Coupled Physical Field Simulation based on Comsol

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Abstract. This paper investigates the effects of coupled physical fields on silicon materials using COMSOL Multiphysics and MATLAB, emphasizing the importance of multiphysics field coupling in material science, microelectronics, and interdisciplinary research. It builds upon foundational theories in electronic system-level design and multiphysics applications to explore the behavior of silicon materials under various physical conditions. The research methodology involves constructing a geometric model of a silicon rectangular prism and simulating different deformation scenarios—bending, elongation, and torsion—through physical field simulations. The study utilizes the superposition of mechanical and electrical fields to observe complex interactions within the material, demonstrating COMSOL's capability in handling dynamic simulations. Significant findings include detailed visualizations of deformation effects and their impact on electrical properties, providing a comprehensive understanding of material behavior under complex loading conditions. The integration of MATLAB enhances data analysis and visualization, facilitating a deeper insight into the interplay between mechanical stresses and electrical characteristics. Overall, the study showcases the robust capabilities of COMSOL and MATLAB in advancing material science research, offering innovative methodologies for simulating complex physical interactions and promoting technological education and interdisciplinary applications. This research contributes to the development of new materials and optimization of product design, highlighting the relevance of simulation tools in bridging theoretical research with practical applications.

Keywords: Coupled field, Simulation, MATLAB

1 Introduction

This study delves into the behavior of silicon materials when subjected to various physical fields, utilizing the integrated capabilities of COMSOL Multiphysics and MATLAB. The relevance of investigating multiphysics field coupling has surged in recent years, driven by its critical applications in material science, microelectronics, and interdisciplinary scientific endeavors. Silicon materials are pivotal in numerous technological advancements, yet their behavior under simultaneous mechanical, thermal, and electrical stresses is not fully understood. This research addresses this gap by employing advanced simulation tools to capture the complex interactions of

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these fields, providing a comprehensive understanding that could drive future innovations in material design and application.

Several foundational studies underpin this research, providing a theoretical and practical framework. In Delin Hu, Haotian Li, Francesco Giorgio-Serchi, and Yunjie Yang’s study.It focuses on the development of simulation models that integrate soft robotics and sensing systems to enable soft robots with perception capabilities. The research introduces Coupling Field Simulation (CFS), which integrates mechanical and sensing components. Two primary use cases are examined: a soft square robot arm and a pneumatic soft actuator. In these cases, the authors simulate sensor responses to various deformations such as bending, inflation, twisting, and elongation [1]. This work helps advance soft robotics by integrating sensor simulation with robotic behavior, providing insight into sensor performance, and helping optimize sensor design before physical implementation. The study of how solids deform under external forces and electric fields is crucial in material science and engineering, impacting the development of technology like sensors, actuators, and smart materials. This research helps tailor materials to specific needs, improving functionality and efficiency across various industries, including automotive, aerospace, electronics, and more. Understanding material deformation is fundamental for advancing technologies and innovating in fields like medicine, construction, and robotics, blending physics, chemistry, and engineering principles to enhance and create new applications [2, 3].

The interplay between mechanical forces and electric fields in solid materials can result in intricate deformation patterns and alterations in electrical characteristics, as discussed by Rodzevich et al [4]. The article discusses a study using a 2D transient heat conduction model to explore the effects of a KrF laser on silicon surfaces, comparing different heat distribution patterns like 'gate' and 'gaussian' to analyze their impact on surface temperatures and silicon's thermal properties. The study examines temperature variations at different depths and aims to control the thickness of the melted silicon layer through pulsed laser treatment, crucial for enhancing recrystallization and doping in high-performance poly-Si TFTs for flat panel displays. While the study presents both theoretical and simulated data, it suggests that empirical validation through direct temperature measurements is needed in future work. Overall, the research provides insights into laser-material interactions and contributes to advancements in semiconductor processing techniques [5]. The paper discusses the application of COMSOL Multiphysics to model the trajectories of charged ink droplets in continuous inkjet (CIJ) technology, which is widely used in the packaging industry. The study focuses on predicting the precise placement of droplets on media, crucial for high-quality printing. It incorporates a numerical model that simulates the electrostatic field within the printer's head and predicts the behavior of droplets influenced by various forces, excluding gravitational and drag forces for the current scope [6]. Key findings include that the modeled GCHP system can supply a significant portion of the energy needed by the future research center while maintaining the thermal balance of the surrounding area, thereby operating sustainably. The study also demonstrated that the temperature fluctuations in the surrounding ground remained within acceptable limits, and the performance of the heat pump system met the projected energy needs effectively, although additional

