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ENHANCING SENSITIVITY IN PIEZOELECTRIC MICRO CANTILEVER DESIGNS USING STRESS CONCENTRATION REGIONS FOR LABEL FREE DETECTION

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Abstract: *The focus of this research project is to enhance cantilever beam designs for biosensing applications by including Stress Concentration Regions (SCRs). The stress distribution across several cantilever beam designs was determined by simulating them using COMSOL Multiphysics. The earliest designs were developed utilizing Polyvinylidene fluoride (PVDF) to showcase improved sensitivity for mechanical detection without the need for labels in biosensor applications. The analysis of cantilever beams involves the examination of their eigenfrequency and stationary behavior in the context of piezoelectric effect physics. An analysis is conducted on several cantilever beam structures to determine the most appropriate one. In this analysis, the various beams are exposed to an identical mechanical force, and their respective displacements, potential voltage, von Mises stress, and eigenfrequencies are examined.*

Keywords: Cantilever, stress concentration region, biosensor, COMSOL.

1. Introduction

Cantilever sensors, which utilize surface stress, are becoming increasingly popular for biochemical detection due to their compact dimensions and accurate detection of induced deflection. These sensors can detect biomolecule absorption by detecting changes in surface properties due to the binding or hybridization of analytes to receptor molecules. These self-powered biochips can be used for disease identification and chemical and biological warfare weapon detection. However, they require external equipment for deflection measurements and have high size and power requirements (Kumar, 2023). Micromachined cantilevers are increasingly used as biochemical sensors due to their ability to identify chemical species by altering their mechanical characteristics. Static detection involves stress gradients across the cantilever's thickness, while dynamic analysis involves specific species adhering to the surface, resulting in a change in vibration frequency (Norouzi, 2009). PVDF (polyvinylidene fluoride) and PZT (lead zirconate titanate) are the two most used piezoelectric materials. Scientists demonstrated the ability of PVDF to generate higher voltage output than PZT by conducting experiments with different beam sizes. Both PZT and PVDF piezoelectric beams were tested, and it was discovered that the PVDF beam produced the highest output power (Guo, 2021). Compared to PZT's brittle nature, which can cause fatigue failure under high-frequency cyclic load, particularly in outdoor applications, PVDF performs better due to its high flexibility, lightweight, and low acoustic, and mechanical impedance (Wong, 2017). As a result, PVDF is becoming more popular, and many commercial PVDF sensors make it easier to conduct impact tests. Only a prototype of a PVDF beam (energy harvester) bimorph cantilever was designed and tested (Chu Duc, 2018).

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2. Theory and modeling

A piezoresistive microcantilever beam uses one end fixed and the other free. When a substance is under pressure, its electrical resistivity changes. Microcantilevers resonate at their most conspicuous oscillation frequency. For self-sensing biosensors, semiconductor microcantilevers with piezo resistivity are ideal. Analyte-receptor responses on its active surface stress their piezo resistor, causing it to change electrical resistance. The maximum deflection, maximum stress, and resistance change are critical parameter for analyzing a beam stationary at one end. These crucial insights disclose the beam's structural integrity, mechanical performance, and material properties (Brugger, 1999). Two strategies to increase resistance change are to increase differential surface stress or decrease microcantilever thickness. Material qualities affect resistance change. Lower beam stiffness or deformation resistance may cause increased deflection. This may indicate structural integrity or stability difficulties. Low deflection indicates a stiffer, more deform-resistant beam (Selvan, 2020).

3. Design and simulation

A design is a mechanical structure with one rigid end and a free end that moves when acted upon by a force. The cantilever acts as a sensor, detecting both cantilever bending and changes in vibration frequency. The structure and material used in the design play an important role in determining beam stiffness. Applied force and geometry information are shown in the table below. The features of the PVDF material, such as its elasticity and density, were allocated to correctly mimic the conditions that exist in the real world. The use of boundary conditions was done to simulate a fixed-free cantilever configuration. For modeling the dynamic behavior of the cantilever while it is being loaded, the appropriate physics modules in COMSOL Multiphysics were chosen. The geometry information is shown in Tab. 1.

Beam length	Beam width	Beam height	Holes radius	Applied force
200 μm	100 μm	1.5 μm	5 μm	2.10^{-7} N

Tab. 1: Beam details.

To conduct precise numerical analysis, the solver settings were adjusted. To investigate the distribution of stress under the conditions of loading that were stated, a von Mises stress analysis was carried out. First step was to design 2 different microcantilever to test PVDF piezoelectricity properties for sensor application and evaluate result of applying SCR.

