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Published in:
Micro and Nano Engineering

Link to article, DOI:
10.1016/j.mne.2019.05.002

Publication date:
2019

Document Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):
Research paper

Towards diamond micro four-point probes

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\textbf{ARTICLE INFO}

\textbf{Keywords:}
- Diamond MEMS
- Diamond cantilevers
- Micro four-point probes
- Polycrystalline diamond thin-film

\textbf{ABSTRACT}

Diamond has extreme physical properties, and it is used for critical applications in micro- and nanotechnology and nanosciences. Micro four-point probes for electrical characterization of metal and semiconductor thin-films are made from metal coated silicon microcantilevers. The limiting factors in probe lifetime are frictional wear and thermal damage from electrical overstress. Diamond has superior thermal conductivity and wear resistant properties which could improve probe lifetime. In this paper, we present wafer-level fabrication of polycrystalline diamond micro cantilevers for micro four-point probe applications. The process only requires two photolithography steps. We show great design flexibility and demonstrate extremely mechanical robust free-standing diamond cantilever up to 300 μm long. We believe that this process may find important applications beyond micro four-point probes. The next step is to implement micro four-point probes using high quality electrically conductive diamond when it becomes available.

1. Introduction

Diamond is fantastic material with exceptional physical properties (Table 1). For example, it is the hardest material, and it has the highest thermal conductivity. Because of its superior properties, micro- and nanоструктуре на діамантових мікро-кантілеюверах може бути використано для оцінювання мікророзподілу металевої і полупровідникової пленки. Основними факторами, які впливають на тривалість діапазону, є вібраційне знос і теплові шкоди від електричного перенапруження. Діамант має високу теплову проводність та відрізняється від сили, відносно яких може збільшити тривалість діапазону. У цьому праці ми представили виробництво полікристалічних діамантових мікро-кантілеєверів для мікро-четири точкових досліджень. Порядок процесу аж до двох літографічних кроків. Ми виводимо велику гнучкість дизайну та демонструємо високу механічну стійкість свободної діамантової кантілеєвера довжиною до 300 μm. Ми вважаємо, що цей процес може знайти важливі застосування завдяки мікро-четири точковим дослідженням. Наступним кроком є реалізація мікро-четири точкових досліджень використовуючи висококачісну електрично-кондуктивну діамант, коли він стає доступним.

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https://doi.org/10.1016/j.mne.2019.05.002

Received 5 March 2018; Received in revised form 12 April 2019; Accepted 3 May 2019

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of-the-art technology can be improved in several areas. Most importantly, we must improve the life time of the probes. Because of the slight sliding motion every time the nickel coated cantilever makes physical contact with the sample, the nickel film wears out, and the M4PP must be changed and discarded. One way to reduce frictional wear is to make “three-way” flexible electrodes [22,23]. Another approach could be to use diamond. Because diamond is extremely hard, and it has a low friction coefficient (Table 1), it has outstanding wear and tribology properties [24,25]. Diamond coatings are used for most demanding anti-wear applications. If the entire cantilever can be made from conductive diamond, it would be virtually impossible to wear out such probes. Furthermore, AFM using conductive diamond coated probes are regularly used for electrical characterization of semiconductors [26]. Based on the above facts, it became obvious that conductive diamond M4PP could prove a useful alternative to polycrystalline silicon cantilevers. In this paper, we present microfabricated polycrystalline diamond cantilevers for M4PP applications.

