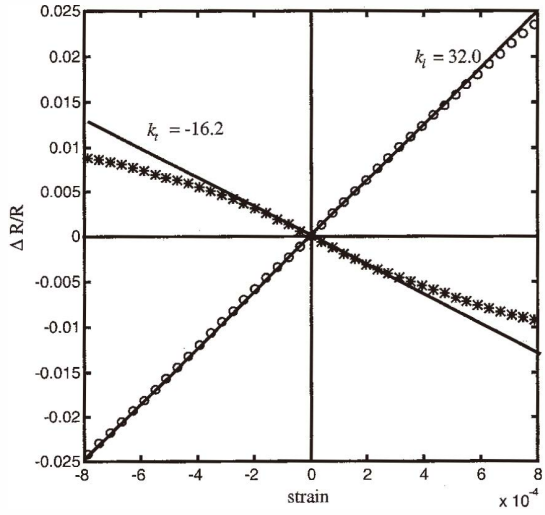

Fig. 7. Sensor response for undoped germanium.

carrier concentration. However, for an Al thickness of 20 Å where near zero TCR is achieved, the gauge factor is still one order of magnitude higher than that of metallic strain gauges.

Finally, Fig. 9 shows how the Al concentration affects the temperature coefficient of the gauge factor. Al doping is effective in lowering the TCk; however, the values obtained are still high and cannot be compensated by TCR in a constant-current configuration, where the requirement is[2]:

$$TCk \cong -TCR. \tag{2}$$

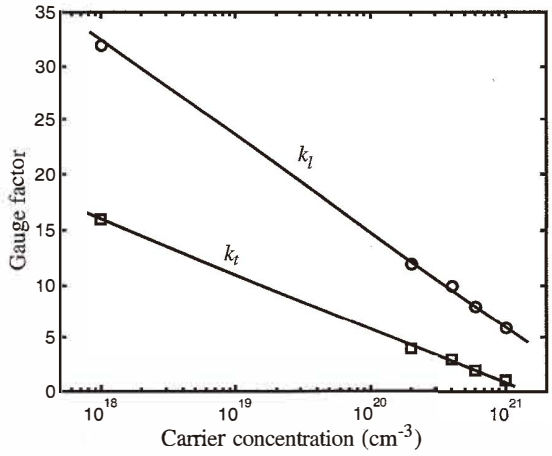

Fig. 8. Dependence of the longitudinal and transverse gauge factors on doping.

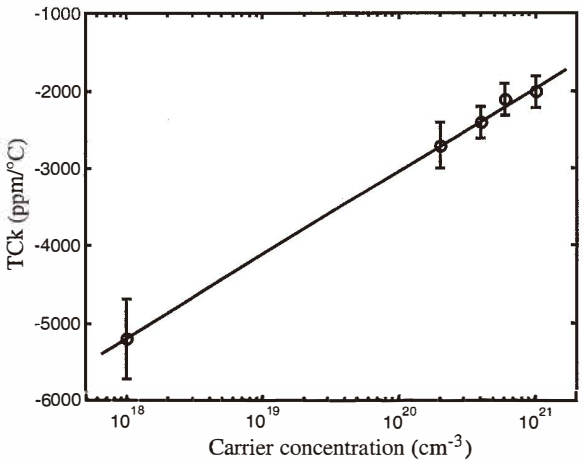

Fig. 9. TCk as a function of doping.

5. Metal-Induced Crystallization (MIC)

It has been reported that the crystallization of germanium can be mediated by the incorporation of copper. Amorphous Ge films are recrystallized at 400°C when annealed in the vicinity of a Cu layer, while solid phase crystallization of Ge occurs at temperatures above 500°C.[10] This is believed to be due to the formation of copper germanide, which

acts as a nucleation seed for germanium. In this section we report the effect of copper-induced crystallization on the piezoresistivity of Ge films.[11]

Germanium films with a thickness of 1000 Å are e-beam deposited on glass substrates. Amorphous Ge samples are prepared at room temperature, while polycrystalline films are deposited at a substrate temperature of 400°C. This is followed by thermally evaporating 100 Å of copper on some of the samples at room temperature. These samples are then annealed ***in situ*** at 400°C for 30 minutes to form copper germanide. Four groups of samples are prepared this way: as-deposited amourphous (a-Ge) and polycrystalline (p-Ge) films, and MIC samples starting from amorphous (MIC a-Ge) and polycrystalline (MIC p-Ge) precursors. For the purpose of electrical measurements, copper germanide and all unreacted copper are etched away using phosphoric acid and germanium islands are then patterned by photolithography. Device fabrication is carried out as described in section 2.

