Study of polycrystalline diamond piezoresistive position sensors for application in cochlear implant probe

Yuxing Tang a,*, Dean M. Aslam a, Jianbai Wang b, Kensall D. Wise b

aMicro and Nano Technology Lab, Department of Electrical and Computer Engineering, Michigan State University, East Lansing, MI 48824, United States
bDepartment of Electrical Engineering and Computer Sciences, University of Michigan, Ann Arbor, MI 48109, United States

Available online 31 August 2005

Abstract

Polycrystalline diamond (poly-C) piezoresistive sensors, with high sensitivity, were fabricated and tested for the purpose of integration with Si-based microsystems. The dependence of piezoresistive gauge factor (GF), from 6 to 70, of poly-C films on film resistivities and grain sizes was investigated in detail. Two seeding methods, with high (10^10 cm^{-2}) and low (10^8 cm^{-2}) seeding density, were used to grow poly-C films with small (0.3 μm) and large (0.8 μm) grains, respectively, on 4 inch oxidized Si wafers. Results show that higher resistivities and larger grain sizes yield higher GF. Poly-C piezoresistive position sensors, with a tested GF of 28 and potential GF of 70, were fabricated and integrated into a Si-based cochlear implant probe for the first time.

© 2005 Elsevier B.V. All rights reserved.

Keywords: Polycrystalline diamond; Piezoresistive sensor; Gauge factor; Cochlear implant probe

1. Introduction

Polycrystalline diamond (poly-C) is an excellent sensor material especially at high temperatures and in harsh environments due to its large band gap, high mechanical strength, high thermal conductivity and chemical inertness [1,2]. The piezoresistive GF of poly-C and related piezoresistive sensors have been reported by several groups [2–6] but with large variations in the piezoresistive GF; typically in the ranges of 8–100 [2–4], 500–3200 [5] and 4000 [6] for poly-C inter-grain, single crystal diamond and poly-C intra-grain, respectively. Normally, the high GF values in the prior studies were achieved from films with resistivities over 50 Ω cm, which are impractical for sensor application due to the high film resistances and high noise levels. In this work, poly-C thin films, with thicknesses around 1 μm and with different resistivities, were fabricated and tested to explore how the film properties affect the piezoresistive GF. Films with two different grain sizes, realized by two different seeding methods, were used to study the relation between the GF and the film grain size.

A new application of poly-C film in Si-based microsystems was demonstrated for the first time by integrating the poly-C piezoresistors into a cochlear implant probe as high-sensitivity position sensors. A cochlear prostheses has been used as a hearing enabling technology to help profoundly deaf people by electrically stimulating the cochlear nerve cells with the implanted electrode [7]. The performance of the cochlear prosthesis can be improved by integrating a distributed series of piezoresistors along the insertion part of the cochlear probe. It can enhance the signal efficiency and accuracy by detecting the position and curvature of the probe during insertion and post-operation [7,8]. The present work focuses only on optimizing the poly-C seeding, growth, doping and dry etching processes for high piezoresistive sensitivity and compatibility with Si-based probe fabrication process.

2. Experimental

2.1. The fabrication process of poly-C piezoresistors

The CVD growth of poly-C films requires a pretreatment step to generate seeds (or nuclei) before the growth begins.
For electrical insulation, poly-C films were grown on silicon wafer covered with a layer of Si$_3$N$_4$ or SiO$_2$. Two different spin seeding methods, diamond powder loaded water (DPLW) [9] and diamond powder loaded photoresist (DPR) [10], were used to provide different seeding densities. DPLW or DPR was spin coated on the samples with a typical spin speed of 3000 rpm. Table 1 compared the two seeding methods in preparation, seeding density and grown film morphology.

After the seeding procedure, the sample wafer was loaded into a bell jar type MPCVD chamber (Wavemat MPDR 313EHP) for diamond growth. The wafer was heated to a growth temperature of 700°C by the methane/hydrogen (CH$_4$:H$_2$ = 1:100 sccm) plasma, which was generated by a 2.45 GHz, 2.5 kW microwave power supply (Sairem). Hydrogen diluted trimethylboron (B(OCH$_3$)$_3$, TMB) gas (TMB:H$_2$ = 0.1% in volume ratio) was introduced during the growth for in situ boron doping which can lead to a resistivities from 0.05 to 70 Vcm.