2. Materials and methods

2.1. Polycrystalline diamond M4PP fabrication process

The starting substrates are AQUA50 DOI wafers from Advanced Diamond Technologies, USA (Fig. 1a). To be compatible with the measurement instrument that is designed for silicon 4PP, we needed diamond 4PPs that have approximate the same length and spring constant as the silicon 4PP. This is achieved by selecting a thinner diamond film, which is nominally 1-μm-thick (silicon probes are 7-μm-thick). The buried oxide layer (BOX) is 1-μm-thick, the substrate is a 500-μm-thick silicon wafer 100 mm in diameter. The DOI wafers have silicon dioxide layers on both sides and a very thin layer of PCD on the back side of the wafer. These thin-films on the backside were removed (Fig. 1b). We removed the backside PCD by inductively coupled plasma (ICP) etching using a MESC Multiplex ICP instrument from STPS, UK. The process parameters were 30 sccm Ar, 90 sccm O2, 1000 W coil power, 200 W platen power, and 20 mTorr pressure. This process is referred as the “diamond etch”. To remove the backside silicon dioxide the wafer was wet etched in buffered HF. We used photolithography and lift-off to pattern Al, which is used as etch-mask for both diamond and deep reactive ion etching (DRIE) of silicon (Fig. 1c). The thickness of Al mask was 200 nm. We optimized a DRIE process to etch silicon from the backside (Fig. 1d). Diamond etch was used to etch the diamond thin-film (Fig. 1e). The remaining Al mask was removed in AZ 400 K photoresist developer that contains KOH (Fig. 1f), and buffered HF was used for release diamond cantilevers from the DOI substrate (Fig. 1g). To reduce the series resistance of the probes and the electrical leads to the bonding pad, a metal layer was evaporated on top of the diamond after the BHF release (Fig. 1h1). This process step is well established for the fabrication of commercial M4PP, which utilize the undercut in the oxide BOX layer to avoid electrical short circuit (Fig. 1h2) [27].

Table 1

<table>
<thead>
<tr>
<th>Material</th>
<th>Young’s modulus (GPa)</th>
<th>Fracture strength (GPa)</th>
<th>Fracture toughness (MPa m½)</th>
<th>Friction coeff.</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon</td>
<td>150</td>
<td>0.3</td>
<td>1.6</td>
<td>0.02-0.7</td>
<td>[9,10]</td>
</tr>
<tr>
<td>SiC</td>
<td>373</td>
<td>1.44</td>
<td>4</td>
<td>0.2-0.5</td>
<td>[11,12]</td>
</tr>
<tr>
<td>UNCD</td>
<td>400-1100</td>
<td>1-5</td>
<td>4-9</td>
<td>0.008-0.05</td>
<td>[13,14]</td>
</tr>
<tr>
<td>MCD (this study)</td>
<td>800-1200</td>
<td>1-5</td>
<td>5-9</td>
<td>0.1</td>
<td>[13,15]</td>
</tr>
</tbody>
</table>

Fig. 1. Diamond M4PP fabrication process and M4PP measurement geometry.
pads that are easy to access during the wire bonding process. For each M4PP probe, there are 4 diamond cantilevers protruding from the silicon probe chip (Fig. 2b). We inspected the probes from different angles by SEM, and we observed that the cantilevers protruded from the silicon probe extremely straight, which proves that we did not induce any undesired stress during fabrication. On the same M4PP probe we integrated a strain gauge cantilever sensor used for surface detection [18] (Fig. 2c). Fig. 2d shows a high magnification of the tip of a cantilever. We observed the facets of the micrometer sized diamond crystals. There is a 300 nm wide “strip” around the tip, and which is the projection of the positive etch angle that is shown later. At the edge of the cantilever, we see that the crystals are “cut” by the etching process. This observation is important because we can then make structures smaller than the grain size. For 4PP measurements, diamond probes made from diamond thin-films with very rough surface may scratch the sample. To reduce the surface roughness and also the friction coefficient (Table 1), we could either select a diamond thin-film with 3 nm grainsize [1], or use the smooth diamond surface facing the oxide layer.

