Screen-Printed Carbon Nanotube Polymer Composites for Impact Sensing in Electric Vehicle Batteries

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ABSTRACT

Under-floor impacts are a major cause of thermal-runaway in EV battery packs, yet existing metal or MEMS sensors are heavy, costly, and cover only limited areas, leaving significant portions of the battery unmonitored. We introduce an ultralight, flexible, screen-printed carbon-nanotube (CNT)/epoxy patch sensor that detects impacts through piezoresistive resistance shifts. Conductivity increases with CNT loading, but impact sensitivity peaks at an intermediate CNT fraction and smaller print diameters, defining an optimal window of CNT content, print passes, and sensor footprint. Mounted on a prismatic 8 kWh module, the patches detected impacts ranging from 5–20 J within 20 ms, showcasing over tenfold improvement in strain sensitivity compared to conventional sensors, with negligible added mass. Furthermore, these sensors offer exceptional flexibility and adaptability, enabling their application across various complex battery pack geometries. These results demonstrate a scalable, practical route to comprehensive pack-level impact monitoring. Ongoing research will extend detection capabilities to impacts below 5 J and integrate artificial intelligence (AI) algorithms for mapping resistance signals to impact energy, precise location, and damage severity, paving the way for self-reporting battery-management systems capable of proactively preventing catastrophic failures. This advancement significantly enhances the safety, reliability, and operational efficiency of electric vehicles, promoting broader adoption and consumer confidence in EV technologies.

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INTRODUCTION

The rapid adoption of lithium-ion batteries in electric vehicles (EVs) highlights the critical need for advanced safety monitoring systems capable of preventing catastrophic failures such as thermal runaway. Recent reports have documented an alarming increase in EV-related fires and accidents, underscoring the urgency for enhanced battery monitoring and diagnostics. Traditional protective measures, such as heavy metal enclosures, significantly increase vehicle weight and lack real-time monitoring capabilities. Furthermore, existing sensing technologies, including piezoelectric and optical fiber sensors, face limitations regarding flexibility, cost-effectiveness, and integration complexity. Thus, the development of lightweight, scalable sensing solutions capable of real-time detection and localization of impact events has become a key challenge in advancing EV battery safety systems [1–2].

Carbon nanotube (CNT)-based epoxy composites have attracted significant attention due to their excellent electrical conductivity, mechanical strength, and piezoresistive sensitivity. These composites convert mechanical strain or pressure into measurable electrical resistance changes, enabling real-time structural health monitoring. Recent research has demonstrated the adaptability and effectiveness of CNT-based sensors in various applications, from aerospace damage detection to wearable electronics [3–6]. Additionally, screen-printing techniques offer a cost-effective, scalable method for fabricating flexible CNT/polymer sensors capable of conforming to the complex shapes of battery surfaces, overcoming the limitations of rigid conventional sensors. The adaptability of CNT-based composites makes them particularly suitable for EV battery packs, which involve complex geometries and varying thermal environments.

Despite these advancements, the application of CNT/epoxy composites specifically for dynamic impact detection in EV batteries remains insufficiently explored. Previous studies, such as those by Jung et al., have demonstrated the feasibility of screen-printed CNT/polyurethane sensors for structural impact monitoring, achieving notable strain sensitivity and spatial resolution [7]. Similarly, Wang et al. developed stretchable CNT dilatometers for real-time detection of battery swelling [8]. However, these studies did not fully address integration challenges or optimize sensor performance specifically for EV battery modules.

In this study, we develop a screen-printed CNT/epoxy composite sensor optimized for real-time impact detection in EV battery modules. By systematically investigating the effects of CNT concentration and sensor geometry on performance, this research aims to establish clear design guidelines for highly sensitive, scalable battery monitoring systems. Our approach addresses existing limitations by providing enhanced impact sensitivity, improved flexibility, and better thermal stability compared to conventional sensing methods. Additionally, the proposed sensor design incorporates strategies to ensure long-term durability under the harsh operating conditions typically experienced by EV batteries, including thermal cycling, mechanical vibrations, and environmental exposure. The remainder of this paper presents details of the materials and methods, experimental results on sensor performance under controlled impact conditions, and concludes with insights into future applications for battery monitoring systems.

