

Stress-Enhanced MEMS Trapezoidal Microcantilever Sensor for Enhanced Detection of Respiratory Syncytial Virus

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Abstract: Early detection of disease-causing antigens plays a crucial role in preventive healthcare. Biosensors are devices that monitor and diagnose human health by converting biological interactions into measurable signals. In recent years, microcantilever-based biosensors have gained significant attention due to their high sensitivity, miniaturization capability, and rapid response characteristics. This paper focuses on detecting the RSV-G protein of Respiratory Syncytial Virus using a paddle-type trapezoidal microcantilever with different stress concentration regions. The cantilever is designed using SU-8 polymer material with a density of 1123 kg/m³, Young's modulus of 5 GPa, and Poisson's ratio of 0.22. The sensing mechanism is modeled in static mode, where antigen-antibody binding is represented as an equivalent surface-stress-induced loading condition in the finite element simulation. Comparative analysis of different SCR geometries shows that the rectangular SCR configuration yields a maximum displacement of 6.8×10^{-18} μm, demonstrating a nearly fourfold enhancement over the conventional design without an SCR. This improvement is attributed to localized stress concentration and reduction in effective structural stiffness under identical loading conditions. The results indicate that geometry-driven stress concentration significantly enhances the mechanical sensitivity of the microcantilever sensor and provides an effective approach to structural optimization for viral biosensing applications.

Keywords: Microcantilever biosensor, Stress concentration region, Surface stress modeling, RSV-G protein detection, MEMS-based sensor.

1 INTRODUCTION

Respiratory Syncytial Virus (RSV) is a common respiratory pathogen that primarily affects infants, young children, and elderly individuals [1]. It is a major cause of lower respiratory tract infections, such as bronchiolitis and pneumonia, and remains a significant contributor to hospitalization worldwide. Rapid and accurate detection of RSV is essential for effective clinical management and prevention of severe complications. Several diagnostic techniques are currently available for RSV detection. Rapid Antigen Detection Tests (RADTs) provide quick results but may suffer from limited sensitivity [2]. Direct Fluorescent Antibody (DFA) testing depends strongly on sample quality and operator expertise [3]. Polymerase Chain Reaction (PCR) offers high sensitivity and specificity; however, it is relatively expensive and requires laboratory infrastructure and a longer turnaround time [4]. These limitations highlight the need for alternative sensing platforms capable of rapid, sensitive, and cost-effective detection of RSV-specific biomarkers.

Biosensors are analytical devices that integrate a biological recognition element with a transduction mechanism to convert biological interactions into measurable signals. A typical biosensor consists of a bioreceptor, a transducer, and a signal processing unit. The performance of a biosensor primarily depends on its sensitivity, selectivity, and response time. Among various biosensing approaches, microelectromechanical systems (MEMS)-based sensors have attracted significant attention due to their miniaturization capability and high mechanical sensitivity [5]. Microcantilever-based biosensors operate by converting biochemical interactions occurring on a functionalized surface into measurable mechanical deformation [6]. When antigen-antibody binding occurs on the surface of a microcantilever, differential surface stress is generated between the upper and lower surfaces of the beam, resulting in bending under static mode operation. The relationship between surface stress variation and induced curvature can be described using Stoney's formulation:

$$\Delta\sigma = \frac{Et^2}{6(1-\nu)L} \cdot \kappa \quad (1)$$

where $\Delta\sigma$ represents the change in surface stress, E is Young's modulus, t is the cantilever thickness, ν is Poisson's ratio, L is the length of the cantilever, and κ denotes curvature. This relation indicates that mechanical deformation in static mode is directly proportional to the surface stress induced by biomolecular interactions. Enhancing structural geometry to amplify localized stress can improve deformation sensitivity without increasing device dimensions.

Stress Concentration Regions (SCRs) can be introduced within the cantilever structure to localize stress and enhance bending response under equivalent surface loading conditions. In this work, a paddle-type trapezoidal microcantilever incorporating various SCR geometries is proposed for detecting the RSV-G protein in static mode. The main contributions of this study are the structural integration of stress-concentration regions within a trapezoidal microcantilever, surface-stress-based static modeling of RSV-G protein interaction under equivalent loading conditions, and a comparative evaluation of different SCR geometries to assess displacement enhancement performance.

