

# Piezoresistive effect in DLC films and silicon

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## ABSTRACT

Hydrogenated amorphous diamond-like carbon (DLC, a-C:H) films were integrated in silicon boss membrane as a strain gauge material. The films were deposited at a bias voltage of -800 V by plasma-assisted chemical vapour deposition (PACVD). The a-C:H film with a ~12-13 % of hydrogen showed hardness of 23 GPa. The film has around 24 % of sp<sup>3</sup> content. The I-V characteristic is found to be Ohmic and the film has activation energy of around 0.32 eV. High gauge factor ( $K$ ) values in the range of 16-36 were obtained, which were found to be independent of longitudinal and transversal strain configurations, current injection direction and of temperature in the range of 22-45 °C. P-diffused strain gauges using Borofilm 100 were also integrated in the boss membrane. High sensitivities in the range of 0.33-0.63 mV/V/mN were obtained, when vertical load was applied on the boss membrane.

**Keywords:** hydrogenated amorphous carbon, tactile sensor, 3D, force measurement, boss membrane

## 1 INTRODUCTION

The increasing use of micro systems in industry combined with an ever-increasing demand for higher measurement accuracy has led to ongoing developments in the field of dimensional metrology. Although optical- and laser-based measurement on multi-sensor systems provide highly accurate measurement on visible surfaces, it is difficult to use these systems for 3 dimensional measurements. This is an important reason why many groups are working on developing a tactile sensor using boss membrane [1-4] for contact probing. To improve the sensitivity of the boss membrane tactile sensor: 1) the p-diffused strain gauges can be optimized or replaced by another piezoresistive material 2) the structure of boss membrane can be modified. Both aspects are equally important. Many groups are concentrating on modifying the boss membrane design by using eight beams [5], by using twin membrane [6] or by using five boss design to get comparable stiffness in the membrane in  $x$ ,  $y$  and  $z$  direction. [7].

In this work we concentrated on improving the sensitivity of tactile sensor by concentrating on strain gauge material. We have integrated diamond-like carbon (DLC) films and p-diffused strain gauges in boss membrane as strain gauge material. P-diffusion strain gauges were diffused using Borofilm 100. Diamond-like carbon was coined in 1971 by Aisenberg and Chabot [8] for ion-beam deposited amorphous carbon thin films that

showed properties resembling diamond as opposed to graphite. These films were found to have mixed phases of diamond and graphite but no long range order i.e. they were amorphous in nature.

Single crystalline and polycrystalline diamond films shows gauge factors ( $K$ ) in the range of 500-4000 and 10-100 [9], respectively, compared to DLC films 36-1200 [10-11]. The advantage DLC has over diamond films is that the deposition temperature for DLC films is lower than 150 °C.

In previous work the transversal gauge factor ( $K$ ) of DLC [10-11] was studied. Here, the transversal and longitudinal gauge factor of DLC films are reported along with results on p-diffused strain gauges.

## 2 EXPERIMENTAL

Hydrogenated amorphous carbon films were fabricated using PACVD [12]. The deposition was carried out by the use of a commercial rf sputter plant (Balzers, BAS 450) working at 13.56 MHz, in a mixture of acetylene (C<sub>2</sub>H<sub>2</sub>) and argon (Ar). The C<sub>2</sub>H<sub>2</sub>/Ar gas-flow ratio or pressure was maintained constant throughout the deposition process. The bias voltage was kept constant at -800 V in this work. Within this parameter range, the substrate temperature was < 150 °C. The properties of DLC, depends primarily on bias voltage ( $V_b$ ), source gas, deposition pressure and gas flux. Measured properties of a-C:H films deposited at -800 V, 0.5 Pa constant pressure and approximately 105 ml/min of total gas flux Ar/ C<sub>2</sub>H<sub>2</sub> is summarized in Table 1 [10-14]).

a-C:H properties	
Roughness	8.5 nm
Deposition Rate	36.7 nm/min
H content	12.8-13.1 %
Hardness	23 GPa
sp <sup>3</sup>	24 %
Tauc optical bandgap	1.03 eV
Activation energy	0.32 (eV)
Film type	p
Thickness	0.5 μm

Table 1: Properties of a-C:H films deposited at -800 V.