EXPERIMENTAL

Materials

The multi-walled carbon nanotubes (MWCNTs) used in this study were K-Nanos 210T (Kumho Petrochemical, Seoul, Republic of Korea), synthesized via chemical vapor deposition (CVD). The MWCNTs exhibited individual tube diameters of 7–20 nm, aggregated bundle lengths of 40–50 μm, and an average of 12 concentric walls, with a carbon purity exceeding 95%. The epoxy matrix, DH-EM80 (Daehwa Precision, Gyeonggi, Republic of Korea), had a room-temperature curing time of 24–48 hours and a pre-curing viscosity of 800–1,200 mPa·s, as specified by the manufacturer. Acetone (99.7% purity, Samchun Chemical, Gyeonggi, Republic of Korea) was employed as a processing solvent to reduce the epoxy viscosity and facilitate nanotube dispersion.

Fabrication of screen-printed carbon nanotube/epoxy composite sensors

The CNT/epoxy composite ink was prepared by dispersing 1.5 wt% multi-walled carbon nanotubes into epoxy resin using acetone as a processing solvent. To ensure homogeneous dispersion, the mixture underwent pulsed ultrasonication (15 seconds on/15 seconds off) for 40 minutes in an ice bath maintained below 10°C, minimizing thermal degradation of the epoxy. Residual acetone was removed by heating at 60°C for 2 hours under fume extraction. The epoxy hardener was subsequently incorporated at a 3:1 resin-to-hardener weight ratio, followed by sequential homogenization using a three-roll mill (CA, USA) at a roller speed of 200 rpm. This process ensured nanoscale dispersion while minimizing agglomeration.

The resulting CNT/epoxy ink was screen-printed onto an inkjet label sheet using a 110-mesh screen, which had been selected based on previous studies [9-10]. The printed sensors were cured at room temperature for 24 hours. After curing, conductive silver paint was applied to both sides of the printed circular sensor to form wing-shaped electrodes, as illustrated in Figure 1. The electrodes were also dried at room temperature for one day. All sensors were fabricated using the same procedure to ensure consistency.

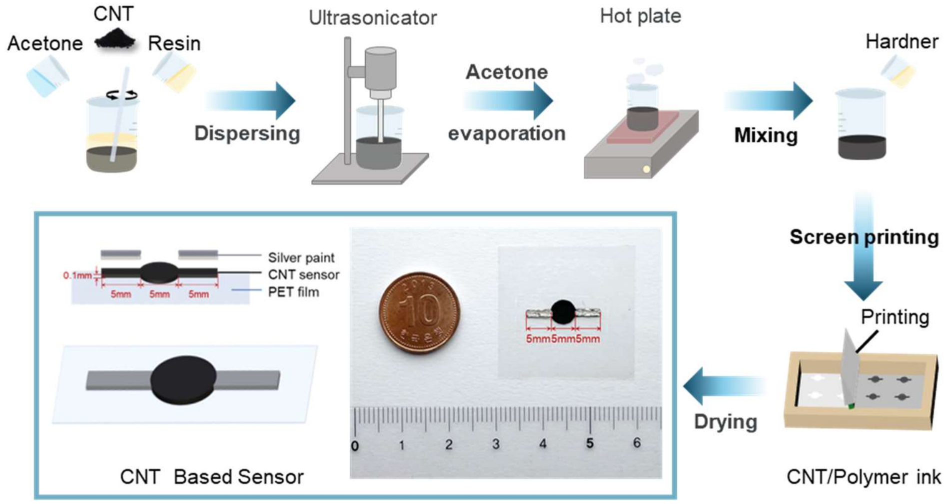


Figure 1. Fabrication procedure of the multi-wall carbon nanotube/epoxy composite sensor.