2 RELATED WORK

2.1. Biosensor Background

In a biosensor, the interaction between an antigen and its corresponding antibody produces a measurable response in the transducer. The performance and efficiency of a biosensor depend primarily on geometrical parameters, material properties, and sensitivity. The output of a biosensor varies with analyte concentration and the intended application. The development of biosensors began with the electrochemical sensor introduced by Clark in 1956, which played a significant role in advancing biosensing technology [7]. Clark's group later reported an enzyme-based glucose sensor for continuous monitoring during cardiovascular surgery. The glucose concentration was measured using an oxygen electrode with immobilized glucose oxidase. The introduction of home glucose testing devices in the 1980s further accelerated biosensor development [8].

Mediator-based systems, such as ferrocene combined with glucose oxidase (GOD), were later introduced to eliminate dependence on oxygen concentration and reduce interference from other molecules [9]. These developments led to improved sensitivity and reliability in electrochemical biosensors. Most biosensor systems integrate electronic components, signal conditioning circuits, and output devices for real-time measurement [10]. Immobilization techniques are essential for binding biological recognition elements onto the sensing surface to ensure stable and efficient signal generation [11]. A biosensor's unique capability lies in its ability to specifically recognize target analytes and convert biochemical interactions into measurable signals. Based on the nature of interaction, biosensors are broadly classified into affinity-based, biocatalytic, and synthetic types [12].

2.2. Microcantilever Theory and Modes of Operation

Microcantilever-based biosensors have emerged as effective platforms for biomolecular detection due to their high sensitivity, compact size, and label-free detection capability [13]. These sensors convert biochemical interactions occurring on a functionalized surface into measurable mechanical deformation. When biomolecules adsorb onto a cantilever surface, differential surface stress is generated between the upper and lower surfaces of the beam. This stress induces bending under static mode operation. The relationship between surface stress change and curvature can be described using Stoney's formulation. This relation indicates that the bending displacement is directly proportional to the change in surface stress induced by antigen-antibody interactions.

Microcantilever sensors operate in two primary modes: static and dynamic. In static mode, adsorption-induced surface stress causes bending deformation. In dynamic mode, the cantilever vibrates at its resonance frequency, and biomolecule binding changes the effective mass, leading to a frequency shift. The fundamental resonance frequency of a cantilever beam is expressed as:

$$f_r = \frac{1}{2\pi} \sqrt{\frac{k}{m_{\text{eff}}}} \quad (2)$$

where k is the stiffness and m_{eff} is the effective mass of the cantilever. Although dynamic mode offers high sensitivity, its performance in liquid environments may be affected due to reduced quality factor (Q-factor). Therefore, static mode operation is often preferred for biosensing applications in biological media. Several researchers have explored microcantilever-based detection of biomolecules. Ziegler et al. [14] demonstrated displacement-based detection techniques. Cheng et al. [15] highlighted biomolecular interactions in miniaturized sensing platforms. Ansari et al. [16] reported high sensitivity of microcantilever sensors due to surface-induced effects. Gopinath et al. [17] and Parsediya et al. [18] investigated trapezoidal cantilever geometries for enhanced sensing performance.

2.3. Trapezoidal Cantilever Designs and Research Gap

Among various microcantilever geometries, trapezoidal configurations have been reported to offer improved mechanical sensitivity compared to rectangular beams due to non-uniform stress distribution along the beam length [19]. Structural modifications to the cantilever shape influence the stiffness distribution and deformation characteristics, thereby affecting sensitivity. Previous studies primarily focused on optimizing beam shape or analyzing static versus dynamic operational modes. However, limited attention has been paid to localized stress-concentration-based structural modifications in trapezoidal microcantilever designs. Systematic evaluation of stress concentration regions for enhancing deformation sensitivity under surface-stress-based loading conditions remains underexplored.

Furthermore, while microcantilever biosensors have been widely studied for various biomolecular applications, targeted structural optimization for RSV-G protein detection has not been comprehensively investigated. Therefore, the present work focuses on integrating stress-concentration regions into a trapezoidal microcantilever structure and evaluating their influence on displacement enhancement under static surface loading.

