

# Longitudinal and transversal piezoresistive effect in hydrogenated amorphous carbon films

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Received 19 June 2006; received in revised form 5 March 2007; accepted 19 March 2007

Available online 27 March 2007

## Abstract

We report a large piezoresistive effect of the plasma assisted chemical vapor deposited hydrogenated amorphous carbon (a-C:H) films deposited at bias voltages of  $-350$  and  $-800$  V. The gauge factors were measured in transversal, longitudinal strain configurations and lateral, vertical current flow directions with respect to the layer surface. The gauge factor measurements were performed in the temperature range of  $23$ – $60$  °C. A model is proposed to explain the origin of piezoresistive effect in the a-C:H films. From the experimental results we suggest the parameters which can further enhance the gauge factor values in the films.

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PACS: 72.15 Cz; 72.20.-I; 72.20. Fr; 73.40. Gk; 73.40. Vz

Keywords: Diamond-like carbon; Piezoresistive gauge factor; Hydrogenated amorphous carbon;  $I$ – $V$

## 1. Introduction

Diamond piezoresistive sensors outperform their Si and SiC counterparts in sensitivity, especially in harsh environments [1]. Although single crystalline diamond and polycrystalline diamond films shows a high gauge factors in the range of  $500$ – $4000$  [2,3] and  $(10$ – $100)$  [3–6], respectively, compared to diamond-like carbon (DLC) films  $36$ – $1200$  [7–9] it is too costly to be used in practical sensors because it requires a high pressure and a high temperature for manufacture. The choice of substrate is also limited on which crystalline diamond films can be deposited because to deposit diamond seed for nucleation are required which is not a case for DLC films.

In this paper, we report the quantitative study of the piezoresistive gauge factor ( $K$ ) of a-C:H films deposited at different bias voltages using plasma assisted chemical vapor deposition (PACVD).

The advantage a-C:H strain gauges has over silicon strain gauge is that the gauge factor in a-C:H films is not direction

dependent whereas in silicon it is. Moreover a-C:H films can be deposited on mechanical parts which enable to use a-C:H films in smart washers [10], and grippers.

In the previous study the transversal gauge factor (vertical current flow through the films) of a-C:H strain gauges deposited at a bias voltage of  $-350$  V were reported [8,9]. Here, transversal and longitudinal gauge factors (vertical and lateral current flow through the films) of a-C:H films are reported at a bias voltage of  $-800$  V. The gauge factors of a-C:H films deposited at  $-350$  and  $-800$  V are measured, compared and discussed as to which parameters can further enhance the gauge factor. Also an attempt is made to introduce a model which could explain the origin of piezoresistive effect in the DLC films.

## 2. Principle of boss membrane test structure

The structure used for piezoresistive gauge factor measurements is a boss membrane. It consists of a frame, a membrane and a boss (Fig. 1). When a force is applied on the boss from the top or bottom (Fig. 1a, b) the membrane deforms, creating maximum, nearly uniaxial strain at the membrane surface near the boss and the frame (lower part of Fig. 1a, b) and hence a-C:H resistors were placed near the boss and the frame where

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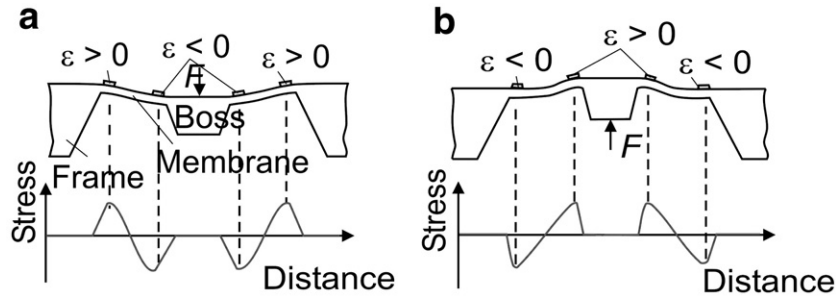


Fig. 1. Principle for measuring gauge factor using boss membrane test structure.

maximum strain was expected. When the force is applied on top of the boss, the resistors near the boss are under compressive strain and the ones near the frame are under tensile strain (Fig. 1a) and vice versa when force is applied from the bottom (Fig. 1b).