Characterization and measurement

The electrical resistance of the CNT/epoxy composite sensors was measured using a two-point probe configuration with a Keithley 2450 SourceMeter (Keithley Instruments, OH, USA). Five independent samples were evaluated for each composition, with resistance recorded at three distinct locations on each sample to ensure spatial uniformity. The reported resistance values represent the mean ± standard deviation across all measurements. The electrical conductivity (σ, S/m) of the samples was calculated using Equation (1):

$$\sigma = L/AR \qquad (1)$$

Where σ (S/m) is the electrical conductivity of the CNT/epoxy composite, R (Ω) is the electrical resistance of the CNT/epoxy composite, L is the distance between the two electrodes, and A is the area of the electrodes.

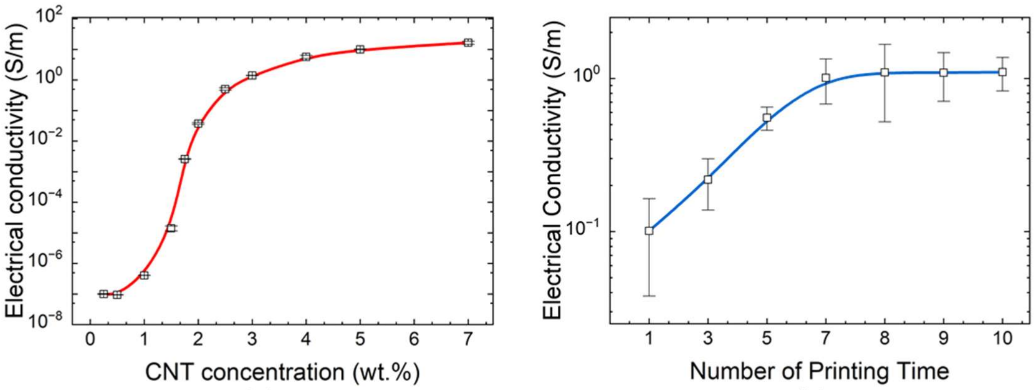
RESULT AND SICUSSIONS

Electrical conductivity as a function of CNT concentration and printing time

Figure 2a illustrates the electrical conductivity of CNT/epoxy composites as a function of CNT concentration (wt.%). A clear percolation behavior is observed, with conductivity sharply increasing between 1.0 and 2.0 wt.% CNT, indicating the formation of a continuous conductive network. Beyond 5.0 wt.%, conductivity plateaus, showing minor incremental gains, consistent with classical percolation theory. The critical percolation threshold is estimated between 1.5 and 2.0 wt.% CNT.

Figure 2b presents the relationship between electrical conductivity and the number of screen-printing passes. Conductivity significantly increases up to approximately five printing passes, after which it stabilizes. This underscores the importance of multiple printing passes in establishing a sufficiently interconnected CNT network, although further printing beyond an optimal thickness offers minimal additional benefits.

Overall, these results emphasize the need to carefully optimize CNT concentration and screen-printing parameters to achieve optimal conductivity with efficient material use and scalability for large-area manufacturing.



(a) (b)

Figure 2. Electrical conductivity as a function of (a) CNT concentration and (b) printing time.

