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PIEZORESITIVE DIAMOND-LIKE CARBON MICRO STRAIN GAUGES

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Abstract: Hydrogenated (a-C:H) and hydrogen-free (a-C) amorphous diamond-like carbon (DLC) strain gauges have been successfully integrated on micromachined silicon boss-membrane force sensors. DLC strain gauges were investigated under vertical and horizontal connection as well as longitudinal and transversal orientation at temperatures between RT and 60°C revealing piezoresistive gauge factors typically in the range of 50-90 (a-C:H) and 20-30 (a-C).

Keywords: Diamond-like carbon (DLC), piezoresistive gauge factor, micromachined boss membrane sensor.

1. INTRODUCTION

Hard carbon coatings (so-called diamond-like carbon, DLC) has many useful properties of diamond, e.g. low friction and wear rate combined with high hardness, chemical inertness and biocompatibility. For sensor applications piezoresistivity is attractive which is observed in poly-crystalline diamond (poly-C). Therefore, poly-C has been proposed as strain gauge material for cochlear implant probes [1]. Unfortunately, it requires high deposition temperatures (520-780°C) thereby restricting its application to selected substrates and fabrication processes.

DLC can be deposited at low temperature on a variety of substrates using plasma-assisted chemical vapor deposition (PACVD, a-C:H) or magnetron sputtering (a-C) [2]. Strength of material combined with its biocompatibility makes DLC an ideal solution for many applications in medicine, e.g. as coating for intravascular stents [3] or prosthetic implants for hip and knee joints [4]. However, knowledge on piezoresistivity of DLC which is an attractive property for many sensor applications, i.e. strain gauges, is lacking. Therefore, in this study the piezoresistive response of low-temperature deposited DLC on micromachined silicon sensors is addressed.

2. SENSOR MODEL AND FABRICATION

The piezoresistive properties of DLC were studied using a boss-membrane force sensor displayed in Fig. 1. Sensor function shall be described using the schematic in the upper part of this figure.

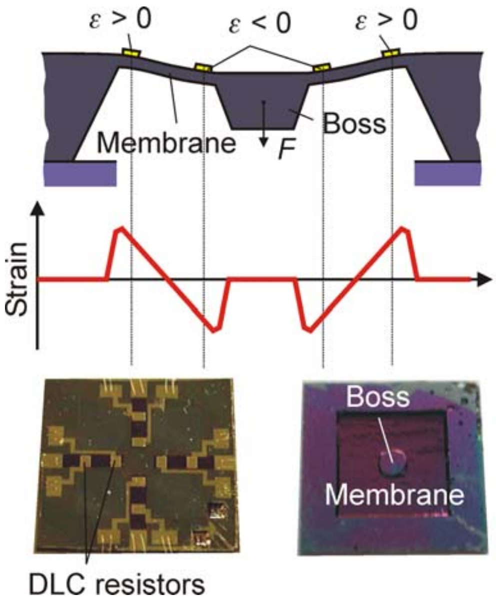

Fig. 1. Boss-membrane micro force sensor with DLC strain gauge resistors.

An applied force F causes the boss to be deflected out of its position of rest. Transversal tensile ($\varepsilon > 0$) and compressive ($\varepsilon < 0$) strain, respectively, is generated at the top surface of the membrane and transferred to DLC gauge resistors located close to the frame and the boss. The area of the membrane and the boss is 4×4 mm^2 and 2×2 mm^2, its thickness is 30-70 µm and 0.4 mm, respectively. The DLC resistors have an area of 0.6×0.8 µm^2 and a thickness of 0.5 to 1.0 µm. Owing to the large thickness ratio of membrane to DLC resistor we can assume a nearly uniform strain across the resistors along the vertical direction.