Hydrogenated amorphous carbon films deposited using low-energy ion-assisted deposition showed the hardness in the range of 12-30 GPa [15], which is comparable to our results. The hardness of a-C:H film is comparable to that of silicon carbide (SiC) (25 GPa) [16]. The Tauc bandgap of hydrogenated amorphous silicon (a-Si:H) is 1.72 eV [17], which is higher than that of a-C:H found in

this study. The Tauc bandgap is 1.1 eV for tetrahedral amorphous carbon (ta-C) films [18] which is comparable to our results.

In case of diffused strain gauges, Borofilm 100 was spun on the samples and then diffusion took place at approximately 1170 °C.

### 3 WORKING PRINCIPLE

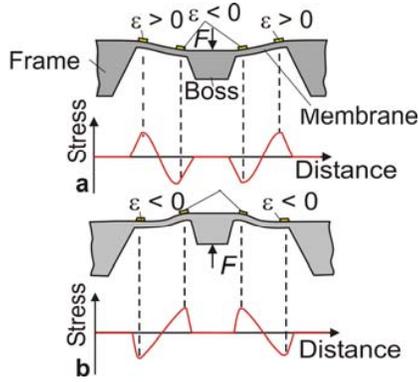


Figure 1: Principle for measuring gauge factor using boss membrane test structure.

Boss membrane consists of a frame, a membrane and a boss (Figure 1). When a force is applied on the boss from the top or bottom (Figure 1a,b) the membrane deforms, creating maximum nearly uniaxial strain near the boss and the frame of the membrane (lower part of Figure 1a,b) and hence strain gauges were placed near the boss and the frame where 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 (Figure 1a). When the force is applied from the bottom on the boss (Figure 1b), the strain gauges near the boss have tensile strain and the ones near the frame have compressive strain.

### 3 FABRICATION OF SENSORS

The test structures using boss membrane design were fabricated using bulk silicon micromachining. In this work piezoresistive effect of DLC films and diffused silicon is studied. Fabrication of sensors using these two different materials are presented below:

#### 3.1 DLC STRAIN GAUGES

Hydrogenated amorphous carbon films deposited at -350 V has very high resistivity (100-700 MΩcm) [10]. Resistivity of the films can be controlled by the deposition voltage [13]. Films were deposited at -800 V to get lower resistivity. To measure the longitudinal gauge factor, the current should flow laterally through the film, which was made possible by a finger-like structure (Figure 3b and c).

Figure 2 shows schematic cross-sections of the test structure after the main process steps. The process was started using thermal oxidation of the *p*-Si wafer, which

was then structured on its backside using photolithography. The structured sample was then chemically etched using TMAH to obtain a boss membrane structure as shown in Figure 2a.

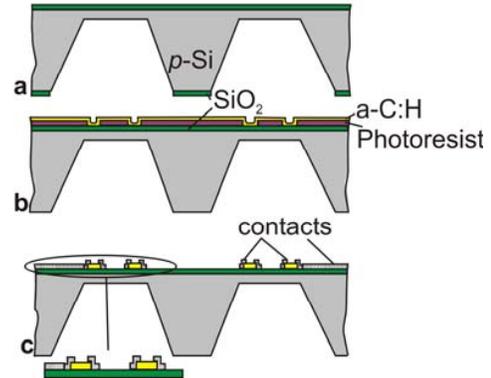


Figure 2: Schematic cross-sections of the test structure during fabrication: a) membrane etching of *p*-Si in TMAH, b) holes opened for a-C:H deposition using a photoresist mask on the oxide, c) lift-off of a-C:H and evaporation of metal for contacts.

The holes were opened for the a-C:H strain gauges on top of the oxide using photoresist as a mask. Hydrogenated amorphous carbon (0.5 μm) was structured using lift-off to obtain a-C:H strain gauges on the membrane near the boss and near the frame (Figure 1c). Cr/Au (30 nm / 300 nm) was used for contacts, which was deposited using e-beam evaporation. The fabricated test structure's photograph can be seen in Figure 3a. The optical microphotographs of the strain gauge under longitudinal (Figure 3b) and transversal (Figure 3c) strain are shown along. The current flew laterally through the films.

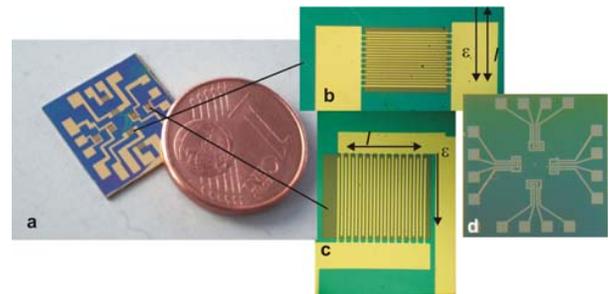


Figure 3: a) Photograph of a fabricated test structure, b) optical microphotograph of a strain gauge which has longitudinal strain configuration and c) one which has transversal strain configuration, d) photograph of a test structure with *p*-diffused strain gauges on backside of boss membrane structure.

