



A superelastic and cushioning aerogel with dual sensing for intelligent safety protection

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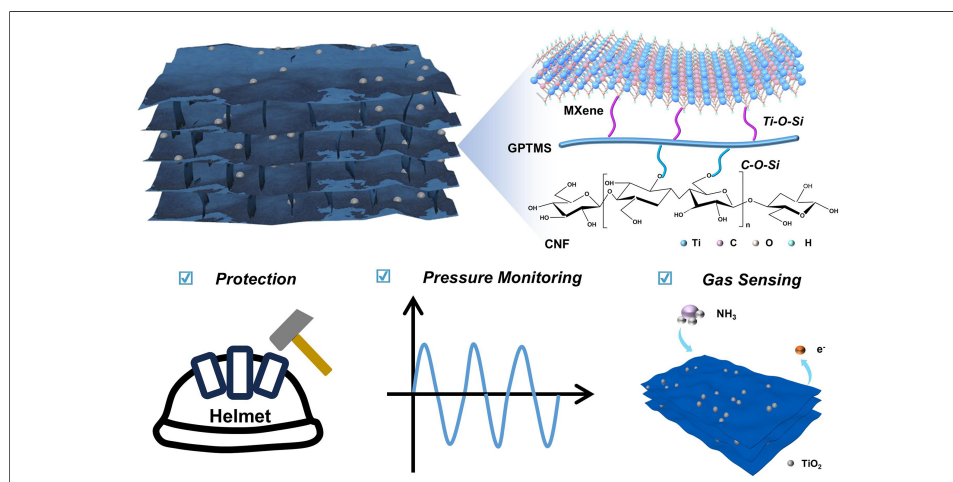
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Abstract

Safety protection equipment necessitates the use of aerogel materials with effective mechanical impact resistance. However, conventional materials often suffer from limited resilience and a lack of multi-sensing functionality, making them inadequate for safety monitoring in complex scenarios. To address this, we developed a composite aerogel (denoted as G-T@M/C) based on cellulose nanofibers and MXene, fabricated through oxidation, cross-linking, and freeze-drying. This aerogel demonstrates mechanical resilience, achieving a rebound rate of 95% even under 90% compressive strain. It showed a static cushioning coefficient of 3.32 in the stress range of 2.4–36.2 kPa, and demonstrated significantly better practical cushioning performance than expanded polyethylene and expanded polystyrene. Moreover, this aerogel exhibits piezoresistive sensitivity of 3.9 and high stability throughout 1,500 compression-release cycles at 80% strain. Simultaneously, this aerogel possesses sensitive gas sensing capabilities, exhibiting a response concentration to ammonia gas ranging from 0.001 to 10 ppm, with a response time to



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1 ppm NH_3 achieved within 17 s. These characteristics enable its integration into blasters' safety helmets, providing not only reliable impact protection but also early warning of ammonia leaks in the environment, thereby ensuring timely safety alerts.

INTRODUCTION

With the development and progress of society, people's fields of work have become increasingly specialized. Correspondingly, the personnel protection requirements for certain specialized work environments have diversified. For example, nitramine-based explosives find extensive application in blasting operations within the mining, civil engineering, and defense sectors. Despite their utility in military and demolition contexts, explosives carry significant risks. In particular, ammonium nitrate explosives have been involved in more than 50 major incidents worldwide over the past one hundred years, resulting in a total death toll above 2,700^[1,2]. It not only generates substantial quantities of toxic gases (e.g., NH_3) prior to explosion, but its detonation also releases intense shock waves and flying debris^[3,4]. Traditional safety equipment mainly provides mechanical impact protection, yet it generally lacks real-time toxic gas monitoring and early warning functions, preventing it from delivering pre-accident alerts. This limitation makes it inadequate for the safety requirements of complex blasting conditions. In recent years, significant advances have been made in flexible gas sensing technologies for toxic gas detection, including self-healing nanocomposite sensors with enhanced mechanical robustness^[5], wireless metal organic framework (MOF)-based sensor patches with interference suppression^[6]. Additionally, quantum dot-sensitized MXene sensors have shown promise for breath analysis in hazardous environments^[7].

Aerogels are lightweight solid materials characterized by a three-dimensional nanoporous network structure. This unique architecture imparts a range of exceptional properties, such as low density, high specific surface area, and tunable pore structures^[8]. These attributes make aerogels well-suited to meet both the lightweight requirements and the multifunctional integration needs of modern protective equipment. In recent years, ongoing innovations in material design, composition, and preparation techniques have led to the development of lightweight and multifunctional aerogels and established a material foundation for technological advances in personal protective equipment. For example, Zhou *et al.* have developed a composite material that combines thermal management with intelligent protection capabilities. It absorbs 55.4% of the force during low-speed impacts and retains its electrothermal functionality even after deformation^[9]. Nevertheless, its long-term cyclic stability still requires improvement. Wang *et al.* prepared an aerogel for firefighting protective clothing that triggers a fire alarm within 2.03 s and exhibits low thermal conductivity (0.06233 W/m·K)^[10]. However, the complexity of its fabrication process and its relatively low mechanical strength limit broader application. Hu's team also developed a multi-scale biomimetic composite aerogel^[11]. This material demonstrates a high tensile strength of 3.70 MPa and a buckling strength of 0.66 MPa. Nevertheless, its long-term stability and overall protective efficacy have not yet been assessed. Therefore, integrating aerogels that combine excellent cushioning, high elasticity, and multi-sensing capabilities remains a persistent challenge.

Herein, a simple approach is proposed to prepare layered porous composite aerogels, designated as G-T@M/C [with G for "crosslinked by (3-glycidyloxypropyl) methyl-diethoxysilane (GPTMS)", T for TiO_2 , @ for TiO_2 attached to the MXene surface, M for MXene, and C for cellulose nanofibers (CNFs)]^[12-14]. By combining material selection with structural design, the resulting aerogel achieves a combination of elasticity with 95% height retention after 90% compression. It demonstrates an optimal static cushioning coefficient (SCC) value of 3.32 at 8.3 kPa, while maintaining piezoresistive sensitivity of 3.9 and gas detection capability for ammonia at low concentrations down to 1 ppb. The integration of this multifunctional aerogel into safety

helmets combines physical impact monitoring, effective personal protection, and early warning of hazardous gases.

EXPERIMENTAL

Materials

2,2,6,6-Tetramethylpiperidinyloxy (TEMPO) and lithium fluoride (LiF) were obtained from McLean Biochemical Technology Co., Ltd. (China). Sodium hypochlorite (NaClO) was sourced from Beijing Huaxia Yuanyang Technology Co., Ltd., while sodium hydroxide (NaOH), sodium bromide (NaBr), and hydrochloric acid (HCl) were provided by Jiangtian Chemical Technology Co., Ltd. (China). Ti_3AlC_2 powder was supplied by Laizhou Kaikai Ceramic Materials Co., Ltd. