Available online at www.sciencedirect.com
SCIENCE DIRECT
Sensors and Actuators A 130–131 (2006) 75–82
SENSORS AND ACTUATORS A PHYSICAL
www.elsevier.com/locate/sna

Micro force sensor with piezoresistive amorphous carbon strain gauge

E. Peiner [a,*], A. Tibrewala [a], R. Bandorf [b], S. Biehl [b], H. Lüthje [b], L. Doering [c]

[a] *Technical University Carolo-Wilhelmina at Braunschweig, Institute for Semiconductor Technology, Hans-Sommer-Str. 66, D-38106 Braunschweig, Germany*
[b] *Fraunhofer Institute for Thin Film and Surface Engineering, Bienroder Weg 54e, D-38108 Braunschweig, Germany*
[c] *Physikalisch-Technische Bundesanstalt (PTB), Nano- and Micrometrology, Bundesallee 100, D-38116 Braunschweig, Germany*

Received 2 June 2005; received in revised form 16 September 2005; accepted 22 November 2005
Available online 20 January 2006

Abstract

In this contribution we report for the first time on the successful integration of amorphous carbon (a-C) as a piezoresistive strain gauge into a silicon micro cantilever force sensor. Sputter-deposited a-C layers showing excellent tribological properties contain a percentage of nearly 20% of tetrahedral sp^3 carbon bonds as observed by optical absorption and Raman spectroscopy. Temperature-dependent transport measurements revealed hopping conduction between conducting sp^2 carbon sites embedded in the insulating skeletal matrix of sp^3 bonds. Changing their distance by strain a change of resistivity could be expected, which was investigated with layers sputter-deposited on a silicon membrane and structured by the lift-off technique using photo resist. Cantilevers comprising a-C strain gauges were etched out of this membrane using tetra methyl ammonium hydroxide (TMAH) and potassium hydroxide (KOH) solutions in a bulk silicon micromachining process. Realised prototypes were tested by applying a variable load to the cantilever free end. We found linear characteristics of the strain gauge resistance versus the applied force in the range of 0 to $\pm 600\ \mu N$ revealing piezoresistive gauge factors of a–C within 36–46.

Keywords: Amorphous carbon; Hopping conduction; Piezoresistive gauge factor; Bulk silicon micromachining; Micro force sensor

1. Introduction

Diamond and hard carbon coatings are widely used to improve the micro tribological properties of micro electro mechanical systems (MEMS) [1-3]. Due its hardness, wear resistance as well as robustness to harsh environment diamond is an attractive material for many MEMS applications, e.g. micro grippers and atomic force microscope (AFM) probes. These micro components could be realised by selective deposition of polycrystalline diamond on silicon substrates and molds, respectively, using SiO_2 as a sacrificial layer [4]. Furthermore, diamond is one of the most promising materials for high-frequency nano electro mechanical systems (NEMS) or surface acoustic wave (SAW) devices [5] since it exhibits the highest sound velocity of all semiconductors with 1.8×10^4 m/s as estimated by the square root of the Young's modulus-to-density-ratio.

Piezoresistivity is an important property of materials to be used, e.g. for strain gauges in mechanical sensors. Boron-doped polycrystalline diamond (poly-C) grown on commercial poly-C substrates exhibits a considerable piezoresistive effect with gauge factors K of a few hundreds and more than 4000 under inter- and intra-grain probing conditions, respectively [6]. In a recent study a best value of the piezoresistive gauge factor of 50 was reported for boron-doped poly-C on oxidised silicon substrates [7]. A poly-C position sensor integrated on a silicon-based cochlear implant probe has a gauge factor of 28 [8]. K depends on grain size and resistivity of the poly-C. Maximum values of 70–80 were obtained at around $10^2\ \Omega$cm [9].

Unfortunately, chemical vapour deposition (CVD) which is conventionally used for the growth of poly-C requires a substrate temperature of 500–900 °C [7,8] which is much too high for substrates alternative to diamond or silicon like large-area plastics. Furthermore, it is not favourable for the deposition on micro-structured silicon. Correspondingly, low-temperature deposition, e.g. plasma-enhanced or -assisted CVD, of amorphous (a-Si:H) and microcrystalline (μc-Si:H) silicon at low substrate temperature (<150 °C) has recently found much atten-

* Corresponding author. Tel.: +49 531 3913761; fax: +49 531 3915844.
E-mail address: e.peiner@tu-bs.de (E. Peiner).

