Development of a Fiber-Shaped ML-Perovskite Sensor for Structural Health Monitoring in Composites

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ABSTRACT

Composite materials are widely used in various industries due to their high strength-to-weight ratio and appealing properties. However, the detection and assessment of damage in composite structures can be challenging, requiring the use of effective structural health monitoring (SHM) techniques. This study explored the potential of an embedded fiber-shaped mechanoluminescence (ML)-perovskite sensor for real-time monitoring of impact events in composites. The sensor was fabricated by coating a perovskite photodetector with a sensing layer comprising copper-doped zinc sulfide (ZnS:Cu)/polydimethylsiloxane (PDMS) blend, using carbon nanotube (CNT) yarns as a substrate. The sensor was characterized and its ability to detect low-energy impact events, which is an important indicator of SHM, was assessed. ML materials emit light when subjected to mechanical stress, which can be detected by a perovskite photodetector and converted to an electrical current. The variations in the electrical current can be measured to provide in-situ and real-time information on the condition of the structure. CNT yarns are a suitable candidate for embedded sensors in composite structures due to their high sensitivity and exceptional mechanical properties. The flexibility of the CNT also allows the sensor to be weaved within a composite fabric, minimizing the intrusiveness effect of the embedment process. The experimental result showed that the CNT ML-perovskite sensor demonstrated good sensitivity and response time to mechanical stimuli, and a direct correlation was observed between the intensity of the electrical current and the impact energy. The ML-perovskite device showed the potential as a promising embedded sensor for impact monitoring, which could significantly contribute to the field of SHM.

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1. INTRODUCTION

The need for reliable SHM systems continues to grow in importance across materials science and engineering, finding applications in industries such as aerospace, civil infrastructure, and renewable energy [1–4]. The continuous and autonomous monitoring of impact damage in composite structures is of particular interest, an area that has been the subject of extensive research [5,6]. Despite the advancements in conventional SHM technologies, these often fall short in power efficiency, size, and compatibility with the host structure, underscoring the need for innovative solutions [7–11].

In response to this demand, this study presents the development and characterization of a novel fiber-shaped ML-Perovskite sensor for in-situ impact detection in composite materials. With its unique fiber-shaped architecture, the sensor demonstrates a significant breakthrough in sensor technology, addressing many of the limitations associated with traditional SHM systems.

The ML-Perovskite sensor is an innovative combination of ML and a perovskite photodetector, assembled in a vertical structure that includes CNT yarn as the electrodes, tin oxide (SnO_2) as the electron transport layer, and the perovskite as the active layer. The ML layer, composed of ZnS:Cu-PDMS, serves a dual purpose. Firstly, it responds to mechanical stress or impact by emitting light, a property characteristic of its mechanoluminescent nature. Secondly, it functions as an encapsulation layer, providing the necessary protection for the sensor during the embedment process in the composite structure [12–15].

Upon impact, the emitted light from the ML layer is captured by the perovskite photodetector, which converts the collected light into an electrical current. This current is continuously monitored and used to correlate the impact damage. Notably, the self-powered capability of the sensor is attributed to the unique optoelectronic properties of the perovskite structure, allowing it to convert optical signals into electrical signals without an external power source [12–15]. This feature makes this fiber-shaped sensor particularly suitable for monitoring structures with limited or unreachable power supply, such as offshore wind turbines or spacecraft.

The research process involved the characterization and performance assessment of the fiber-shaped ML-Perovskite sensor when embedded in a composite structure. The sensor was subjected to mechanical stress, drop-weight impact, and cyclic bending tests to evaluate its mechanical and sensory performance.

The fiber-shaped ML-Perovskite sensor has demonstrated promising potential for application in embedded SHM systems, emphasizing the potential of this technology to revolutionize the field of SHM. This paper offers an initial assesment of the sensor's development and characterization, providing insights into its potential and setting the foundation for further research and refinement. It contributes to the ongoing discourse on SHM sensor technology and aims to inspire continued innovation and exploration in this area.

2. MATERIALS AND METHODS

2.1 Materials

Methylammonium Iodide (CH_3NH_3I), gamma-butyrolactone (GBL), N-methyl-2-pyrrolidone (NMP), and Diethyl Ether (DEE) were procured from Sigma–Aldrich. Lead iodide (PbI_2) was sourced from Acros Organics, while Lead bromide ($PbBr_2$) and the SnO_2 colloid precursor (15% in H_2O colloidal dispersion) were obtained from Alfa Aesar. Nanocomp supplied CNT yarns. The ZnS:Cu phosphor, GL29/B-C1, was purchased from Phosphor Technology Ltd.