Figure 10 shows the XRD spectra of these samples. Curve (a) in this figure presents the XRD data for as-deposited a-Ge films, while curve (b) shows the spectrum for a-Ge films after recrystallization. Correspondingly, spectra (c) and (d) illustrate the results obtained for as-deposited polycrystalline Ge and MIC p-Ge films, respectively. The formation of copper germanide is observed in MIC samples particularly when an amorphous Ge precursor is used. There is another difference between MIC a-Ge and MIC p-Ge samples. When an amorphous precursor is used, significant crystallization is observed with a dominant orientation of Ge(111). However, when the film is initially polycrystalline, the crystallization is not as high. This is consistent with previously published work[10] and may be explained by the fact that an already polycrystalline film requires more activation energy for reconstruction. An increase in the Ge(220) peak may also be attributed to the formation of copper germanide and the resulting $Cu_3Ge(111)$ peak.

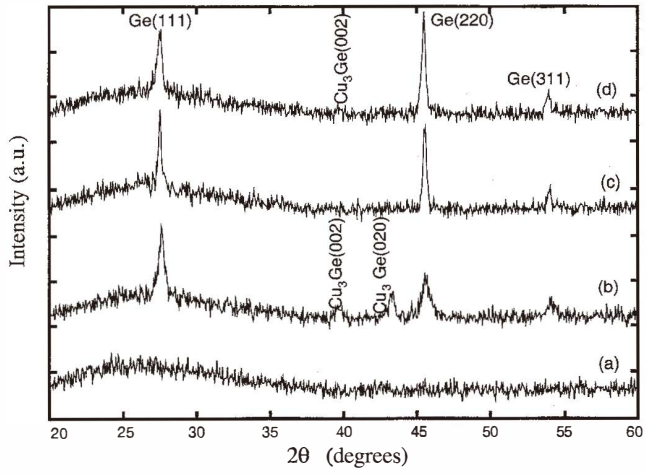

Fig. 10. XRD spectra for (a) a-Ge (b) MIC a-Ge (c) p-Ge and (d) MIC p-Ge samples.

Sheet resistance measurements indicate that the etching step is sufficient to remove the conductive germanide layer and any unreacted Cu. Hole mobility is measured using the Hall effect, and Table 1 summarizes the values obtained for different samples. A significant increase in the gauge factor of MIC p-Ge samples can be explained by their larger grain size, while the high mobility of MIC a-Ge samples is an evidence of crystallization. Also presented in Table 1 are the results of piezoresistance measurements for these samples. A transition from negative longitudinal gauge factors to positive values upon annealing of amorphous Ge is due to the formation of a polycrystalline structure,[1,4] while the increased longitudinal gauge factor in MIC p-Ge samples as compared to p-Ge is the result of grain growth.[1,4] The average grain size of MIC p-Ge samples is 0.3–0.5 μm compared to 0.1–0.2 μm for as-deposited polycrystalline germanium. The fact that the transverse gauge factor does not increase upon annealing can be attributed to the preferred (110) orientation in the MIC p-Ge sample, which results in more anisotropy in the mechanical sensitivity.[1] Also, these results show that the MIC sample has lower temperature sensitivity. This could be due to the presence of metal atoms at the grain boundaries, which lower the barrier height.

6. Conclusions

A fabrication procedure for miniaturized thin-film germanium strain gauges was presented. A simple doping technique was proposed which uses the solid-source diffusion of a deposited Al layer. This approach was shown to be effective in controlling film conductivity and thermal sensitivity. Sensors with TCR values comparable to those of metallic strain gauges and with much higher mechanical sensitivity were obtained. Enhancement of mechanical sensitivity has also been observed with the copper-induced crystallization of germanium. Longitudinal gauge factors as high as 54 were obtained upon annealing 100 Å of Cu deposited on the Ge film and subsequently etching away the copper germanide layer and any unreacted Cu.

Table 1
Hall mobility, gauge factor, and temperature sensitivity of the samples.

Sample	a-Ge	MIC a-Ge	p-Ge	MIC p-Ge
Mobility ($cm^2/V.s$)	-	18	55	95
k_l	–8	25	32	54
k_t	–7	–9	–16	–14
TCR (ppm/°C)	-	-	3500	1670
TCk (ppm/°C)	-	-	4800	2400

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