After the growth, the samples were annealed at 600°C in vacuum (10$^{-5}$ torr) for 30 min to remove the hydrogenated surface layer.

The dry etching of poly-C film was carried out in an electron cyclotron resonance (ECR)-assisted microwave plasma system with a 2.45 GHz microwave power of 400 W. An RF power of 100 W was coupled into the chamber to generate a negative bias from −50 to −200 V, which is critical for the etch rate. The O$_2$, SF$_6$, and Ar gases were used for etching at a pressure of 4–8 mtorr. Patterned Al films were used as a mask for the etching. A typical etch rate for poly-C film was 120 nm/min achieved by a pressure of 5 mtorr and a substrate bias of −130 V.

An Au/Ti metal stack was e-beam deposited and patterned. An ohmic contact between the Au/Ti metal stack and poly-C film was achieved by a vacuum annealing at 500°C.

### 2.2. The fabrication process of the cochlear implant probe with poly-C sensors

The probe fabrication begins with two boron diffusions (shallow and deep) to define the profile of the probe, which has thin (4 µm) shank and thick (14 µm) backend. A stress-compensated dielectric stack of SiO$_2$/Si$_3$N$_4$/SiO$_2$ is deposited before conducting lines are defined using p$^+$-implantation in poly-Si [7,8]. Another dielectric stack of Si$_3$N$_4$/SiO$_2$ is deposited to cover the poly-Si lines before poly-C is deposited and patterned using the process described in previous section. DPLW seeding was used here to get smooth surfaces and structures for better integration. A metal stack of Ti/TiN/Al is sputtered and patterned by lift-off, which acts as interconnect between poly-C and poly-Si through the contact holes. A layer of Ir/Ti is sputtered and patterned by lift-off to define the stimulating sites. Gold bonding pads are formed on the back-end of the probe in a similar manner. After these fabrication steps, the probes were released using EDP etching of the silicon substrate.

### 3. Results and discussions

#### 3.1. The piezoresistive gauge factor of poly-C films

Fig. 1 shows, for both the DPLW and DPR methods, the scanning electron microscope (SEM) pictures before and after the growth of poly-C films with 1 µm thickness. As shown in Table 1, the DPLW spin yields a seeding density of over 10$^{10}$ cm$^{-2}$, which leads to a small grain size and smooth surface after growth. Although low seeding density (10$^8$ cm$^{-2}$) causes rough surface and pinholes in the thin film, it leads to large grain sizes which can result in higher GF.

For testing the GF of poly-C thin film, a piezoresistive sensor was fabricated on an oxidized silicon wafer and measured using a cantilever beam setup as shown in Fig. 2. The oxidized wafer, with a thickness of 500 µm, was cut into pieces with sizes of 1 × 5 cm and clamped from one end. Bending the free end of the beam through a distance of δ, the longitudinal strain ε on the surface of

![Fig. 1. SEM pictures of a) DPLW seeding; b) poly-C film (with thickness of 1 µm) seeded by DPLW; c) DPR seeding; d) poly-C film (with thickness of 1 µm) seeded by DPR.](image-url)
the beam can be calculated using the parameters shown in the Fig. 2a,

\[ \varepsilon = \frac{3h}{2l^3} \left[ l - \frac{(a+b)}{2} \right] \delta, \]  

(1)

If the thickness of the poly-C resistors is very small as compared to \( h \), \( \varepsilon \) is approximately equal to the strain in the poly-C resistors. The calculated strain was verified by attaching a commercial metal strain gauge on the beam and showed an error of less than 5%. The gauge factor of the poly-C can be expressed as

\[ \text{GF} = \frac{R - R_0}{R_0} \frac{1}{\varepsilon} = \frac{2(R - R_0)l^3}{3R_0h\delta \left[ l - \frac{(a+b)}{2} \right]} \],

(2)

where \( R \) is the resistance with strain \( \varepsilon \) and \( R_0 \) is the resistance at zero strain. Fig. 2b shows a typical relationship between the fractional resistance change and strain for a poly-C piezoresistor prepared by DPR seeding.