The distribution of strain at the membrane surface which acts nearly uniaxial in the direction depicted in Fig. 1 is analyzed using finite element modeling (ANSYS 8.1, [5]). The resistors are located close the positions of maximum strain. An effective strain ε_m is induced leading to a resistance change:

$$\frac{\Delta R}{R} = K\varepsilon_\mathrm{m} \tag{1}$$

with the gauge factor K. The value of ε_m which depends on the applied force and the membrane thickness is calculated for each sensor by averaging the strain at the membrane surface over the resistor length. The strain gauge resistors are electrically connected using highly p-doped and Au/Cr lines for the bottom and top contacts, respectively (vertical connection, Fig. 2a). Horizontal connection is achieved by Au/Cr lines deposited over an insulating SiO_2 layer (Fig. 2b).

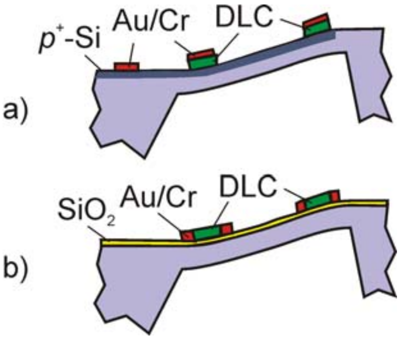

Fig. 2. Schematic cross section across a boss membrane (only left part) supporting DLC strain gauges. The resistors are connected vertically (a) and horizontally (b), respectively.

Sensor prototypes with integrated DLC strain gauge resistors were realized using a bulk silicon micromachining process based on standard photo-lithography, thermal oxidation and wet etching (Fig. 3, [5]).

The process is started by thermal oxidation of an n-type (001) silicon wafer which is structured at its back side. Anisotropic etching using aqueous tetra methyl ammonium hydroxide (TMAH, 20%, 80°C) solution is performed in the opened windows resulting in a boss membrane. Highly p-doped lines are realized at the top surface using boron diffusion (1200°C) through an oxide mask. DLC is then deposited by low-temperature plasma assisted chemical vapor deposition (PACVD, DiaForce®, [2,6]) onto structured photo resist. Excess DLC is removed by lifting the resist off resulting in strain gauge resistors of the designed geometry. Finally, an Au/Cr metallization is deposited by e-beam evaporation. Completed prototypes of the boss membrane sensor are glued onto a printed circuit board and bonded using gold wires (Fig. 4).

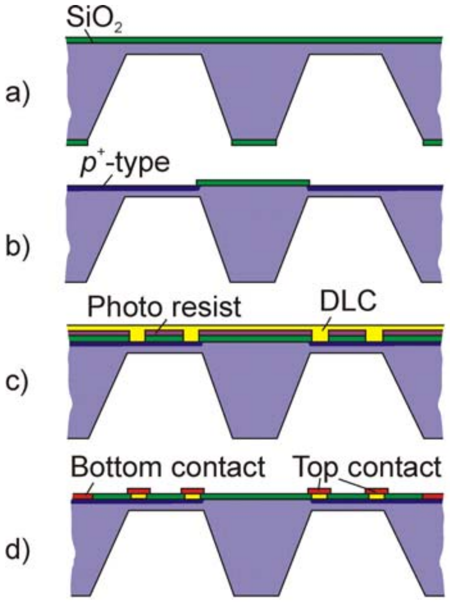

Fig. 3. Schematic of micro-force sensor fabrication process.

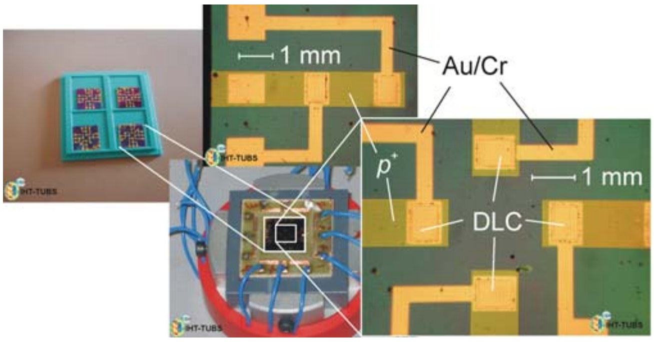

Fig. 4. Realized prototypes of boss membrane sensor. DLC strain gauge resistors are located at the positions of maximum membrane stress and connected vertically.