BHEs might be necessary to fully meet peak demands. This research serves as a valuable reference for the design and implementation of sustainable geothermal energy systems in urban environments [7]. After that, comsol with simulation all can deal with energy problem, for example: the paper written by Iliya K. Iliev, Azamat R. Gizzatullin etc, This research focuses on developing a comprehensive model using COMSOL Multiphysics to simulate the behaviors and processes within an electrochemical cell, specifically a Solid Oxide Fuel Cell (SOFC) operating on different fuels such as hydrogen, methane, and syngas. The study aims to incorporate the effects of electrochemical heating and non-isothermal fluid flow on the temperature fields and reaction rates within the cell. By using COMSOL, the authors model physical phenomena like electron and ion transport, gas species diffusion, electrochemical reactions, and heat transfer, to accurately predict the SOFC's performance [8].

2 Methods

2.1 Geometry Model Construction

This study utilizes COMSOL Multiphysics software to construct a simple geometric model of silicon.

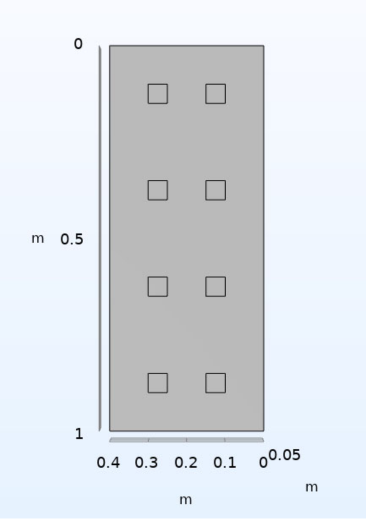


Fig. 1 Geometric models using silicon materials (Photo credited: Original)

Fig. 1 shows a silicon rectangular prism constructed with COMSOL Multiphysics, with dimensions of 0.4 m * 1.0 m * 0.1 m. The rectangular surface has eight electrodes ready for excitation. The physical properties of silicon are shown in the following Table 1.

Table 1. Silicon physical properties [9]

Density	1.28e3
Young’s moduls	4.15e6

Poisson’s ratio	0.47
Electrical conductivity	2
Relative permittivity	80

2.2 Coupled Physical Field Simulations

Simulation for Solid Machanics. For Bending: The experiment involved a setup where a silicon rectangular prism was securely fixed on one end to a surface aligned perpendicular to the y-axis. The opposite end of the prism, which remained free, was subjected to a mechanical force directed upwards along the z-axis. This application of force induced a bending deformation, where the free end of the prism moved in the z-direction while the fixed end remained stationary. The stress distribution and the degree of bending were quantitatively analyzed to understand how the silicon material behaves under such stress, revealing insights into the material's flexibility and structural integrity. This setup provides crucial data on the bending resistance and mechanical properties of silicon, which are essential for applications in construction and microelectronic devices.

In the Elongation Scenario: The elongation test was conducted by fixing one surface of the silicon rectangular prism perpendicular to the y-axis, ensuring it remained immobile. The surface opposite to the fixed side was then pulled in a controlled manner along the y-axis, leading to the elongation of the prism. This test aimed to measure the material's tensile strength and its ability to maintain integrity under strain. By elongating the silicon, researchers could observe the elastic and plastic responses of the material, critical for understanding its behavior under tensile stress which is commonly encountered in flexible electronics and stretchable materials.

During Rotation: For the rotational deformation, one side of the silicon rectangular prism was clamped perpendicular to the y-axis, rendering it unable to move. The opposite side was then twisted counterclockwise around the y-axis. This action caused torsional deformation in the silicon, characterized by the twisting of the material around its longitudinal axis. The degree of torsion was closely monitored to evaluate the shear stress and modulus of rigidity of the silicon. Torsional tests are particularly valuable in applications where materials are expected to withstand rotational forces, such as in automotive and robotic components.

