Bioinspired, Uncooled Chitin Photomechanical Sensor for Thermal Infrared Sensing

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Abstract—We have designed and fabricated a novel, polymer-ceramic bimorph infrared (IR) sensing element for uncooled operations. The developed sensors utilize biopolymer chitin on ceramic beams, which deflect with changing temperature due to the mismatch in thermal expansion coefficients of the two materials. This is the first known instance of a polysaccharide-based material used in the development of IR sensors. To maximize the bi-material bending effect, a thin layer of chitin is deposited onto a stiff layer of polysilicon. As in nature, chitin makes an ideal absorbing layer for the sensors because of its high thermal expansion coefficient and natural vibrational resonances in the IR range. Experiments using finite element analysis (FEA) simulation showed that the sensitivity of the polymer-ceramic bimorph sensor was 50 times of the sensitivity of the commonly-used metal-ceramic bimorph sensor. The proposed device offers high sensitivity and significant cost savings compared to existing competitive technologies.

I. INTRODUCTION

Infrared sensors are critical for both military and civilian applications, such as reconnaissance, targeting [1] [2] and medical imaging [3]. However, the most effective IR sensors today are primarily photon-detection type sensors, which require expensive cryogenic cooling. It has been of particular interest to develop low cost IR imaging technologies which uses uncooled thermal IR sensors. There are primarily four types of uncooled IR sensing mechanisms: resistive bolometry, pyroelectric sensing, thermal electric sensing and micro-cantilever bimorph based thermal-mechanical sensing. A micro-cantilever bimorph based sensor can be extremely sensitive to external stimuli such as temperature changes making it a strong candidate for uncooled thermal IR sensing applications. Optical readout method was adopted as the deflection sensing method in this paper. This is because optical readout methods do not require high sensitive readout circuits connecting to each sensing unit. In addition, they are not limited by the lack of thermal isolation and Johnson noise, which are the common limitations for electrical readout. Oak Ridge National Lab was one of the first to develop IR detectors using bimaterial microcantilever [4]. Majumdar et al. used gold on top of silicon nitride to develop a bimorph microcantilever structure that exhibited temperature resolution of about 2K [5]. Subsequent efforts were made to improve the sensitivity of uncooled thermal-mechanical IR sensors [6] [7].

In this work, we propose the use of chitin-polysilicon bimorphs as IR sensing elements. Our technology is inspired by the pyrophilic beetle Melanophila acuminata, which uses a photo-mechanical IR detector organ to detect forest fires from a distance of 1km or more based on the strong absorption bands of chitin: 3-5\(\mu\)m Mid-Wavelength Infrared and 8-10\(\mu\)m Long-Wavelength Infrared. Chitin-based bimorphs have the potential of surpassing the sensitivity of metals and semiconductor bimorphs due to chitin’s higher relative coefficient of thermal expansion. Chitin’s ability to absorb wavelength-specific incident radiation can replace the need for expensive infrared filters, which are required in existing thermal infrared sensors. In addition, chitin is an extremely rugged material and therefore resistant to chemical and radiation exposure.

In this paper, we propose a novel polysaccharide-ceramic bimorph IR sensing element with high sensitivity and low cost for uncooled operations. The sensor was fabricated by surface micro-machining technology. In addition, FEA simulations showed that the proposed device exhibited high sensitivity.

II. SENSOR DESIGN

A. Flat Pad Bimorph Sensor Design

The schematic diagram of proposed flat pad bimorph sensor design is shown in Figure 1. The structure consists of a flat pad suspended by two folded beams. Poly-Si is used as the structural layer, with a chitin membrane deposited on top of the two folded beams to form two bimorph beams. The chitin layer has the ability to absorb wavelength-specific incident IR radiation and increase the temperature of the whole structure. The structure deflects with changing temperature
TABLE I
DIMENSIONS OF THE MEMS IR DETECTORS USED IN FEA SIMULATIONS.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pad dimension (µm)</td>
<td>200 × 200</td>
</tr>
<tr>
<td>Anchor arm length (µm)</td>
<td>300</td>
</tr>
<tr>
<td>Anchor arm width (µm)</td>
<td>10</td>
</tr>
<tr>
<td>Support arm length (µm)</td>
<td>100</td>
</tr>
<tr>
<td>Anchor length (µm)</td>
<td>50</td>
</tr>
<tr>
<td>Structural layer thickness (µm)</td>
<td>0.5</td>
</tr>
<tr>
<td>Polymer layer thickness (µm)</td>
<td>0.5</td>
</tr>
<tr>
<td>Structural layer initial stress</td>
<td>-310</td>
</tr>
<tr>
<td>Polymer layer initial stress</td>
<td>165</td>
</tr>
</tbody>
</table>

TABLE II
MATERIAL PROPERTIES USED IN FEA SIMULATIONS.