2.2 Fabrication of the Fiber-Shaped ML-Perovskite Sensor

The fabrication process of the fiber-shaped ML-Perovskite sensor began with the preparation of a CNT yarn as the lower electrode. To ensure uniform coating and enhanced structural stability for the fabrication process, the CNT yarns were braided using a four-strand Kumihimo technique, thus providing a robust and well-structured framework for subsequent layer deposition.

A layer of SnO_2 was then deposited on the CNT yarn. The SnO_2 colloidal solution was diluted with deionized water, drip-coated onto the CNT yarn substrate, and dried at room temperature. A thermal annealing process was conducted via joule heating to ensure the proper formation of the SnO_2 layer.

Subsequently, the perovskite active layer was applied to the SnO_2 layer. The fabrication of the $MAPb(Br_{0.1}I_{0.9})_3$ perovskite layer began with preparing a precursor solution. 380 mg of CH_3NH_3I, 91.8 mg of $PbBr_2$, and 826.2 mg of PbI_2 were combined in a mixed solvent of 1 mL NMP and 0.2 mL GBL. The solution was then stirred continuously on a hot plate maintained at 70ºC overnight. The precursor solution underwent an additional heating period for 30 minutes at the same temperature immediately before the deposition process. This solution was then drip-coated onto the previously deposited SnO_2 layer and allowed to dry at room temperature. A secondary thermal annealing process was carried out using joule heating to ensure proper crystallization of the perovskite layer [12–15].

The upper electrode was formed by wrapping another braided CNT yarn around the perovskite layer. Next, the mechanoluminescent and encapsulation layers of ZnS:Cu-PDMS were prepared and drip-coated onto the structure. The ZnS:Cu-PDMS layer was subsequently cured using the joule heating method. The schematic of the sensor can be seen in Figure 1.

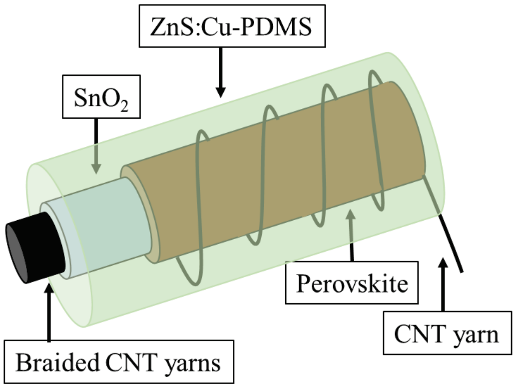

Figure 1. Schematic of the fiber-shaped ML-perovskite sensor

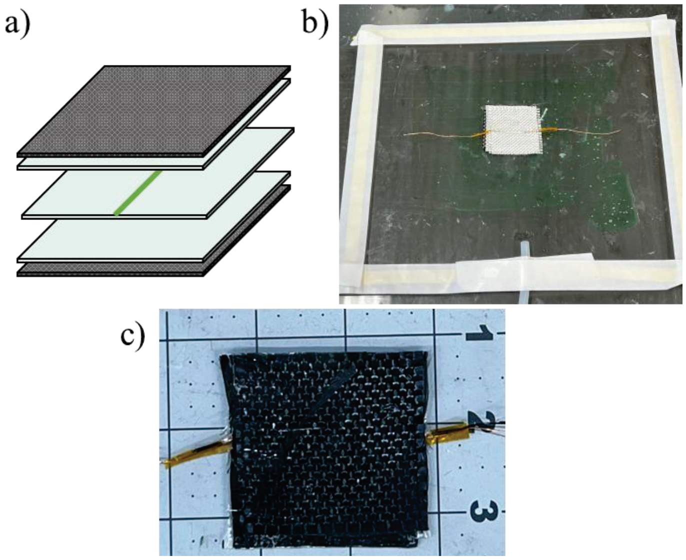

Figure 2. a) Schematic of the embedment process, b) vacuum bagging setup, and c) composite sample with the embedded sensor.

2.3 Sensor Embedment

Following the sensor's fabrication, the device was woven within the middle glass fiber (GF) fabric and then embedded into a carbon fiber (CF)/GF composite laminate. The laminate layup configuration was CF/GF/GF/GF/CF, where all fabrics were woven, as seen in Figure 2a. The use of GF layers served not only as the sensor's housing but also to prevent any potential electromagnetic interference from the CF. The composite layup process was done using the hand layup method with a vinyl ester resin and subsequently cured under vacuum bagging (Figure 2b) conditions for 24 hours at room temperature. This method ensured complete resin curing and solidification of the laminate structure. Figure 2c shows the final composite panel with the embedded sensor.