#### 3.2 P-DIFFUSED STRAIN GAUGES

The test structures with *p*-diffused strain gauges were started with structuring the silicon dioxide on its frontside using photolithography for strain gauge diffusion. *P*-diffusion was then performed by spinning Borofilm 100

on the substrate and heating it at around 1170 °C in the presence of nitrogen and oxygen (Figure 4a) followed by second lithography step for p<sup>+</sup>-diffusion (Figure 4b) to get ohmic contacts. Cr/Au was then evaporated for contacts. Nitride was deposited on the backside using PECVD and structured to etch the membrane (Figure 4b). The top side was protected with nitride (Figure 4c). After etching the membrane nitride can be easily etched in plasma etching.

The photograph of the fabricated test structure is shown in the Figure 3d. On each side of the boss the p-diffused strain gauges (concentration 10<sup>18</sup> cm<sup>-3</sup>) were connected into four Wheatstone bridges design.

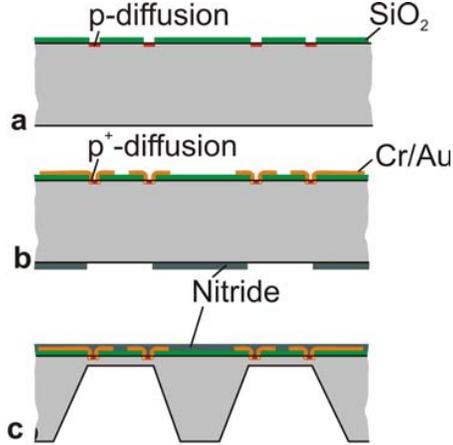


Figure 4: Schematic cross-sections of the test structure during fabrication: a) p-diffusion on top side b) p<sup>+</sup>-diffusion on the top side and nitride deposition and structuring on the backside c) membrane etching of p-Si in TMAH. Frontside protected with nitride.

## 4 RESULTS AND DISCUSSION

A typical I-V plot of metal/a-C:H/metal is shown in the Figure 5a. The I-V curve is linear, confirming Ohmic behaviour of the films in the voltage range of ± 4 V. The Arrhenius plot of conductivity versus inverse temperature is shown in Figure 4b. The activation energy of the a-C:H films examined in this work (0.32 eV) is comparable to values reported by other groups for ta-C and boron doped diamond films (Table 2).

Film	$E_A$ (eV)
ta-C [18]	0.45
ta-C [19]	0.22
lightly boron doped diamond [20]	0.26 - 0.38
boron doped diamond [21]	0.38

Table 2: Comparison of activation energy measured in this work with work done by other groups.

A constant voltage of 1 V was applied across the a-C:H resistor and change in current with respect to force was measured. The resistance versus force plot is shown in the Figure 6a, along with thickness of the membrane and

the unstressed resistivity. The measured data points were fitted using [10]

$$\frac{\Delta R}{R_0} = K \varepsilon_m \frac{F}{1 + aF^2} \quad (1)$$

where  $K$  and  $a$  are the fitting parameters,  $\Delta R = R - R_0$ ,  $R_0$  and  $R$  are the resistances at zero strain and at strain  $\varepsilon$ , respectively.  $F$  is the applied force,  $\varepsilon_m$  is the mean value of strain in the strain gauge. The derivation of the formula is discussed in detail elsewhere [10].

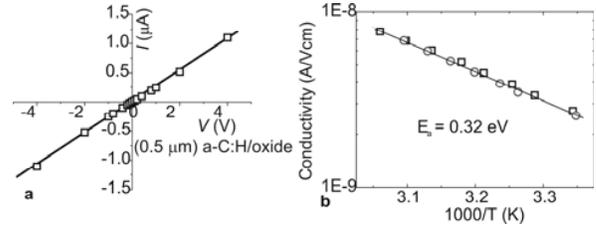


Figure 5a: a) Typical I-V plot of a-C:H/oxide, b) Arrhenius plot of conductivity versus inverse temperature for a-C:H/oxide.