Fig. 2 provides a visual representation of these three deformation modes, depicting the experimental setup and the resultant deformations in a clear and concise manner. The diagrams in this figure illustrate the specific areas where forces were applied and show the resulting changes in the shape of the silicon prism under each type of stress. These illustrations are crucial for understanding the complex behavior of silicon materials when subjected to different physical forces, offering visual insights that complement the experimental data collected during the tests. The three different methods was shown in Fig. 2.

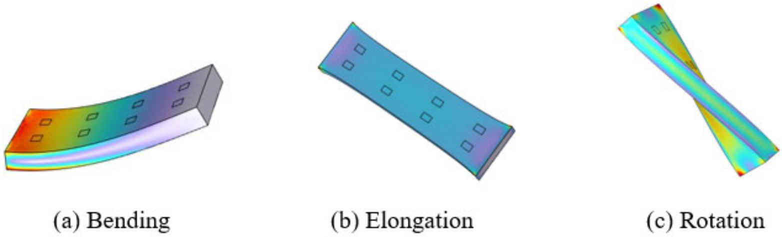

(a) Bending (b) Elongation (c) Rotation

Fig. 2 Three different methods for physical deformation (Photo credited: Original)

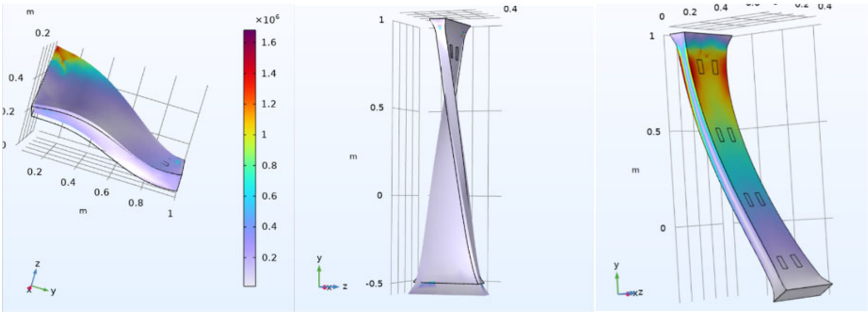
Superposition of Solid Mechanical Field. Fig. 3 showcases three distinct deformation scenarios of a silicon rectangular prism subject to mechanical stresses, simulated using COMSOL Multiphysics. Each scenario is depicted through a combination of deformation modes, providing a comprehensive analysis of the material's response to various forces.

Rotation+Bending: The first visualization illustrates a scenario where the prism undergoes both rotational and bending stresses. It is depicted from a perspective where the z-axis is vertical, the y-axis is depth, and the x-axis is horizontal. The deformation pattern suggests that the bottom of the prism is anchored, while the top experiences a twist along with a downward force, resulting in a contorted shape. The color gradient, representing the magnitude of deformation, transitions from blue to red, indicating an increase in strain from the fixed end to the free end.

Elongation+Rotation: The central image demonstrates the prism subjected to elongation accompanied by rotation. The prism appears elongated along its vertical axis, and a twist around this axis is also apparent, especially at the top end, which appears to be free to move. The elongation causes a visible distortion along the length of the prism, with the color intensity suggesting stress concentration areas. This scenario would test the material's tensile strength as well as its resistance to torsional forces.

Elongation+Bending: In the third visualization, the prism is being stretched and bent simultaneously. Here, one end of the prism is extended along the y-axis while simultaneously being bent downward. This results in a complex deformation where the elongation-induced stress is compounded with the bending stress. The color coding highlights areas of maximum stress concentration, particularly where the bending moment induces the most significant curvature.

These simulations provide valuable insights into the multi-axial stress responses of silicon materials, which are crucial for the design of silicon-based components in various applications, such as in structural engineering and microelectronic devices. The detailed color mapping and deformations presented in the figure are instrumental in understanding the intricate behaviors of the material under combined loads, guiding the optimization of material properties for specific applications.