### 3. Film deposition and test structure fabrication

The a-C:H films are deposited using PACVD. The deposition details are mentioned elsewhere [11]. The deposition was carried out in the mixture of acetylene ( $C_2H_2$ ) and argon (Ar).

The working pressure was kept constant at 0.5 Pa and total  $C_2H_2$ /Ar flux was around 105 ml/min. The films were deposited at substrate bias voltages of  $-350$  V and  $-800$  V (Table 1). The resistivity and activation energy of samples deposited at  $-350$  V and  $-800$  V are mentioned in the Table 1. The  $sp^3$  content for the a-C:H films deposited at  $-350$  V is  $\sim 34\%$  and  $\sim 24\%$  for the films deposited at  $-800$  V [9].

Two designs were used to fabricate the sensor, to be able to inject current vertically and laterally through the a-C:H films. When current is injected vertically through the a-C:H films one can measure only transversal configuration of strain. Transversal strain is induced in the strain gauge when current and strain is perpendicular to each other as shown in the Fig. 2a. The fabrication steps for transversal configuration are described in detail elsewhere [8]. When current flows laterally through the a-C:H films then one can get longitudinal as well as transversal strain configuration. For current to flow laterally through the high resistive a-C:H films (Table 1, sample 4), finger-like structure was used (Fig. 2b and c).

The dotted rectangles in Fig. 2b and c represent the a-C:H films. The finger-like structures are the contact metal. The current ( $I$ ) flows laterally in both the direction as presented in the figure, from one end to other end of the finger. Fig. 2b shows strain ( $\epsilon$ ) and current are perpendicular to each other, i.e. we have a transversal strain configuration whereas in Fig. 2c the current and strain are parallel to each other, i.e. we have a longitudinal strain configuration.

Current flowed vertically through the a-C:H films deposited at  $-350$  V (Table 1, samples 1–2) and hence we were able to measure transversal strain configuration on the strain gauges where as current flowed vertically (Table 1, sample 3) as well laterally (Table 1, sample 4) when films were deposited at  $-800$  V and hence we were able to measure both transversal and longitudinal strain configurations on the strain gauges. Not only

we were able to measure transversal and longitudinal strain configurations on samples 3–4, we were also able to compare results when current flowed vertically and laterally through the films. The fabrication steps used for the longitudinal strain configuration are described here.

The test structures using boss membrane design were fabricated using silicon substrates. Fig. 3 shows schematic cross-sections of the test structure after the main process steps. The process was started using thermal oxidation of the Si wafer, which was then structured on its backside using photolithography. The structured sample was then chemically etched using tetra methyl ammonium hydroxide (TMAH) to obtain a boss membrane structure as above in Fig. 3a.

The holes were open in the photoresist mask to deposit the a-C:H films. The films were deposited on oxide and hence the current flow through the silicon substrate was blocked. Hydrogenated amorphous carbon ( $h=0.5$   $\mu\text{m}$ ) was deposited using PACVD and structured using lift-off to obtain a-C:H strain gauge resistors on the membrane near the boss and near the frame (Fig. 3c). The thickness of the a-C:H film was maintained at  $0.5$   $\mu\text{m}$ , because films thinner than this may not be uniform and can exhibit pin holes, whereas films thicker than this were difficult to structure by liftoff. Chromium (Cr)/gold (Au) (30 nm/300 nm) was used for contacts, which were deposited using e-beam evaporation.

The contact pads were on the frame so that the membrane was not stressed due to contacts. The width of the frame was

Table 1  
Deposition parameters and electrical information for a-C:H films

Sample	Total Ar/ $C_2H_2$ gas flux (ml/min)	Substrate voltage ( $V_b$ )	Pressure (Pa)	$E_A$ (eV)	$\rho$ ( $M\Omega$ cm)	Comments
1–2	$\sim 105$	$-350$	0.5	$0.48 \pm 0.01$	(350–750)	The pressure was kept constant
3–4	$\sim 105$	$-800$	0.5	$0.39 \pm 0.01$	Sample 3 Vertical current flow (1–5) Sample 4 Lateral current flow (0.5–5)	The pressure was kept constant

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