The average value of  $K$  is  $29 \pm 4$  at room temperature. It can be observed that resistance decreases with the increase in the force, indicating compressive stress on the strain gauge. The measured resistor was under longitudinal stress. When measured under transversal stress, similar plot was obtained. To observe the effect of direction of current, current was also vertically injected through the a-C:H films and gauge factor values are measured, which are summarized in Table 3. In Table 3, average gauge factor values of around ten strain gauges measured in longitudinal tensile and compressive strain configuration and transversal compressive and tensile configuration are presented. It was observed that reproducible values of gauge factors were obtained. The measurements were performed in the temperature range of 22 - 45 °C and it was observed that gauge factor was independent of temperature in this range.

$h$	$t$	$\rho$	$K_{TT}$	$K_{TC}$	$K_{LT}$	$K_{LC}$	$K_{TC(\text{vertical})}$
0.5	34	0.5	30	22 ± 6	26 ± 8	28 ± 8	23 ± 5
	-35	-5	± 4				

Table 3 Average gauge factors measured in the temperature range of 22 - 45 °C.

$h$  is the thickness of the films in  $\mu\text{m}$ ,  $t$  is the thickness of the membrane in  $\mu\text{m}$  and  $\rho$  is the resistivity of the films in  $\text{M}\Omega\text{cm}$ .  $K_{TT}$  - transversal tensile,  $K_{TC}$  - transversal compressive,  $K_{LT}$  - longitudinal tensile and  $K_{LC}$  - longitudinal compressive. Vertical current injection in  $K_{TC(\text{vertical})}$ , others have lateral current injection.

The gauge factor values were found to be independent of direction of current flow (lateral and vertical) and of longitudinal/transversal strain configurations. By measuring several strain gauges in different strain configuration the gauge factor values in the range of 16-36 were obtained.

In Figure 6b, output voltage vs force is plotted for three bridges at a vertical load. The strain gauges have transversal and longitudinal strain on them. The change in resistance due to the applied voltage can be measured in the form of bridge voltage, which is presented in Figure 6b.

Under an assumption that all of the diffused strain gauges have a same value the relative change of output voltage directly corresponds to the relative change of resistance in the bridge. In Figure 6b, Signal A refers to output voltage of the bridges. The sensitivity is around 0.4 mV/V/mN. By measuring several bridges the sensitivities in the range of 0.33-0.63 mV/V/mN were obtained, which were higher compared to work done by other groups [1-2,4].

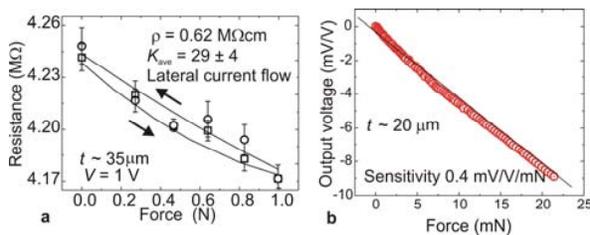


Figure 6 a) Typical resistance versus force plot for a-C:H film on a strain gauge under compressive stress, b) Output voltage of p-diffused strain gauges on the backside of a boss-membrane structure at vertical load.

DLC has very high activation energy, which makes them highly temperature sensitive in comparison to p-diffused strain gauges. DLC films have resistivity ( $\rho$ ) of more than 0.5 M $\Omega$ cm and p-diffused silicon has less than 0.002  $\Omega$ cm. This study shows that both the materials can be used as force sensors, for e.g. in 3D coordinate measuring machine (CMM). Depending on the application either DLC or p-diffused silicon can be selected as a piezoresistive material where one has high resistivity, and the other has low resistivity, respectively. In future it would be interesting to form Wheatstone bridges out of DLC strain gauges. Sensitivity measurements in x and y direction would also be very interesting.

## CONCLUSIONS

Hydrogenated amorphous carbon films of 23 GPa hardness fabricated by PACVD were successfully integrated in boss membrane. We found a-C:H to be a promising material since it combines favourable mechanical properties like adhesion, hardness and wear resistance with a large piezoresistive effect which is independent of longitudinal and transversal strain configuration and of current injection direction. It could be deposited at low substrate temperatures on the silicon membranes, which could be easily structured by lift-off using photoresist. Piezoresistive effect in DLC film is independent of direction is the advantage these films have over diffused silicon strain gauges. The p-diffused strain gauges using standard CMOS process showed high sensitivity in the range of 0.33-0.63 mV/V/mN.

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