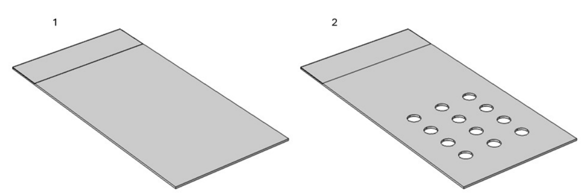

Fig. 1: Geometry before and after SCR.

As the simulation process progressed, iterative optimization was carried out whenever it was deemed necessary. This involved the modification of virtual models and simulation parameters to improve accuracy. This study highlights the comprehensive technique of simulating cantilever behavior in COMSOL Multiphysics. This approach mirrors situations that occur in the real world and provides insights into the performance of structures under various scenarios.

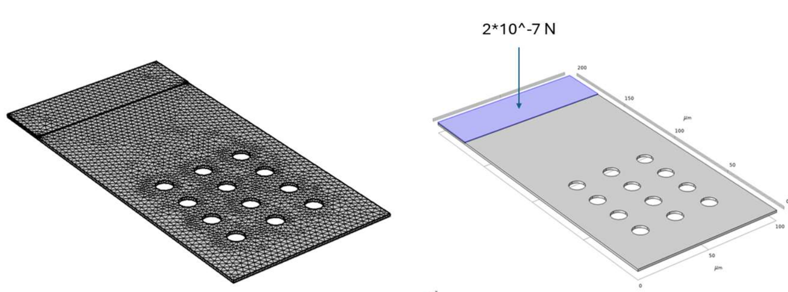

Fig. 2: Boundary load and meshing.

4. Results and discussion

This study examines the performance of two microcantilever samples made from PVDF, specifically designed for early detection purposes. Sample 1 is a basic cantilever beam, whereas Sample 2 is the same as Sample 1 but has holes, which create areas of stress concentration. The primary parameters examined comprise displacement, Von Mises stress, eigenfrequency, and electric potential as shown in Fig. 2. The analyzed parameters encompass displacement, Von Mises stress, eigenfrequency, and electric potential. Sample 2 demonstrates a marginally greater displacement in comparison to Sample 1. The heightened displacement observed in Sample 2 could potentially be attributed to the incorporation of holes, indicating potential modifications in structural flexibility. Sample 2 exhibits an elevated level of Von Mises stress. The existence of voids in Sample 2 can result in localized stress concentrations, thereby contributing to an overall elevated stress level. Sample 1 has a greater eigenfrequency.

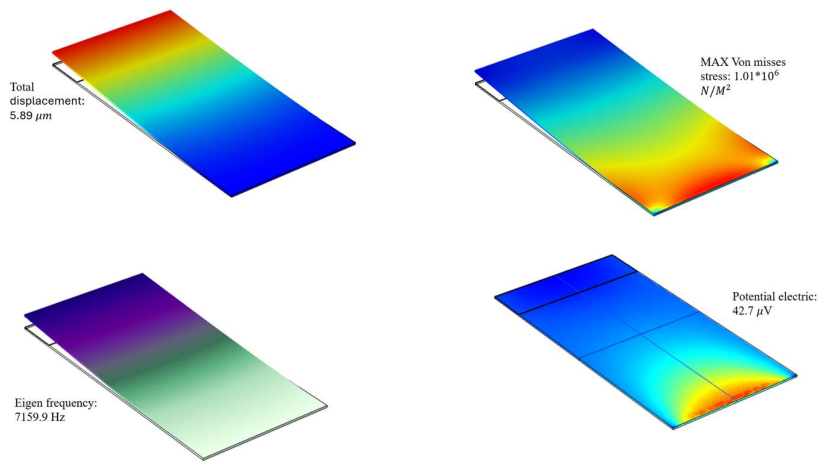

Fig. 3: Simulation results without applying SCR, as shown in Tab. 2. Four important parameters were measured.