2.4 Characterization and Performance Assessment

Electrical characterization of the ML-Perovskite sensor was performed using a Keitlhey 2410 source meter unit. Current-voltage (I-V) curves were subsequently obtained under both dark and illuminated conditions (Figure 3). These curves played a pivotal role in investigating the sensor's intrinsic electrical properties and assessing its performance characteristics.

Mechanical characterization, specifically the sensor's response to impact loading, was carried out using a custom made drop tower. Impact energies were varied systematically in the range of 0.5 to 5 J to emulate a wide spectrum of potential real-world impacts. This comprehensive series of impact tests was instrumental in assessing the sensor's capability to reliably detect impact events.

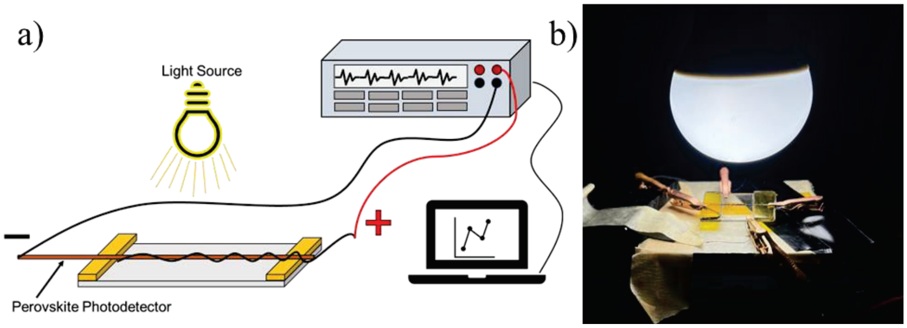

Figure 3. a) Schematic of the testing setup, and b) actual testing conditions.

RESULTS AND DISCUSSION

A rigorous investigation into the characteristics and performance of the ML-Perovskite sensor has been conducted. Emphasis is placed on the intricate details of fabrication steps, the complex properties of the materials used, and the sensor's behavior under mechanical stress. An inital examination of the electrical behavior of the fiber-shaped ML-Perovskite sensor was conducted through the I-V curve measurements. The dark current, an essential parameter representing the baseline noise level intrinsic to photodetector devices, was approximately 10^{-9} A. Although not extremely low, this value is sufficiently low to permit the discernment of signals from the ML layer against the backdrop of this noise. The importance of maintaining a low dark current in photodetectors stems from its direct relationship with the sensor's overall sensitivity. A lower dark current typically enables a more sensitive response, as the sensor signal is not masked by high intrinsic noise.

The I-V curve of the sensor illustrated a critical feature of the device's performance: an increase in current output under illuminated conditions, coupled with a notable shift towards the right, as seen in Figure 4a. This distinctive shift corroborates the successful operation of the perovskite layer, which, as a photodetector, is expected to generate an electric current upon receiving the light emitted from the mechanoluminescent layer.

The sensor's response characteristics was further investigated by subjecting it to a 60 Hz blinking blue LED light source. The sensor exhibited repetitive and consistent signals (Figure 4b), underscoring its response's reliability and potential for real-world applications where repetitive stress detection is expected. This capability is fundamental to effectively implementing the sensor in structural health monitoring scenarios, where consistent and reliable signal generation in response to mechanical changes is paramount.

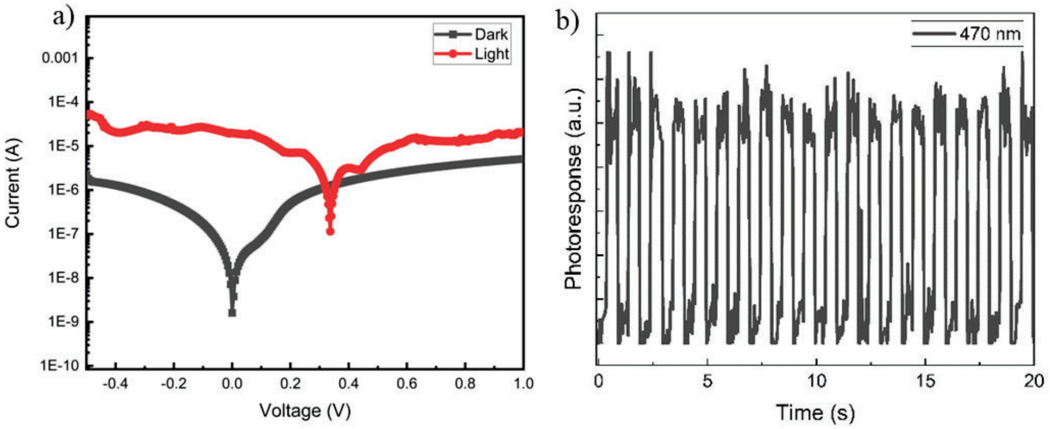

Figure 4. a) I-V curves of the perovskite photodetector under dark and light conditions, and b) on-off cycles of the photodetector.