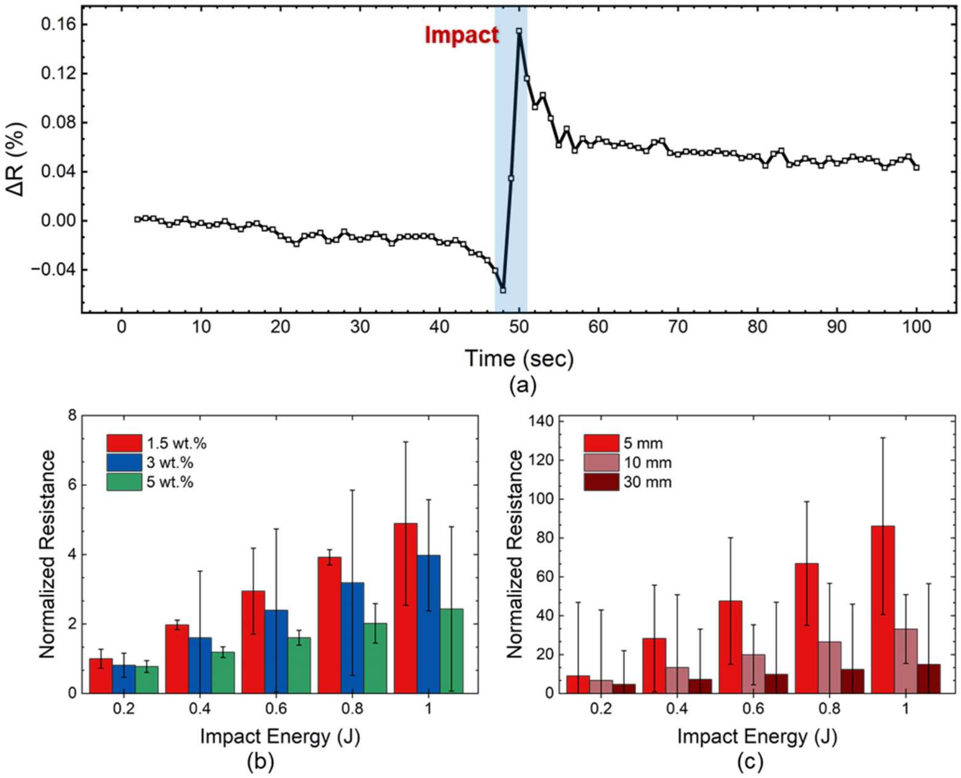
Impact sensitivity of CNT/Epoxy sensors

Figure 3 presents the normalized resistance change (ΔR/R₀) of screen-printed CNT/epoxy composite sensors under controlled impact loading as a function of CNT concentration and sensor diameter.

Figure 3a displays a representative time-resolved resistance profile for a sensor containing 1.5 wt.% CNT subjected to a 1.0 J impact, exhibiting an immediate resistance spike followed by partial recovery. This transient response indicates reversible disruption and reformation of the CNT network within the epoxy matrix due to mechanical strain.

Figure 3b demonstrates that sensors with 1.5 wt.% CNT show the highest resistance changes across all tested energy levels, consistent with classical percolation behavior. Sparse conductive networks near the percolation threshold are particularly sensitive to mechanical disturbances. Increased CNT content results in a denser conductive network, improving electrical stability but decreasing sensitivity.

Figure 3c examines the effect of sensor diameter, highlighting that smaller sensors (5 mm diameter) experience larger resistance changes due to shorter electrode spacing and fewer conductive paths, while larger sensors (30 mm diameter) have lower sensitivity but improved signal stability. These findings highlight the importance of optimizing both CNT content and sensor geometry, considering the trade-off between sensitivity and reliability to ensure effective integration into EV battery safety systems.



(a)

(b)

(c)

Figure 3. Impact-induced resistance response of CNT/epoxy sensors as a function of CNT concentration and sensor size.