<table>
<thead>
<tr>
<th>Material</th>
<th>Chitin</th>
<th>Poly-Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s Modulus</td>
<td>2.2</td>
<td>185</td>
</tr>
<tr>
<td>Poisson Ratio</td>
<td>0.35</td>
<td>0.27</td>
</tr>
<tr>
<td>Coefficient of Thermal Expansion</td>
<td>280E-6</td>
<td>4.16E-6</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>0.26</td>
<td>163</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>1500</td>
<td>2330</td>
</tr>
<tr>
<td>Specific Heat (J/kg-K)</td>
<td>1700</td>
<td>703</td>
</tr>
</tbody>
</table>

due to the mismatch in thermal expansion coefficients of the two materials. The proposed design has a large, flat optical read-out pad and nearly pure vertical motion due to the symmetric thermally-driven bending moments. This feature highly simplifies the measurement process and enhances the sensor’s sensitivity. Moreover, the sensors have longer, higher-response thermal bimorphs, nearly-square pixel size, and are less sensitive to process variations. By adding an IR absorption layer on top of the moving pad, we can further increase the IR sensing sensitivity. Furthermore, it can be easily expanded to a 2D array to form a focal plane array for thermal imaging system.

B. FEA Simulation

FEA simulations were performed using COMSOL to study the thermal and thermal-structural behaviors of the micro-cantilever. Our preliminary FEA simulations showed that the sensitivity of the chitin-Si bimorph sensor was 50 times of that of the commonly used metal-ceramic (Au-Si in the simulation) bimorph sensor. The device dimensions and material properties used in the simulations are listed in Table I and Table II.

Thermal analysis was first performed to calculate the maximum temperature and temperature distributions of the structure for a given IR input power density. Figure 2(a) is a contour plot of the temperature distribution on the sensor when a fixed input power density of 2000W/m² was sustained on the upper side of the chitin layer. The substrate was held at 20°C. The highest temperature occurred at the end of beam far from the anchor. There was also a 74°C temperature difference from the pad to the anchor. This created a temperature gradient in the structure which helped to increase the sensor’s sensitivity.

Thermal-structural simulation was then performed to analyze the sensor pad’s movement, as shown in Figure 2(b). When the input power density was increased, the pad moved up and the distance between the pad and the substrate also increased. Such change in separation can be detected precisely by optical readout methods. Radiation heat loss was ignored in this simulation. More simulation results are discussed in Section IV.

III. FABRICATION

We fabricated our micro-mechanical sensor using surface micro-machining techniques. The detailed fabrication process is shown below.

- A p-type Si wafer was selected as the substrate.
- First, a 200nm thick highly doped poly-Si layer was deposited using LPCVD furnace. This layer was used as an etch stop layer.
- Second, 1.5µm sacrificial oxide layer was deposited on both sides of the wafer using an oxide furnace. The upper oxide layer was patterned using reactive ion etch.
- Third, LPCVD was used for poly-Si deposition as the structural layer. A 400nm poly-Si structural layer was deposited and patterned.
- Then, single layer lithography of chitin was started with spin-casting chitosan solution onto the silicon wafer. A low cost, low temperature, spin-on chitin deposition
process was developed and tested for integration of chitin into sensors. The polymer layers could be deposited with thickness ranging from 100nm to 800nm. The solution was prepared using 3.5% w/v medium molecular weight chitosan (Sigma Aldrich, St. Louis, MO) in a 1:100 mixture of acetic acid (HAc). Details on the preparations of the solution can be found in [8]. Chitosan can be converted to chitin by dipping into 5% acetic acid and methanol solution at 40°C for 2 hours [9]. The wafer was baked at 95°C for 5 minutes to dry the chitin film. Photoresist developer attacked the chitin film during the development process. Therefore, C5 PMMA was spun-cast onto the wafer before the lithography step as a protection layer. The PMMA film was baked at 95°C for 5 minutes as well. Subsequently, a 2µm OCG-825 G-line photoresist was spun onto the wafer and baked for 60 sec at 90°C. Low vacuum contact printing was used to pattern the photoresist and then the photoresist was developed using OCG-934 2:1 photoresist developer. The wafer was hard baked using UV bake. Oxygen plasma etching was performed after the chitin layer was patterned.