Rotation+Bending Elongation+Rotation Elongation+Bending

Fig. 3 A superimposed simulation of three forces (Photo credited: Original)

Force and Electric Coupling for Simulation. Because bending, elongation, and rotation will cause the density of the cuboid to change, its related voltage will also change, so we analyze the voltage effect diagram of these three cases, select any two of the 1-8 electrodes to apply the opposite voltage value, and ground at any point at the lower end of the cuboid.

In this case , we only show two types of simulation: raw, elongation. The different voltage in original state was shown in Fig. 4. And, Fig. 5 showed the average value of the excitation electrode and its voltage after elongation.

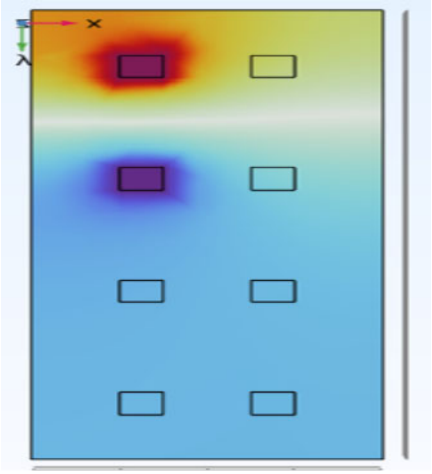


Fig. 4 The average value of the primary excitation electrode (Photo credited: Original)

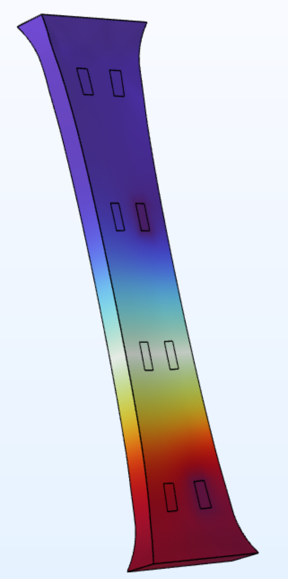


Fig. 5 The average value of the excitation electrode and its voltage after elongation (Photo credited: Original)

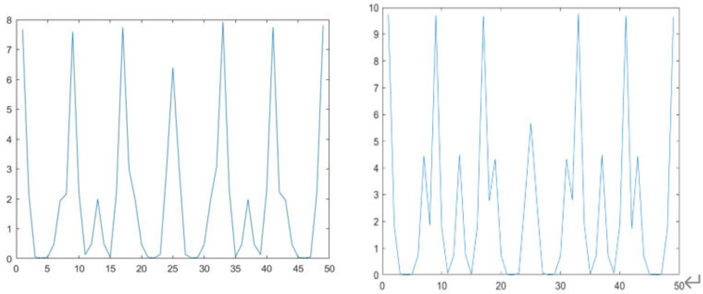
The provided figure showcases an imaginative and striking depiction of a tall structure, resembling a skyscraper or tower, that exhibits a distinct bending posture. This artistic rendering is characterized by a gradient color transition that flows from a cool blue at the top to a warm red at the bottom. The structure is adorned with several rectangular windows, which are aligned vertically along its length, adding an element of realism to the otherwise whimsical portrayal. The seamless blending of colors imparts a surreal and fluid visual effect, making the structure appear as if it is in motion or affected by some unseen force.

Accompanying this visual illustration is a text that delves into the technical realm of electrical engineering. It describes diagrams that represent the variations in average voltage values of an excitation electrode when subjected to different mechanical forces. These voltage changes are critical in understanding how physical forces can influence electrical properties, which is essential for the development of sensors and other responsive technologies. The data, processed using MATLAB, includes 49 average voltage values recorded over two cycles of force application, highlighting the dynamic relationship between force and electrical response.

This combination of artistic representation and technical analysis creates a compelling narrative that bridges the gap between abstract art and scientific rigor. It invites viewers and readers alike to explore the intersections of visual art, structural design, and electrical engineering, fostering a deeper appreciation for the ways in which these disciplines interact and inform each other in both theoretical and practical contexts.