3. RESULTS AND DISCUSSION

3.1 Hydrogenated amorphous carbon (a-C:H)

In a recent study on the optical and transport properties of a-C:H by PACVD we found an optical bandgap of 1.0-1.2 eV and thermally activated (0.2-0.55 eV) p-type conduction [6]. In Fig. 5 typical current-voltage characteristics of a-C:H strain gauges on silicon micro boss-membranes are displayed which were recorded in the temperature range of 30-150°C. We find linear characteristics across the p-Si/a-C:H hetero interface below 2 V, i.e. below a field strength of 40 kV/cm. The specific resistance is in the range of several 10^8 Ωcm decreasing with temperature according to the Arrhenius law with an activation energy of 0.31 eV. Above the given voltage range a field-dependent increase of conductivity is observed corresponding to thermo-ionic emission from non-interacting traps (Frenkel-Poole conduction) [6].

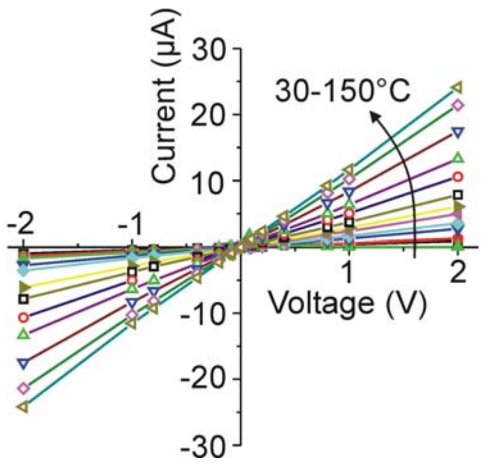

Fig. 5. Current-voltage characteristics across DLC on *p*-type silicon.

In DLC σ-bonded carbon atoms form a rigid skeleton in which sp^2-bonded nanometer-sized clusters are embedded [7]. The π states of sp^2 sites form a semi-filled band which is separated into a filled and an empty band by clustering of sp^2 sites. Therefore, DLC can be described by an amorphous dielectrically inhomogeneous composite of localized conductive nano clusters in an insulating matrix (Fig. 6).

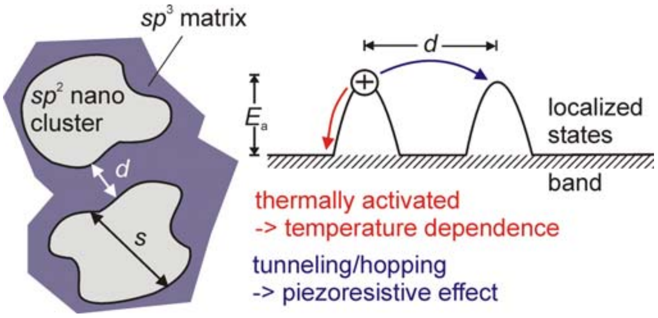

Fig. 6. Carrier transport in DLC according to the cluster model.

Charge transport is expected to occur by activation of holes from localized sites into the conduction band or by tunneling/hopping between the traps (clusters). By strain the distance between the clusters is either increased or decreased resulting in a change of resistance.

The piezoresistive response of DLC is investigated by probing the boss and measuring the resistance change caused by the strain induced at the top surface of the membrane as well as the applied force (Fig. 7a). Calibration of the DLC strain gauges is performed by incrementally moving with the boss against a probing pin mounted on the weighing pan of a high-resolution compensation balance (Fig.7b, [8]). Movement of the cantilever is done at a resolution of 1 nm and a reproducibility of 5 nm using piezoelectric setting and capacitive feedback. The compensation balance offers a resolution of 0.1 µN and a reproducibility of 0.2 µN. The complete setup is mounted in a thermally isolated box ensuring a temperature drift of less than 10 mK/h. During one calibration run (typically 30 min) a temperature drift within 2-5 mK can be maintained. The resistance is measured under constant current using a digital voltmeter. A low current density of 20 µA/cm^2 was selected to avoid heating.