- Finally, the whole structure was released using HF vapor. The selectivity between SiO₂ and Si is extremely high using HF etching.

Several key steps in the process are illustrated by a series of microscope images in Figure 3. In Figure 3-A, the anchors were patterned by patterning and etching the sacrificial oxide layer. Figure 3-B shows the patterned poly-Si layer as the structural layer. The chitin layer was then patterned on top of the poly-Si layer in Figure 3-C. The released device is shown in Figure 3-D.

In this process flow, the anchor was defined so that the structure could be released without precise timing. Chitosan was spun-cast due to its solubility in dilute acetic acid. However, since chitosan is sensitive to ambient humidity variations and not as robust as chitin, chitosan was chemically converted to chitin after it was deposited on the substrate.

IV. RESULTS AND DISCUSSION

A SEM picture of the fabricated IR sensor is shown in Figure 4. It was observed that the bimorph beams bent away from the Si substrate. The bending was caused by residual stress in both chitin and poly-Si thin films. The residual stress includes the intrinsic stress and the thermal stress between these two films due to the difference in thermal expansion coefficients. The intrinsic stress for the chitin film and poly-Si film were measured to be 165MPa tensile and 310MPa compressive respectively. These were the numbers used in the FEA simulation. The symmetric thermally-driven bending beams also kept the sensor pad flat, which was consistent with the FEA simulation.

Figure 5 shows the FEA simulation results for the deflection response vs. input power density for the proposed chitin-Si bimorph sensor and a structurally equivalent Au-Si bimorph sensor. Au-Si bimorph sensor was chosen because it is a commonly used metal-ceramic bimorph sensor in IR detection applications. The graph shows that the proposed device has a linear deflection response with the input IR power density. By calculating the slopes of these linear relationships, the displacement sensitivity of the Chitin-Si bimorph and Au-Si bimorph were 0.824nm/pW·µm⁻² and 0.017nm/pW·µm⁻² respectively. Therefore, the sensitivity of the chitin-Si bimorph sensor was 50 times of the sensitivity of the Au-Si bimorph sensor. This simulation result demonstrated that by taking advantage of the huge mismatch of material properties in the polymer-ceramic bimorph, very high thermal sensitivities could be achieved.

We also studied the relationships between the deflection sensitivity and the chitin to poly-Si thickness ratio. In the FEA simulation, we kept the thickness of poly-Si layer at 400nm. The thickness of the chitin layer was varied from 200nm to 1.8µm. The deflection sensitivity showed a maximum peak at an chitin/poly-Si ratio of around 2. This was because when the chitin layer was thin, the mechanical bi-layer deformation increased as the chitin layer thickness increased. However,
Sensitivity = Deflection / Input power density

Fig. 5. Deflection response vs. input power density.

As the chitin layer thickness increased further, heat loss by thermal conduction through the beams became non-negligible, causing the deflection sensitivity to decrease. The maximum sensitivity was 2.56nm/pW·µm⁻². Though the measurement results of the fabricated chitin-Si bimorph sensor have not yet been obtained at this time, our measurement results of the fabricated photoresist-Si bimorph sensors were consistent with corresponding FEA simulation results.

V. Conclusion

In this paper, we proposed and fabricated a novel, polymer-ceramic bimorph infrared sensing element for uncooled operation. This is the first known instance of a polysaccharide-based material for development of IR sensors. Chitin-polysilicon bimorph beams were used to maximize the bi-material bending effect. Chitin makes an ideal absorbing layer for the sensors because of its high thermal expansion coefficient and natural vibrational resonances in the IR range. A low cost, low temperature, spin-on chitin deposition process was developed and tested for integration of chitin into the sensors.

FEA simulations showed that the sensitivity of the polymer-ceramic bimorph sensor was 50 times of the sensitivity of the commonly-used metal-ceramic bimorph sensor. The high thermal sensitivities were achieved by taking advantage of the huge mismatch of material properties in the polymer-ceramic bimorph. By changing the chitin to poly-Si thin film thickness ratio, the best sensitivity reached approximately 2.6nm/pW·µm⁻². Further characterization of the chitin IR sensor using optical interferometry is currently on-going. Polymer MEMS processing with novel materials such as chitin will have broader impact in increasing fundamental abilities in the fabrication of other sensors and micro-biomedical devices.

Acknowledgment

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References