In the investigation of the sensor's response under various impact energy levels from 0.5 to 5 J, it was established that the sensor could successfully detect energies above 1.5 J. Significantly, above this threshold, the sensor response exhibited a linear relationship with the increasing impact energy, as observed in Figure 5. This linear trend, characterized by a robust correlation of 0.96, is a fundamental property of mechanoluminescence and is particularly advantageous for the sensor's application in SHM, as it simplifies the interpretation of the sensor signal in terms of impact energy.

The focus of the study is on low-energy impacts, specifically those that could result in barely visible impact damage (BVID). Consequently, energies exceeding 5 J, which would typically induce more evident damage, were not included in the scope of this investigation. During an impact event, the energy propagates through the composite structure, generating mechanical stress. This stress triggers the mechanoluminescence process in the ZnS:Cu-PDMS layer of the fiber-shaped sensor, which results in light emission. This light is subsequently detected and converted into an electrical signal by the perovskite photodetector layer, creating a correlation between the impact energy and the sensor's signal output.

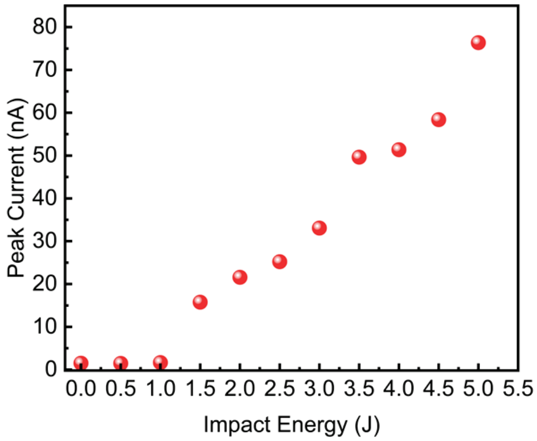

Figure 5. Sensor response for different impact energies.

The fiber-shaped sensor design, with the sensor woven within the composite fibers, offers a significant advantage over the planar configurations, as it is less intrusive and seamlessly integrates with the composite system. This intrinsic integration potentially enhances the accuracy and reliability of sensing, as the sensor is in direct contact with the surrounding material and less susceptible to external disruptions.

Despite the promising findings, challenges persist. Specifically, achieving reproducibility presents a considerable hurdle, mainly due to the flexible nature of the CNT yarn, which serves as the base structure for the sensor. Attaining a uniform and pristine coating of ETL or perovskite layers on this flexible yarn is challenging, and any damage to these active layers can significantly compromise the sensor's performance.

Future research endeavors will focus on optimizing the sensor's performance, addressing the reproducibility challenge, and assessing the sensor's potential for real-world applications in SHM. The findings from this study provide a promising foundation for developing a truly integrated, minimally intrusive SHM sensor with the potential to revolutionize the field.

CONCLUSION

The present study provides crucial insights into developing and assessing a fiber-shaped ML-Perovskite sensor for impact detection, a critical aspect of SHM. The sensor's innovative design, woven within the composite structure, offers a less invasive approach and a more direct interaction with the material system, demonstrating its potential for transformative impact in the SHM field. The sensor's performance, characterized by a distinct electrical behavior and a linear response to increasing impact energy, further reinforces its suitability for SHM applications. Moreover, a robust correlation of 0.96 between the sensor output and impact energy, a characteristic feature of mechanoluminescence, promises a simplified interpretation of sensor signals, enhancing its practical utility.

Nevertheless, challenges persist, particularly in achieving reproducibility due to the flexible nature of the CNT yarn base structure. This challenge and maintaining pristine active layers for optimal sensor performance must be addressed in future investigations. Future research will concentrate on overcoming these challenges and optimizing the sensor's performance. A particular focus will be on harnessing the unique attributes of the ML-Perovskite sensor to enhance its sensitivity and reliability, thereby broadening its potential for real-world SHM applications. The findings from this study represent a significant stride towards developing an integrated, minimally intrusive, and highly efficient SHM sensor.

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