The most challenging process step is diamond etching. Compared to etching silicon, there are only a few reports on diamond etching processes. We selectively list etching processes in Table 2. See also Castelletto et al. for a recent review on diamond nanofabrication [28]. There are two strategies for etching diamond. Either an O₂ and CF₄ plasma combined with a SiO₂ mask, or an O₂ and Ar plasma combined with a metal mask. The etch-rates ranged between 50 and 660 nm/min, and they are very instrument dependent. The etch selectivities of diamond over etch mask are between 8 and 50. For our application, the etching processes must be compatible with most MEMS foundries, and for high resource efficiency, we needed to etch through the PCD layer quickly. Therefore we needed high etch rate, good selectivity, and masking materials that are MEMS compatible. This is possible by using an Al hard mask combined with O₂/Ar plasma chemistry. We used a 200-nm-thick Al mask, and the etch process parameters were 30 sccm Ar, 90 sccm O₂, 1000 W coil power, 200 W platen bias, and 20 mTorr pressure. The etch rate was measured to 90 nm/min, and the etch selectivity was above 8, which is adequate for etching our PCD thin-film. However, the etch rate is lower than previous reports [29,30], which we attribute to the difference between the instruments. The etch profile was measure by SEM to 76° (Fig. 3). For our 1200-nm-thick PCD film, the bottom of the film is 300 nm wider than the top, which is tolerable for M4PP applications. For applications that strictly require vertical walls, we could optimize the etch profile by reducing the platen power [29].

Our process is a full wafer process, and we can fit 330 probes onto a single wafer. We took advantage of this design freedom, and on the very same wafer we included 14 different designs with different applications in mind. For example as shown in Fig. 4, we designed the spring constant by changing the cantilever length and width to control the contact force. And by changing the tip shape we control the contact pressure and penetration depth, as the ideal contact conditions may be different for different materials. Fig. 4c shows SEM images of cantilevers with tip angles very sharp (24°), sharp 90° or blunt. Using optical microscopy and SEM, we did not observe significant wafer level variation of the tip shape nor the distance between probe cantilevers. However, the cantilever length is slightly shorter in areas near the wafer center compared to areas towards the edge of the wafer. The variation is induced in DRIE backside process step (Fig. 1d), and it is caused by the DRIE loading effect which etch the center areas slower than the edge areas, which

![Fig. 2. Diamond M4PP with integrated strain gauge cantilever for surface detection. SEM image of M4PP (a), probe cantilevers (b), integrated strain gauge sensor and cantilever (c). The tip of the diamond cantilever at high magnification (d). Images are taken before final metallization step.](image-url)