3 PROPOSED DESIGN AND MODELING METHODOLOGY

3.1. Stress Concentration Concept and Theoretical Background

Microcantilever-based biosensors operating in static mode rely on surface-stress-induced bending for detection. The induced deformation is governed by the relationship between the applied surface stress and the cantilever's structural stiffness. For a beam under small deflection conditions, the tip displacement can be expressed in proportional form as

$$\delta \propto \frac{FL^3}{EI} \tag{3}$$

where F is the applied equivalent load, L is the length of the cantilever, E is Young's modulus, and I is the area moment of inertia. This expression indicates that displacement is inversely proportional to the structural stiffness (EI). Therefore, reducing the effective stiffness of the cantilever or introducing localized regions of stress concentration can significantly enhance deformation response.

In conventional cantilever structures, stress is distributed relatively uniformly along the beam length. However, the introduction of geometric discontinuities, referred to as stress concentration regions, alters the stress distribution and local stiffness. These regions act as localized compliance zones, enabling higher curvature under identical loading conditions. Fig. 1 illustrates the conceptual difference between a conventional cantilever and a cantilever incorporating SCR. The SCR configuration exhibits localized stress amplification near the discontinuity, resulting in greater deformation than in the conventional design.

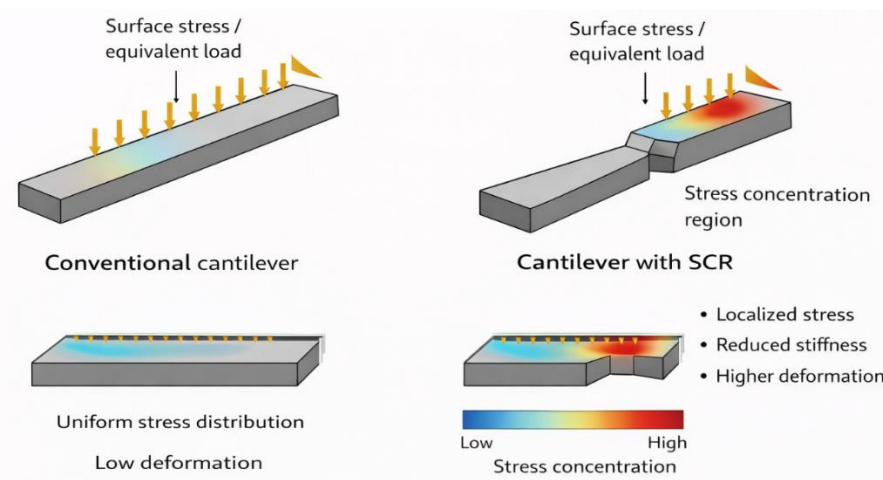


Fig. 1. Schematic illustration of stress concentration mechanism in microcantilever: conventional cantilever with uniform stress distribution, and cantilever with SCR showing localized stress concentration and enhanced deformation

3.2. Geometry and Material Properties

In this study, a paddle-type trapezoidal microcantilever structure is proposed for detecting the RSV-G protein. The design incorporates SCRs within the paddle area to enhance localized deformation under surface loading conditions. The total surface area of the paddle region is maintained at $50,000 \mu\text{m}^2$ for all configurations to ensure consistent comparison. Five structural configurations are analyzed:

- Conventional trapezoidal cantilever without SCR
- Trapezoidal cantilever with triangular SCR
- Trapezoidal cantilever with trapezoidal SCR
- Trapezoidal cantilever with hexagonal SCR
- Trapezoidal cantilever with rectangular SCR

The base of the cantilever (opposite to the paddle end) is fixed to simulate clamped boundary conditions. The baseline trapezoidal microcantilever structure without SCR is shown in Fig. 2. Fig. 3 shows the trapezoidal microcantilever with different SCR geometries. This includes triangular, trapezoidal, hexagonal, and rectangular SCR geometries.