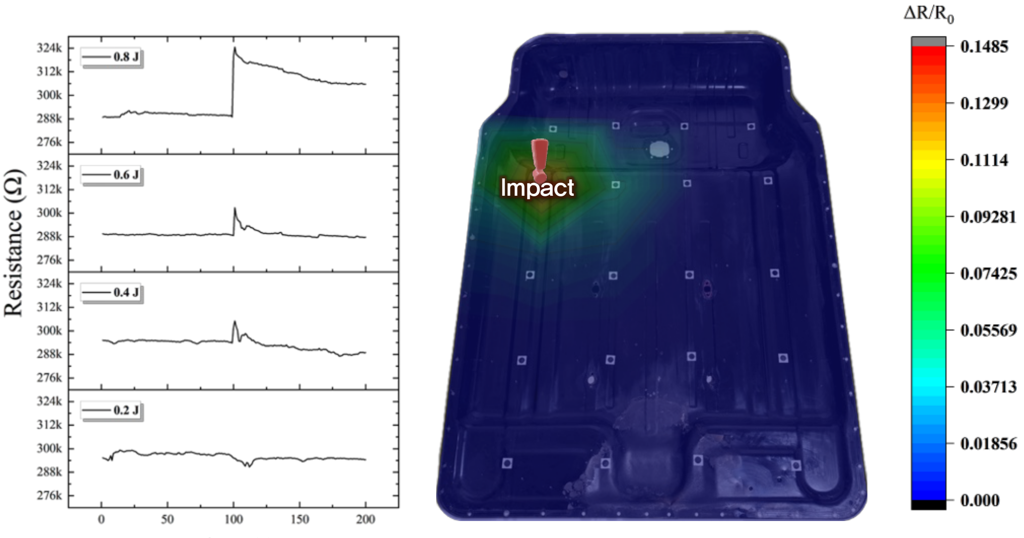
Application CNT/Epoxy sensors to a EV battery enclosure

Figure 4 demonstrates the practical application of screen-printed CNT/epoxy composite sensors for impact detection on an electric vehicle (EV) battery enclosure.

Figure 4a shows time-resolved resistance profiles of a sensor affixed to the battery enclosure surface under various impact energies (0.2–0.8 J). A sharp transient resistance peak occurs immediately after each impact, with response magnitude increasing proportionally to applied energy, confirming the sensor's capability for real-time detection of low-to-moderate impact events.

Figure 4b provides a spatial mapping of normalized resistance changes ($\Delta R/R_0$) on the battery enclosure, revealing a concentrated resistance change at the impact point, confirming the sensor's ability for spatially resolved impact detection. The radial gradient of resistance change illustrates the mechanical strain dissipation across the surface. These results validate the feasibility of integrating CNT/epoxy composite sensors into EV battery modules for effective real-time impact localization, highlighting their potential for scalable deployment in future battery safety systems. Integration of these sensors could significantly enhance predictive maintenance capabilities, ultimately improving EV safety and reducing operational downtime.

Additionally, preliminary testing indicates that these sensors maintain stable performance under repetitive impact loading conditions, demonstrating their robustness for continuous monitoring applications. The flexibility and thin-profile characteristics of the CNT/epoxy composite sensors facilitate easy integration onto various battery module surfaces without compromising structural integrity or adding significant weight. Moreover, their capability to detect and localize impacts promptly provides valuable diagnostic information that could enable preemptive actions to prevent damage propagation.



(a) (b)

Figure 4. Impact response of CNT/epoxy sensors: (a) resistance-time profiles under varying impact energies and (b) spatial mapping of resistance change on a battery enclosure.

CONCLUSION

This study developed a battery impact monitoring sensor based on a screen-printed carbon nanotube (CNT)/epoxy composite tailored for electric vehicle battery modules. The effects of CNT concentration and sensor geometry on sensing performance were systematically investigated, showing that while higher CNT content improves baseline conductivity, excessive loading diminishes impact sensitivity. Sensor dimensions were also found to significantly influence detection capability, underscoring the need for precise design optimization. Compared to conventional metal- and MEMS-based sensors, the proposed CNT/epoxy sensors offer advantages in sensitivity, lightweight construction, mechanical flexibility, durability, low power consumption, and scalability. These characteristics enable early detection of battery damage and contribute to enhanced safety and reliability in EVs. This work lays a foundation for future integration of CNT/epoxy sensors with AI-based data analysis and smart battery management systems for real-time, automated impact monitoring.

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