The dependence of GF on resistivity is shown in Fig. 3 for both DPR and DPLW seeded films with thicknesses of 1 \( \mu \)m. The results show that, for films with resistivity less than 1 \( \Omega \cdot \text{cm} \), the GF values are around 6–10 and don’t change much with the resistivity and grain size. However, the GF increases substantially with resistivity for films with resistivities higher than 1 \( \Omega \cdot \text{cm} \). At the same resistivity, the film with grain size of 0.8 \( \mu \)m (DPR seeding) gave a GF about 3 times higher than that of film with grain size of 0.3 \( \mu \)m (DPLW seeding). This result is consistent with the reported GF of 283 from free standing diamond sample with grains in 50 \( \mu \)m range [6]. The high GF values found in large grain films are believed to be related to high sp\(^3\)/sp\(^2\) ratios caused by lower densities of grain boundaries.

It is also known that high resistivity will cause large thermal noise and high contact resistance [11], which will hinder the sensor application of poly-C films. By optimizing the film grain size and resistivity, the use of poly-C sensors in microsystems is expected to lead to unprecedented sensitivity and promising applications.

3.2. Integration of poly-C sensors in the cochlear probe

Fig. 4 shows the SEM pictures of the cochlear probe with integrated poly-C position sensors. The poly-C film, seeded with a nucleation density of \( 10^{10} \) cm\(^{-2} \) and deposited at 560 °C, has a thickness of 1 \( \mu \)m and resistivity of 40 \( \Omega \cdot \text{cm} \). An array of poly-C positions sensors and an array of Iridium stimulation sites are located on the flexible shank (insertion part) of the probe. There is one U-shaped sensor at the tip of the probe used for monitoring the contact of probe tip with the cochlear inner wall. On the backend of the probe, there are reference sensors which have the same shapes and resistances as the sensors on the shank part. The resistance of the reference sensors will be constant during the insertion because the thick backend will not bend. Serial connection of the position sensor and reference sensor forms a half Wheatstone Bridge, which can convert the resistance change into a voltage output for measurement.

A testchip, with various testing structures, was fabricated on the same wafer with the implant probes to characterize the properties and integration of all used films including...
poly-C. The contact resistivity between poly-C and Ti interconnect metal is approximately 0.2 V cm\(^2\). The dry etching of poly-C produced a minimum feature size of 2 \(\mu\)m and showed reliable step coverage between 2 \(\mu\)m wide poly-Si and metal layers. The resistance of dielectric layers was more than 10\(^9\) \(\Omega\) ensuring an excellent insulation for the poly-C films. These results show a successful integration between poly-C and silicon technologies, which widely extends the potential applications of poly-C films in microsystems.

For measuring the GF of poly-C position sensors, integrated on the cochlear probe, the probe backend was glued on a printed circuit board (PCB) substrate and electrically connected by gold wire bonding. The probe can be treated approximately as a uniform beam with a length of 1.6 cm and a thickness of 6 \(\mu\)m. Strains were applied on the poly-C sensors by bending the probe into different curvatures using a specific stage. The stain \(\epsilon\) was calculated by

\[
\epsilon = \frac{h}{2\rho} = \frac{h}{\rho},
\]

where \(h\) is the probe thickness and \(\rho\) is the radius of curvature. The GF was then calculated using,

\[
GF = \frac{(R - R_0)/R}{\epsilon} = \frac{2(R - R_0)\rho}{R \cdot h}.
\]

A GF of 28 was achieved for the poly-C sensors on the cochlear probe. However, as shown in Fig. 3, higher GF values (above 60) can be achieved using DPR seeding. Currently a new process is being developed to optimize the poly-C position sensor fabrication and integration, which is expected to lead to higher GF.

4. Conclusions

Poly-C piezoresistive position sensors, with a GF value of 28, have been successfully integrated into the cochlear implant probe for the first time. The dependence of GF (from 6–70) on film resistivity and grain size was studied in detail for process optimization. Further work focuses on the improvement of poly-C GF for the next generation of cochlear probe.

Acknowledgements

This work is supported by the Engineering Research Centers Program of the National Science Foundation under Award Number EEC-9986866.

References