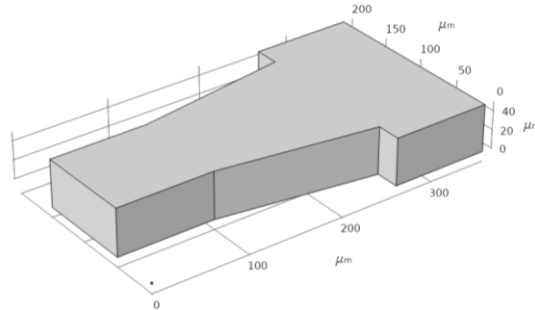


Fig. 2. Baseline trapezoidal microcantilever structure without SCR

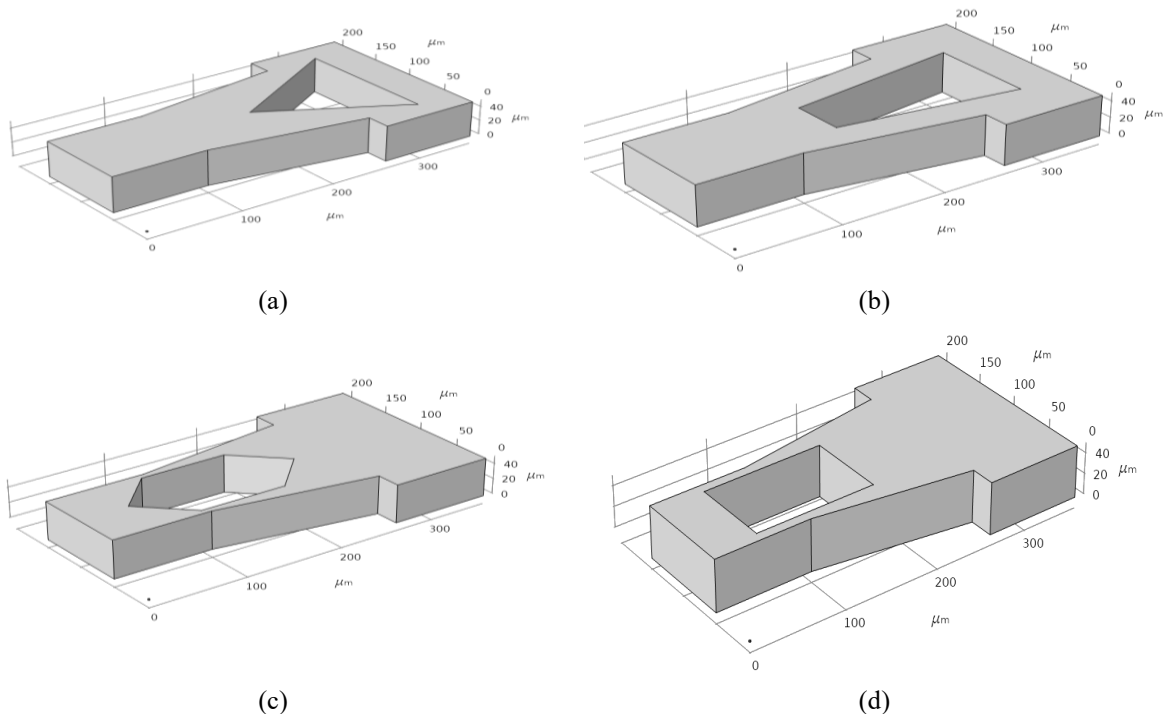


Fig. 3. Trapezoidal microcantilever with different SCR geometries: (a) Triangular, (b) Trapezoidal, (c) Hexagonal, (d) Rectangular.

SU-8 polymer material is selected for cantilever fabrication due to its compatibility with MEMS processes and suitable mechanical properties. The material parameters used in the simulation are:

- Density: 1123 kg/m³
- Young's Modulus: 5 GPa
- Poisson's Ratio: 0.22

These properties are assumed to remain constant throughout the simulation.

3.3. Surface Stress Representation and Loading Model

RSV-G protein is a heavily glycosylated viral surface protein with a molecular weight of approximately 80 kDa [20]. In static-mode microcantilever sensing, biomolecular adsorption generates a differential surface stress that induces bending deformation. In the present work, the antigen–antibody interaction is modeled by applying an equivalent mechanical loading condition to the functionalized cantilever surface. The equivalent load used in the simulation corresponds to 1.295×10^{-21} N, representing the equivalent mechanical effect of surface-stress-induced biomolecular interaction without explicitly modeling molecular binding kinetics. The load is applied as a uniformly distributed boundary load over the SCR region to simulate uniform adsorption effects. This abstraction enables comparative evaluation of deformation sensitivity among different geometrical configurations.