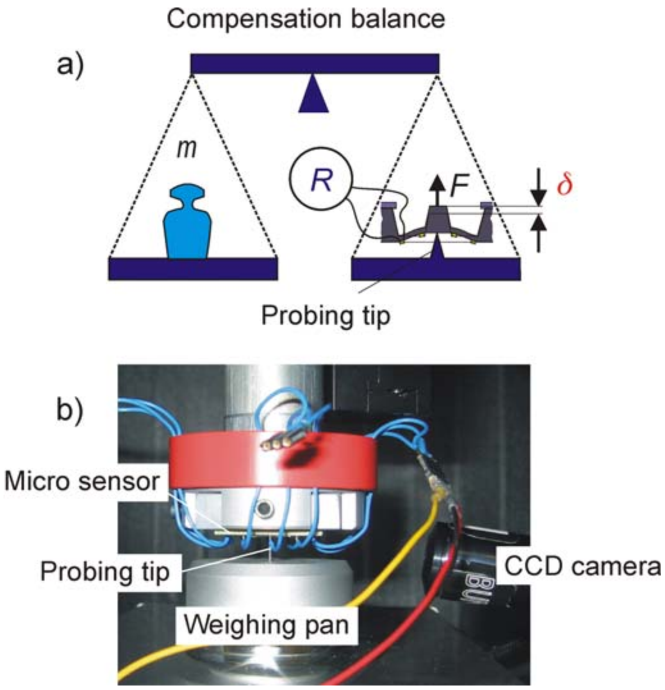

Fig. 7. Force-deflection-gauge-resistance measuring setup for calibration of boss-membrane sensors.

Transversal tensile ($\varepsilon > 0$) and compressive ($\varepsilon < 0$) strain is generated in the gauge resistors located close to the frame and the boss, respectively, by probing the top surface of the boss (cf. Fig. 1). In Fig. 8 typical load-deflection-resistance curves measured with DLC resistors under compressive (a) and tensile (b) strain are shown. We observe force sensitivities of -5.1 %/N and 2.9 %/N corresponding to gauge factors K of 79 and 66, respectively. Equation (1) was used to determine gauge factors from the measured sensitivities. The large difference in sensitivity obtained for both sensors given in Figs. 7a and 7b is mainly contributed to the different membrane stiffnesses k. We find 7.4 kN/m and 9.3 kN/m in accordance with the different membrane thicknesses h of 50 µm and 64 µm, respectively.

A detailed error analysis was performed taking into account the uncertainties of the relevant geometrical quantities (membrane thickness and area, size and position of DLC resistors) which were determined by microscope inspection of realized sensor prototypes. We found values of 5 % and 2.5 % contributed by the membrane thickness and the resistor positioning, respectively. The remaining error sources were estimated well below 1 %. Since the strain depends on membrane thickness according to h^{-2} this is the dominant error source leading to a typical uncertainty of the measured gauge factor of 10 %.

Drift of force sensitivity was investigated during a large number of subsequent measurements as shown for a strain gauge under tensile strain in Fig. 8. We find sensitivities of -0.532±0.004 Ω/µN and 0.231±0.006 Ω/µN for strain gauges under compressive and tensile strain, respectively, revealing a drift within 0.8-2.6 % over a total measurement period of 1.5-4 days. The residuals of the linear fits were averaged amounting to 231 Ω and 199 Ω, corresponding to uncertainties of the derived force of 0.44 mN and 0.86 mN, respectively.