3 Results

The different voltage value was shown in the Fig. 6. The methods from the study of M. Wesam Al-Mufti, U. Hashim, and Tijjani Adam. The authors discuss the significance of computer simulation in the field of nanotechnology, emphasizing its role in optimizing designs and developing new products. They highlight the adaptability of COMSOL Multiphysics as a platform that allows for flexible parameter adjustments to explore various physical aspects of nanostructures. This flexibility is crucial for creating customized solutions in diverse research and industrial applications.



Primary

after elongation↵

Fig. 6 Different average voltage results (Photo credited: Original)

Through detailed examples, the article showcases how simulations in COMSOL have been applied to study the properties and behaviors of different nanostructures, contributing significantly to advancements in nanotechnology research. The review also underscores the potential of these nanostructures in a range of applications from electronics to photonics, and the importance of simulation tools in understanding and leveraging their unique properties for technological advancements [10].

These diagrams illustrate the variations in the average voltage of the excitation electrode under varying force conditions. MATLAB was employed to compute 49 mean voltage values across two force application cycles, with the resulting data presented in the figures.

The research conducted using COMSOL Multiphysics and MATLAB provides an in-depth analysis of the physical behaviors of silicon materials under various mechanical forces. The study is methodical in its approach, employing a simplified geometric model of a silicon rectangular prism with pre-defined dimensions and electrodes for excitation. This foundation allowed for the exploration of fundamental physical deformation effects, showcasing COMSOL's capability in simulating complex multi-physical phenomena.

The findings of the study can be summarized in several key points:

Deformation Simulation: The research successfully demonstrated the simulation of three primary modes of deformation: bending, elongation, and torsion. For bending, the silicon rectangular prism was fixed on one side and a positive force was applied in the z-direction on the other, leading to deformation. Elongation was achieved by fixing one side and moving the opposite side along the y-axis. Torsional deformation was simulated by fixing one surface and rotating the opposite surface counterclockwise around the y-axis. These simulations were illustrated in the paper's Fig. 2, offering visual evidence of the mechanical behaviors under the applied conditions.

Superposition of Forces: An innovative aspect of the study was the superposition of solid mechanical fields to simulate combined forces. The research detailed the process of adding a rigid connection within the solid mechanics field, stretching and rotating the cuboid, and then applying additional forces to mimic real-world material stresses. This approach demonstrated the advanced capability of COMSOL to handle complex physical interactions and provided a more comprehensive understanding of the material behavior when subjected to multiple forces.

Force and Electric Field Coupling: A critical part of the research was to understand how the changes in material density due to deformation affected electrical properties. The study analyzed the voltage effect by applying opposite voltage values to two

4 Conclusion

The culmination of this research demonstrates the robust capabilities of COMSOL Multiphysics when integrated with MATLAB for the simulation of coupled physical fields in silicon materials. This study has delved into the multifaceted aspects of physical deformation, including bending, elongation, and torsional effects, as a response to electrode excitation and force application.

The simulation of silicon deformation under various mechanical forces underscores the fidelity of COMSOL in rendering complex interactions within materials. This is particularly evident in the paper's depiction of the nuanced changes in voltage as a result of the force-induced deformations. By utilizing MATLAB for data processing, the study achieved a detailed visualization of 49 average voltage values over two force cycles, revealing the nuanced interplay between mechanical stress and electrical properties.

Furthermore, the superposition technique developed for this research provides a novel methodology for simulating the concurrent application of multiple forces, advancing the understanding of material behavior under complex loading conditions. The methodical approach to coupling physical fields through simulations offers valuable insights into the development of new materials and the optimization of product design, highlighting the versatility of COMSOL and MATLAB in a wide array of applications.

In summary, this investigation not only affirms the utility of simulation software in scientific exploration but also in practical applications across disciplines such as technical education and interdisciplinary research. It underscores the importance of such tools in bridging the gap between theoretical constructs and real-world scenarios, facilitating the progression of innovative design and contributing to the advancement of technology and engineering education. The insights gleaned from this study advocate for the continued integration of simulation and analysis tools in advancing material science research and application.

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