3.4. Boundary Conditions and Finite Element Modeling

The cantilever base is fixed, and the equivalent surface load is applied on the SCR region. Static structural analysis is performed to evaluate the total displacement response. Finite element modeling (FEM) is employed to simulate structural deformation. A refined mesh is used in the vicinity of the SCR regions to accurately capture localized stress concentrations. Mesh convergence analysis was performed to ensure that displacement variation remained within 2% upon mesh refinement, thereby confirming the numerical stability of the results. All simulations are conducted in static mode, consistent with surface-stress-based deformation analysis. The total displacement at the free end of the cantilever is used as the primary performance metric for comparative evaluation. The governing equations of linear elasticity were solved under static equilibrium conditions. Global evaluation was used to extract maximum displacement and stress values for all configurations.

3.5. Simulation Setup and Parameters

All simulations were carried out using COMSOL Multiphysics (Structural Mechanics Module) under stationary (static) study conditions. A three-dimensional solid-mechanics model was employed to analyze the deformation behavior. The cantilever geometry was discretized using free tetrahedral meshing, with local refinement applied near SCRs to accurately capture stress gradients. The mesh consisted of 280 elements, with a minimum element quality of 0.2571. Mesh convergence was verified by refining the mesh and observing a variation of less than 2% in displacement results.

A uniformly distributed surface load of 1.295×10^{-21} N was applied over the SCR region to represent the equivalent surface-stress-induced interaction. The base of the cantilever was fixed, while all other boundaries were free. Linear elastic material behavior was assumed for the SU-8 polymer, and geometric nonlinearity was neglected due to the extremely small deformation scale. The simulation assumes uniform adsorption of biomolecules over the SCR region and neglects stochastic binding effects. Thermal fluctuations and fluid-structure interaction effects are not considered. All simulations were performed using consistent meshing and solver settings across all geometries to ensure fair comparative evaluation. The analysis assumes linear-elastic behavior and small-deformation conditions, ensuring the validity of the applied finite element model.

4 RESULTS AND DISCUSSIONS

4.1. Displacement Comparison

Static structural analysis was performed to evaluate the total displacement of the proposed microcantilever configurations under equivalent surface loading conditions. Fig. 4 shows displacement contour plots with different geometries. The conventional trapezoidal cantilever without SCR produced a displacement of 1.73×10^{-18} μm . The displacement values obtained for different SCR geometries are:

- Triangular SCR: 1.64×10^{-18} μm
- Trapezoidal SCR: 1.89×10^{-18} μm
- Hexagonal SCR: 5.88×10^{-18} μm
- Rectangular SCR: 6.8×10^{-18} μm

These results indicate that the introduction of stress concentration regions significantly influences deformation behavior under identical loading conditions. Although the absolute displacement magnitudes are small, the relative variation among different geometries highlights the effectiveness of structural modification in enhancing deformation response. Fig. 5 plots displacement values with the above designs.

4.2. Stress Concentration Effect and Enhancement Ratio

To quantify the improvement, the displacement enhancement ratio is calculated as:

$$\text{Enhancement Ratio} = \frac{\Delta_{SCR}}{\Delta_{conventional}} \quad (4)$$

For the rectangular SCR configuration:

$$\text{Enhancement Ratio} = \frac{6.8 \times 10^{-18}}{1.73 \times 10^{-18}} \approx 3.93 \quad (5)$$