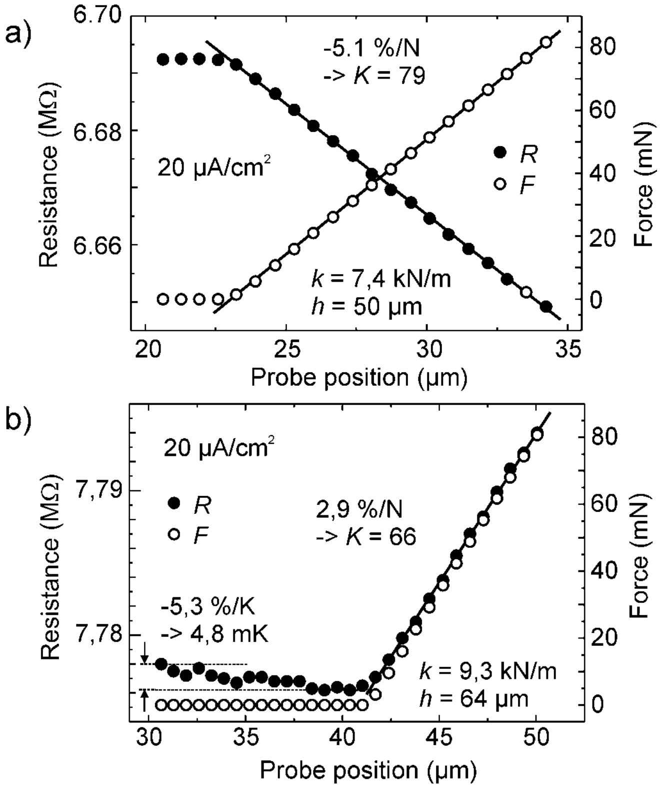

Fig. 7. Typical force-deflection-gauge-resistance characteristic of boss-membrane sensor with a-C:H strain gauges.

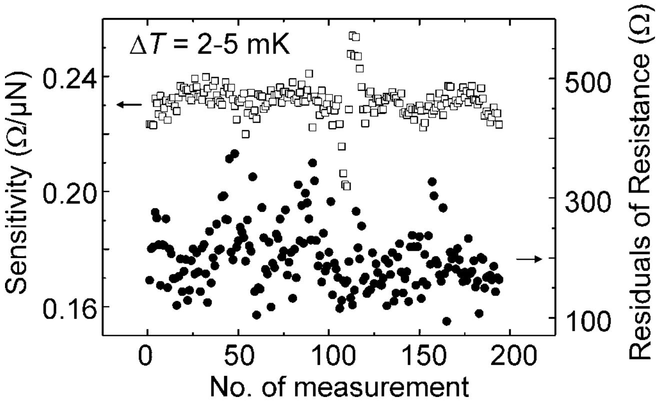

Fig. 8. Sensitivity derived by fitting to measured gauge-resistance-to-applied-force characteristics and standard deviation of fitting residuals.

The temperature dependence of DLC strain gauges was investigated in the range of 20-60°C. While the resistance exhibited a linear temperature coefficient at RT of 4-6 %/K the gauge factor is temperature-independent within the bounds of uncertainty of ± 10 %. In total more than hundred DLC strain gauges of resistivities within 10^8-10^9 Ωcm were analyzed, revealing an average gauge factor of 70±20 independent of the sign of the applied strain.

In addition to vertically connected DLC strain gauges also DLC resistors were designed and realized which are connected horizontally (cf. Fig. 2b). In this case DLC is deposited on oxidized silicon for vertical insulation. Top contacts for horizontal resistance measurement were fabricated by evaporated Au/Cr. Due to the high resistivity of DiaForce®-DLC of several hundreds of MΩcm the deposition conditions of hydrogenated amorphous carbon were changed. The bias voltage was increased from 350 V to 800 V yielding a resistivity of 3 MΩcm. Furthermore, interdigitated electrodes were designed by which the resistance can be reduced into the MΩ range (Fig. 9). Strain gauges oriented parallel (longitudinal effect) and perpendicular (transversal effect) to the direction of strain were investigated showing no difference in the measured gauge factors within the bounds of uncertainty. In total we found gauge factors between 22-30. Reference measurements with vertically connected resistors of the same DLC material yield gauge factors of 23±2 which is well within the above range of values.