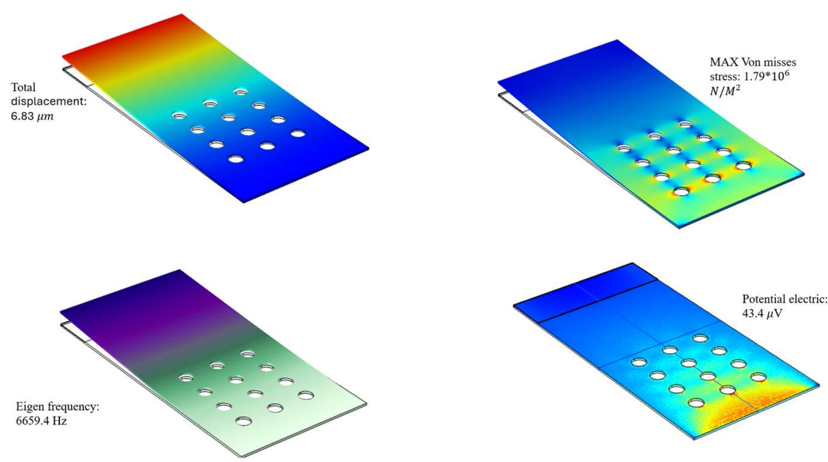

Fig. 4: Simulation results after applying SCR. Parameters are shown in Tab. 2.

The incorporation of voids in Sample 2 may have modified the structural rigidity, leading to a decreased natural frequency. The alteration in eigenfrequency is essential for applications that involve detection mechanisms based on resonance. The electric potential is nearly identical. Microcantilevers are specifically engineered for the purpose of early detection, wherein even slight variations in physical parameters can indicate the existence of conditions or substances. The greater displacement observed in Sample 2 indicates a potentially heightened responsiveness to external stimuli. Nevertheless, it is crucial to thoroughly evaluate the elevated levels of stress and reduced eigenfrequency, as they have the potential to impact both the structural soundness and the speed of response of the cantilever.

The graph shows in sample after applying SCR we are facing three picks which explain the presents of holes. The maximum amount for each parameter was chose for comparison which is in Tab. 2.

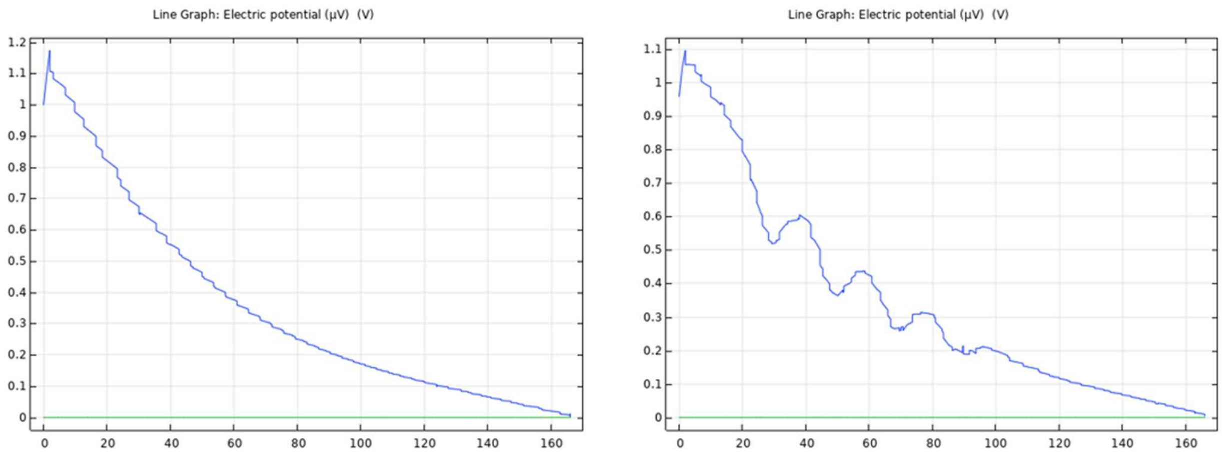

Fig. 4: Electric potential - Arc length graphs for both samples. This graph shows Electrical distribution through the length of the beam.

Parameters	1	2
Von Mises stress $[N/M^2]$	$1.01 \,.\, 10^6$	$1.79 \,.\, 10^6$
Total displacement $[\mu m]$	5.89	6.83
Potential electric $[\mu\text{V}]$	42.7	43.4
Eigen frequency [Hz]	7 159.8	6 659.4

Tab. 2: Results from simulation.

5. Conclusion

This study thoroughly analyzed the performance of two PVDF microcantilever samples created for early detection. The addition of holes in Sample 2 resulted in a slight increase in displacement, indicating possible adjustments in structural flexibility. The almost identical electric potential suggests a uniform characteristic present in both samples. The results show us how utilizing stress concentration regions can be useful in increasing the sensitivity of the cantilever, which is helpful for the early detection of microcantilevers. The addition of holes creates these areas. More tests, experiments, and tweaking should be done to confirm and improve these results. This will make sure that microcantilevers can be used reliably and effectively in early detection systems.

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