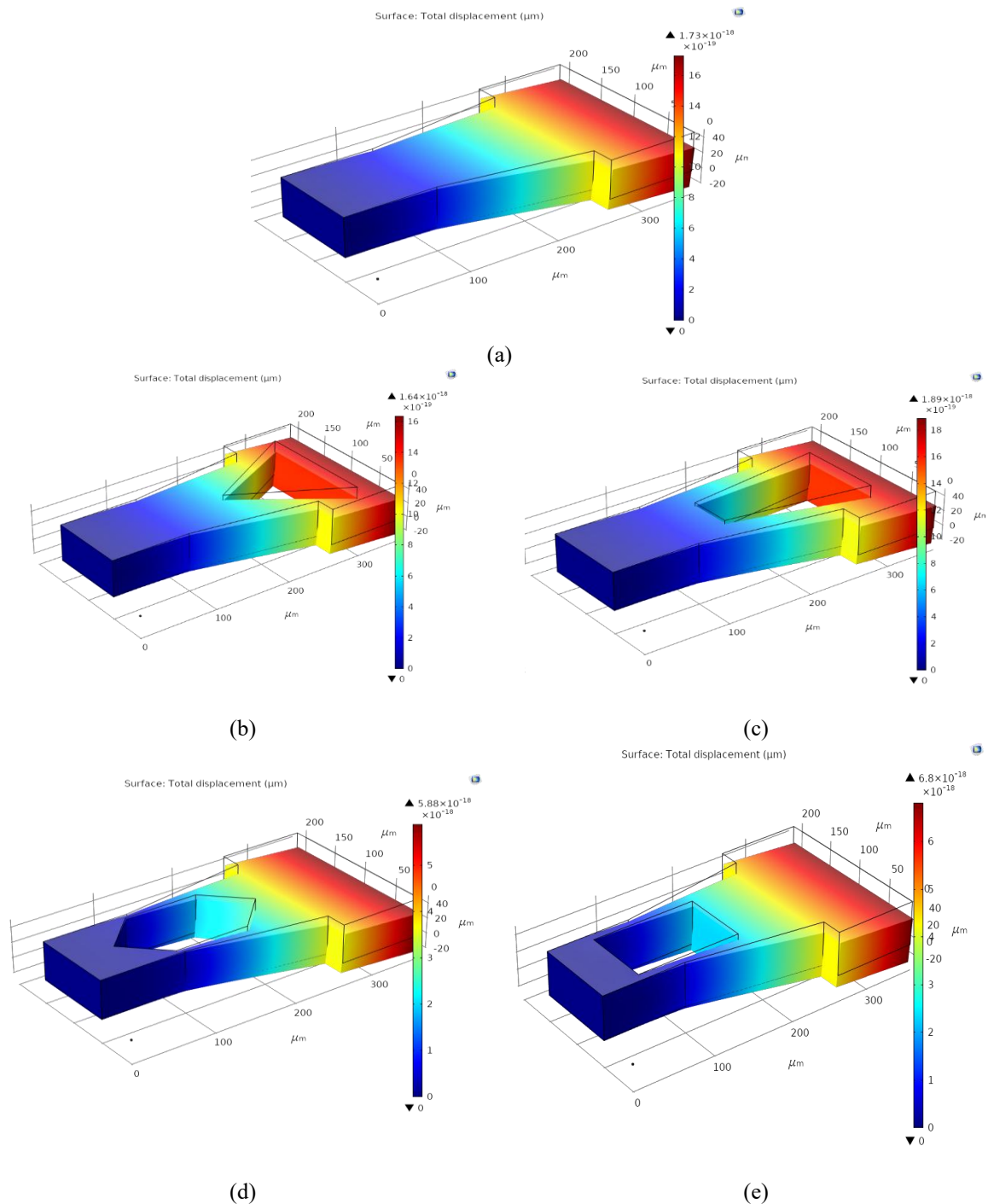


Fig. 4. Displacement contour plots: (a) Without SCR, (b) Triangular SCR, (c) Trapezoidal SCR, (d) Hexagonal SCR, (e) Rectangular SCR.

This corresponds to approximately a fourfold enhancement in deformation response compared to the conventional design. The improvement can be attributed to localized stiffness reduction and stress amplification near the SCR region. By introducing geometric discontinuities, stress distribution becomes concentrated within specific regions, resulting in amplified curvature under identical loading conditions. This behavior is further supported by the von Mises stress distribution obtained from finite element analysis. The rectangular SCR configuration exhibits higher localized stress near the discontinuity region than the conventional cantilever, confirming an effective stress concentration and an improved deformation response. Among the evaluated geometries, the rectangular SCR provides the most effective stress localization, followed by the hexagonal configuration. The triangular and trapezoidal SCRs exhibit comparatively lower enhancement.