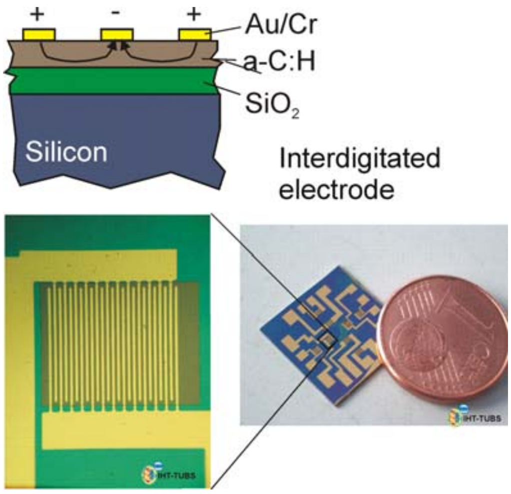

Fig. 9. Boss membrane sensor with DLC strain gauges contacted by interdigitated electrodes.

The above results show a remarkable decrease of the gauge factor obtained for a-C:H with the bias voltage selected during deposition. Recently, we found a decrease of the sp^3 fraction in a-C:H with increasing bias voltage. Carey and Silva found an increase that a higher concentration of more distorted sp^2 clusters is present in a-C:H deposited at higher bias voltage [6]. We conclude that for larger gauge factors of a-C:H formation of sp^2 clusters of uniformly small size should be aspired.

3.2 Hydrogen-free amorphous carbon (a-C)

In addition to hydrogenated DLC (a-C:H) also hydrogen-free amorphous carbon (a-C) is investigated. It is prepared by magnetron sputtering from a graphite target [6]. It has an optical bandgap of 0.6 eV and exhibits *n*-type conduction.

Close to RT conduction is thermally activated (0.04-0.04 eV). In contrast to a-C:H this material is highly conductive with a resistivity around 10^{-1} Ωcm. Therefore in this case interdigitated electrodes are not necessary. A typical sensor prototype is shown in Fig. 10.

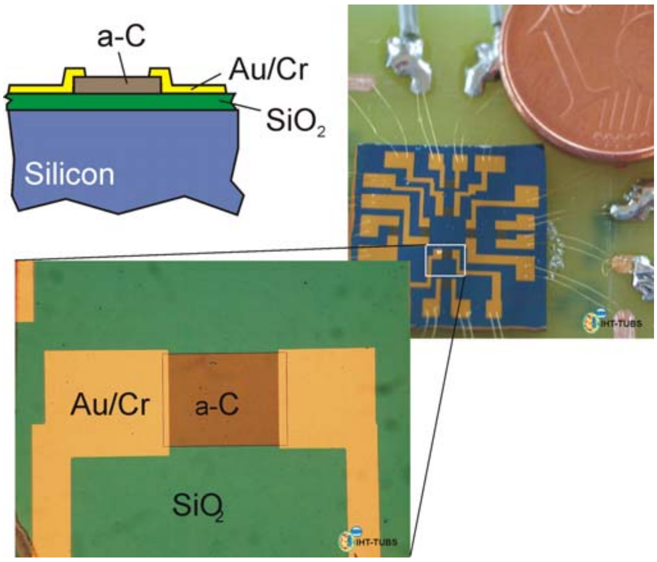

Fig. 10. Boss membrane sensor with a-C strain gauges.

Figure 11 exhibits typical load-deflection-resistance characteristics measured with a-C resistors on a boss membrane (h = 49 µm) under tensile (b) strain. We observe a force sensitivity of 1.2 %/N corresponding to a gauge factor K of 18.