0924-4247/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.sna.2005.11.059

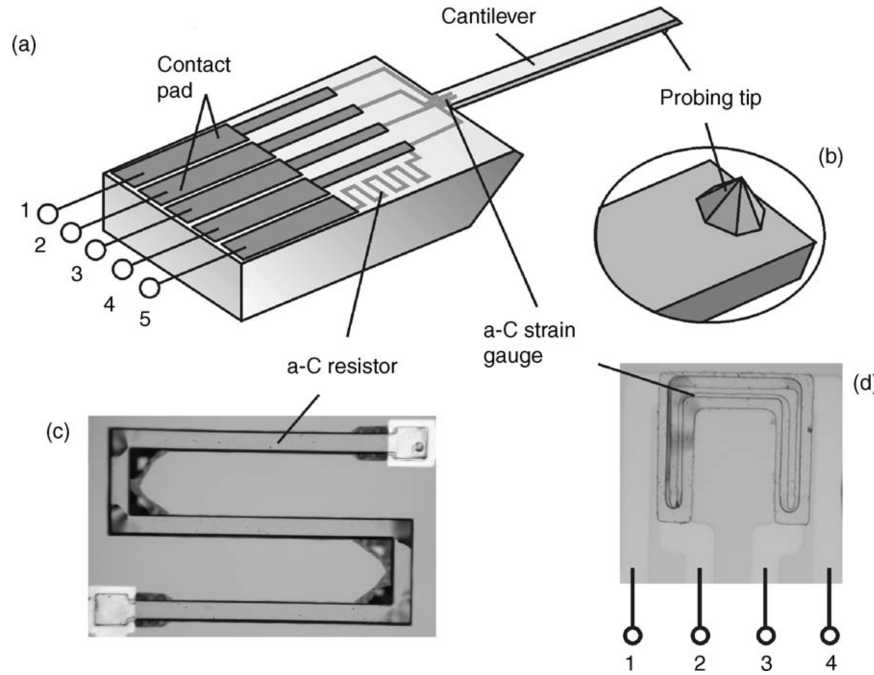

Fig. 1. Schematic of micro force sensor (a) with integrated probing tip at the cantilever bottom side in an enlarged representation (b). Optical microphotographs of the amorphous carbon reference and strain gauge resistors are shown in (c) and (d).

tion [10,11]. An investigation of the piezoresistive properties of low-temperature μc-Si:H on plastic substrates revealed gauge factors in the range of 10–40 [11]. For sputtered amorphous carbon (a-C) investigations on piezoresistivity are lacking.

Therefore, in this contribution we report on the structural and electrical transport properties of sputtered a-C as a material for piezoresistive strain gauges in MEMS. Amorphous carbon is superior to heteroepitaxial and poly-C in terms of production cost and process requirements: high substrate temperatures and additional doping sources are not necessary. Compared to a-Si and μc-Si:H it provides better tribological properties and robustness to harsh environment. In this study the piezoresistive properties of amorphous carbon strain gauges integrated on a bulk micromachined silicon cantilever (Fig. 1) are addressed for the first time.

2. Fabrication and characterization of amorphous carbon films

Amorphous carbon films were deposited on silicon and SiO_2/silicon substrates by rf magnetron sputtering of a graphite target using a Balzers BAS 450 sputter plant. The substrate temperature during deposition was less than 150 °C. A substrate bias of −100 V was maintained leading to superior tribological properties (high hardness, low wear and friction) of 0.25 μm thick a-C layers, e.g. a hardness of 50 GPa [12]. Hardness in the range of a few tens of GPa can be expected for sputtered amorphous carbon with a content of tetrahedral-bonded carbon (sp^3) of around 25% [13]. The hydrogen content in the films determined by secondary ion mass spectroscopy (SIMS) was less than 2%. More details on the a-C deposition process and the tribological testing were reported elsewhere [12].

The structural properties of 0.5 μm thick a-C layers on silicon were investigated by spectroscopic ellipsometry and Raman spectroscopy. Fig. 2 shows the optical absorption coefficient α of a-C measured between 0.8 and 5 eV which can be used to determine the optical band gap. Constructing a plot of $(\alpha h\nu)^{1/2}$ versus the photon energy $h\nu$ the band gap can be determined from the intercept E_T of the extrapolated linear fit of Tauc's relation to the measured data (Fig. 2, Tauc gap, [14]). Alternatively, the photon energy at which the absorption coefficient amounts to 10^4 cm^{-1} is often considered as a measure of the optical gap (E_{04}, [15]). From Fig. 2 we obtain values of 0.65 and 0.8 eV for the Tauc and the E_{04} gap, respectively. By comparison with collected data [15] we can estimate a content of conductive sp^2 bonds of 80–90%.

The Raman spectrum in Fig. 3 exhibits the typical *G*- and *D*-bands which can be assigned to the E_{2g} in-plane stretching mode of graphite and to the A_{1g} breathing mode of aromatic rings

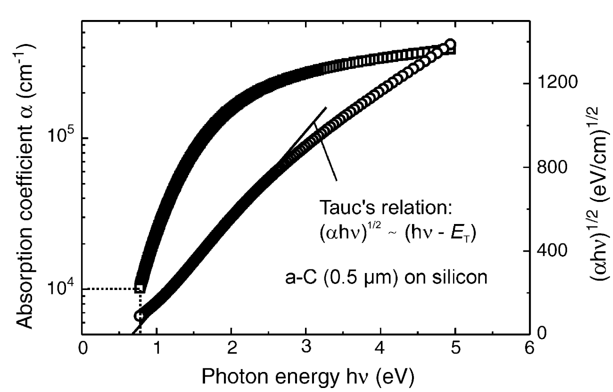

Fig. 2. Absorption coefficient and Tauc plot [14], i.e. $(\alpha h\nu)^{1/2}$ in dependence on photon energy $h\nu$ for a 0.5-μm-thick a-C layer.