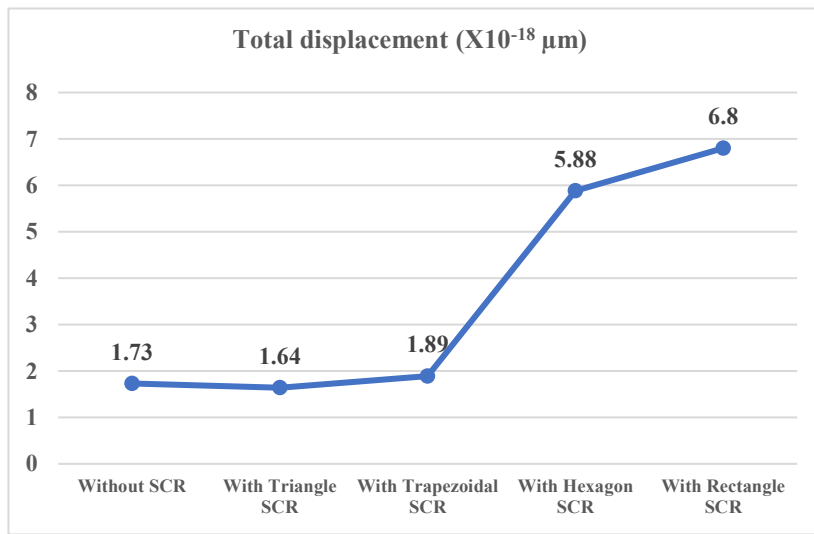


Fig. 5. Displacements with different Designs

The stress distribution obtained from finite element analysis, given in Fig. 6, further validates the deformation behavior. The rectangular SCR configuration exhibits higher localized von Mises stress near the discontinuity region compared to the conventional cantilever. For a clearer quantitative comparison, the displacement and enhancement ratios are summarized in Table 1.

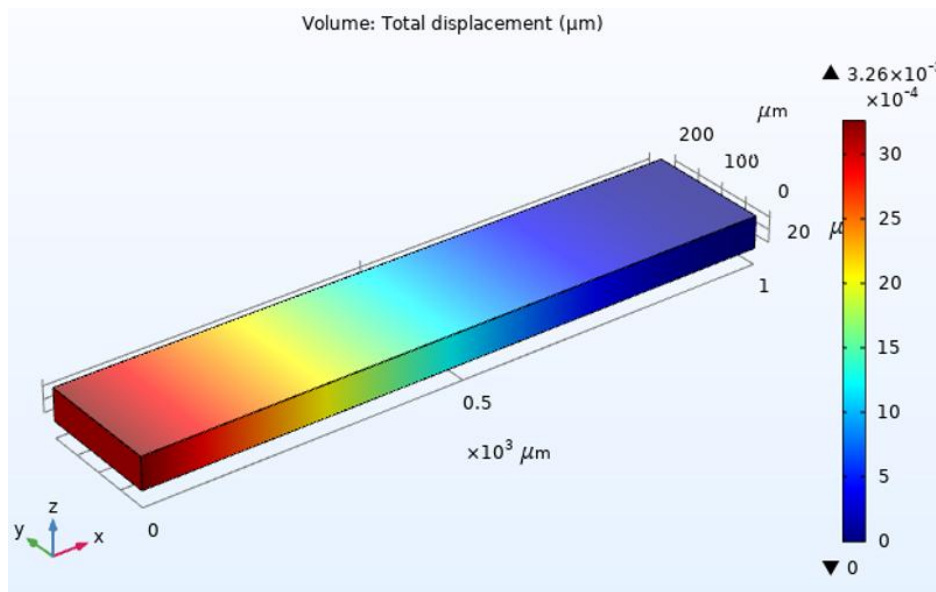


Fig. 6. von Mises stress distribution of the microcantilever showing localized stress concentration near the SCR region

Table 1. Comparison of displacement and enhancement ratio for different SCR geometries

Geometry	Displacement (μm)	Enhancement Ratio	Relative Ranking
Conventional	1.73×10^{-18}	1	4
Triangular SCR	1.64×10^{-18}	0.95	5
Trapezoidal SCR	1.89×10^{-18}	1.09	3
Hexagonal SCR	5.88×10^{-18}	3.39	2
Rectangular SCR	6.8×10^{-18}	3.93	1

Table 1 summarizes the displacement values and corresponding enhancement ratios for different SCR geometries. The enhancement ratio is calculated with respect to the conventional trapezoidal cantilever without SCR. The rectangular SCR configuration exhibits the highest displacement and enhancement ratio, followed by the hexagonal SCR. This trend confirms that geometrical modification significantly influences stiffness distribution and deformation response. Since the applied load remains constant for all configurations, the relative increase in displacement directly reflects an improvement in mechanical sensitivity.