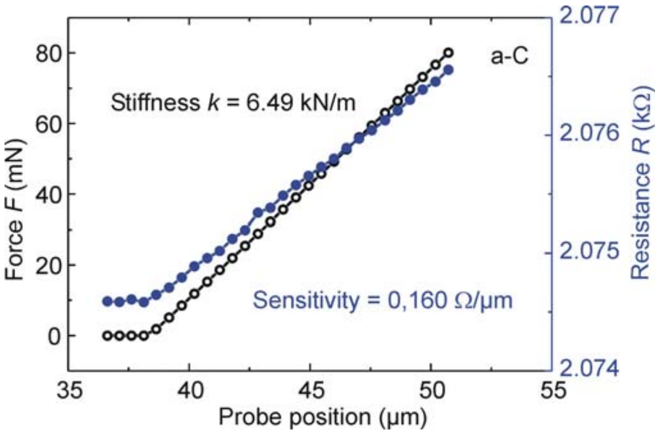

Fig. 11. Typical force-deflection-gauge-resistance characteristic of a boss membrane sensor with a-C strain gauges.

Measurements with different a-C resistors yielded gauge factors within 4-44, typically 20-30. This is slightly less than $36<K<42$ found in a previous study with a-C on micro cantilever sensors [9].

In Table 1 the results of the present study are compared with competing materials, i.e. micro crystalline silicon (µc-Si) [10], polycrystalline silicon carbide (poly-SiC) [11] and polycrystalline diamond (poly-C) [12]. The data shows that DLC offers characteristics, i.e. low deposition temperature T_g, large gauge factors, a wide range of resistivities and reasonable temperature coefficients (a-C) which can be promising for many strain gauge applications.

Table 1. Comparison of poly-crystalline and amorphous strain-gauge materials [10-12]

Material	T_g (°C)	K	ρ (Ωcm)	$\lvert TK \rvert$ (%/K)
µc-Si	100	10-40	0.01 - 0.5	-
poly-SiC	1050 - 1280	0.4 - 2.1	1.3- 8.3	0.5 - 0.7
poly-C	520 - 780	7 - 70	0.1 - 100	-
a-C	< 130	15 - 46	0.02 - 0.2	0.6 - 0.8
a-C:H	< 130	20 - 90	10^6 - 10^9	4 - 6

Thin a-C layers were used to fabricate pure DLC cantilevers on silicon. An example is shown in a scanning electron microphotograph in Fig. 12. Owing to its excellent resistance against chemical etching this structures can be fabricated by several hours treatment in common etchants of bulk micromachining (KOH, TMAH) without special protection of the DLC.

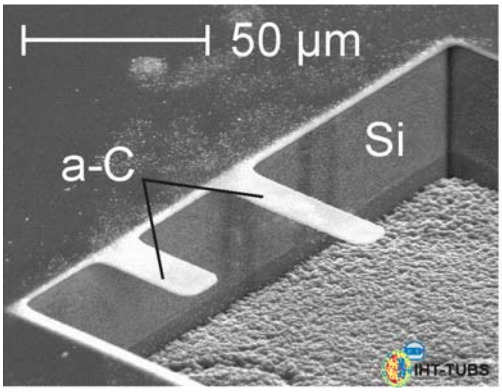

Fig. 12. Free-standing DLC cantilevers fabricated by standard silicon bulk micromachining.

4. CONCLUSION

In this contribution we describe the integration of low-temperature deposited thin diamond-like carbon layers into a bulk silicon micromachining process. DLC strain gauges on boss membrane force sensors fabricated showing typical gauge factors of 20-90. These results compare well with recently published values for boron-doped polycrystalline diamond requiring substrate temperatures well above 500°C. Larger gauge factors may be expected if sp^2 clusters of smaller and more uniform size can be prepared, e.g. by optimizing the bias voltage of the DLC deposition process.

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