<table>
<thead>
<tr>
<th>Reference</th>
<th>Year</th>
<th>Instrument</th>
<th>Plasma chemistry</th>
<th>Mask</th>
<th>Etch rate (nm/min)</th>
<th>Selectivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ando et al. [32]</td>
<td>2002</td>
<td>RIE</td>
<td>O₂/CF₄</td>
<td>SiO₂</td>
<td>150</td>
<td>–</td>
</tr>
<tr>
<td>Hwang et al. [29]</td>
<td>2004</td>
<td>ICP</td>
<td>O₂/Ar</td>
<td>Al</td>
<td>660</td>
<td>50</td>
</tr>
<tr>
<td>Ding et al. [30]</td>
<td>2005</td>
<td>RIE</td>
<td>O₂/Ar</td>
<td>Ni</td>
<td>50</td>
<td>–</td>
</tr>
<tr>
<td>Yamada et al. [33]</td>
<td>2007</td>
<td>ICP</td>
<td>O₂/CF₄</td>
<td>SiO₂</td>
<td>340</td>
<td>10–26</td>
</tr>
<tr>
<td>Hausmann et al. [34]</td>
<td>2010</td>
<td>ICP</td>
<td>O₂</td>
<td>Au, Al₂O₃, SiO₂</td>
<td>200</td>
<td>1:8</td>
</tr>
<tr>
<td>This work</td>
<td>2019</td>
<td>ICP</td>
<td>O₂/Ar</td>
<td>Al</td>
<td>90</td>
<td>8</td>
</tr>
</tbody>
</table>
Having showed that the diamond cantilevers can be fabricated with mechanical integrity, and application driven design flexibility, we tested the mechanical robustness of diamond cantilevers. It would be detrimental if cantilevers broke during a measurement, because debris would contaminate valuable samples. Diamond has much higher fracture strength and toughness (Table 1) than silicon, and indeed we observed that the diamond M4PP did not mechanically yield or show any inelastic deformation using our measurement set-up (microRSP-M200, Capres, Denmark). When the diamond cantilevers was pushed into the sample at an 45° incidence angle, it would first deflect and then lay flat on the sample surface. The diamond cantilever only broke if we crashed the silicon support chip into the sample. To push the mechanical conditions to the extreme, we qualitatively tested the yield conditions by applying mechanical forces and observe under which conditions the cantilevers would break. We mounted M4PPs in an SEM with a micromanipulator, and used the manipulator to apply mechanical force to the cantilevers while observing and recording using the SEM. Fig. 5 show six movie frames testing the mechanical robustness of the diamond cantilevers. The diamond cantilevers were 300-μm-long, 8-μm-wide, and 1200-nm-thick. Firstly, we tested how much out-of-plane bending was required to break the cantilever. The cantilevers were
engaged mechanically using the micromanipulator (Fig. 5a). The cantilever is lifted up by 200 μm (Fig. 5b), but this was not sufficient to break it. Then, we pulled the cantilever back by 150 μm, and it folded back forming a bow shape before it broke (Fig. 5c). From the SEM images, and the cantilever geometry, the bending radius at fracture is above 100 μm. The diamond cantilever is 1.2 μm thick, and assuming the neutral axis is in the center of the cantilever, the fracture strain and stress are calculated to respectively < 0.006 and < 5–7 GPa. These values are consistent and slightly higher than previous reports (Table 1). Secondly, we tested how much in-plane bending was needed to break the cantilever. We engaged a second cantilever (Fig. 5d) and pushed to the left (Fig. 5e) until the cantilever broke (Fig. 5f). For (Table 1). For angular displacements < 13°, the cantilever bends to the left without twisting. At larger angular displacements the cantilever twisted because it relaxes to a state with lower mechanical energy. The cantilever breaks at an angular displacement of 33°. For M4PP applications significant inelastic deformation of the cantilevers is not acceptable, because in the most extreme case the cantilevers can touch each other and cause short circuits. Therefore during these tests inside the SEM we looked carefully for inelastic deformation. Even at very large deflections we did not observe inelastic deformation. These robust mechanical properties are more than adequate for diamond cantilevers to be reliably used for the most demanding M4PP applications.

4. Conclusions and outlook

Diamonds superior physical properties motivated us to fabricate polycrystalline diamond M4PP probes. We developed a very straightforward MEMS foundry compatible fabrication process. The process requires only two photolithography masks. The most challenging process step was dry etching of diamond, because there are only few reports and the fact that the etching rates were highly dependent on the etching instruments. We successfully developed a wafer-level process using argon/oxygen ICP plasma and an aluminum etch mask. 330 etchings based on 14 different designs were fabricated on a single 100 mm in diameter wafer. Because of the inherent outstanding mechanical properties of diamond, the cantilevers are extremely robust, and we demonstrate that they can be used for the most demanding measurement conditions.

Recently, there has been a tremendous interest in diamond based micro and nanotechnology [6,31]. We believe this will drive the development of more affordable and higher quality diamond substrates in the near future. In this work, we have developed the technology and framework for diamond M4PP, such that when high quality conductive diamond becomes available at a competitive price, we can produce conductive diamond M4PP at MEMS foundries of our choice. Furthermore, we believe that our results will interest the scientific and technology communities working with diamond on the micro and nanoscales [28].

Acknowledgements

The authors would like to thank the Innovation Fund Denmark for financial support. Also, we thank the technical staff at DTU Nanolab. The authors have no competing interests.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.mne.2019.05.002.

References

[21] "Capes M4PP."