4.3. Interpretation and Practical Implications

Although the absolute displacement magnitudes are small, the relative enhancement observed among configurations demonstrates the effectiveness of structural optimization. The comparison is therefore focused on relative enhancement rather than absolute displacement magnitude. In microcantilever-based sensing, relative deformation amplification directly influences the signal-to-noise ratio in readout systems such as optical beam deflection or piezoresistive detection. The improved deformation response is also supported by the increased strain energy observed in configurations with stress-concentration regions. Higher strain energy indicates greater elastic deformation under identical loading conditions, consistent with the enhanced displacement observed for optimized geometries.

The results suggest that geometry-driven stress concentration can enhance mechanical sensitivity without increasing device footprint or modifying material properties. This approach provides a structurally efficient pathway for improving deformation-based biosensing performance. The present analysis focuses on mechanical deformation behavior under equivalent surface-loading conditions and does not explicitly account for surface-chemistry kinetics, thermal noise, or fluid-damping effects. Further validation through extended surface-stress modeling and experimental characterization may be undertaken to assess real-world applicability. Compared with previously reported trapezoidal microcantilever designs, the proposed SCR-based approach exhibits an enhanced deformation response without altering material properties or overall dimensions. This highlights the effectiveness of geometry-driven optimization in improving sensor performance.

4.4. Influence of SCR Geometry on Structural Behavior

The observed variation in displacement among different SCR geometries can be attributed to differences in local stiffness distribution and stress concentration characteristics. The rectangular SCR introduces sharper geometric discontinuities and a larger stress concentration zone compared to triangular and trapezoidal shapes, leading to more pronounced localized deformation. In contrast, smoother geometries distribute stress more evenly, resulting in lower deformation. This indicates that SCR geometry plays a critical role in controlling stress localization and bending response of the microcantilever.

4.5. Design Implications

The results suggest that incorporating stress concentration regions with sharp geometric features can significantly enhance deformation response in microcantilever-based sensors. Rectangular SCR configurations are particularly effective due to their ability to induce localized stress amplification. These findings provide a design guideline for optimizing MEMS cantilever structures for improved mechanical sensitivity in biosensing applications.

5 CONCLUSION

Advancements in biomedical engineering and micro- and nanoscale technologies have enabled the development of highly sensitive biosensing platforms. Microcantilever-based sensors offer structural simplicity, miniaturization capability, and mechanical sensitivity suitable for biomolecular detection. In this work, a paddle-type trapezoidal microcantilever incorporating SCRs was analyzed under static mode operation for RSV-G protein detection. The study demonstrates that structural modification through localized stress concentration significantly enhances deformation response under equivalent surface loading conditions. This behavior is consistent with the underlying mechanical principle that cantilever deflection is inversely proportional to structural stiffness (EI), and that introducing geometric discontinuities effectively reduces local stiffness and amplifies curvature. Among the investigated geometries, the rectangular SCR configuration exhibited the maximum displacement, approximately four times higher than that of the conventional design without SCR. This confirms that geometry-driven stress amplification can improve deformation-based sensing performance without increasing device dimensions or altering material properties. The results highlight that controlled introduction of stress concentration regions provides an effective strategy for enhancing mechanical sensitivity in microcantilever-based biosensors. SCR geometries with sharper discontinuities are more effective in inducing localized deformation, offering practical design guidance for MEMS-based sensing applications. The present results are based on finite element modeling under idealized conditions, assuming linear elastic behavior and uniform surface loading. Future work may include extended surface-stress modeling, parametric optimization of SCR dimensions, and experimental validation to further assess practical feasibility.

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ETHICS STATEMENT

This study involved human participants. Informed consent was obtained from all respondents prior to data collection.

STATEMENT OF CONFLICT OF INTERESTS

The authors declare no conflicts of interest related to this study.

LICENSING

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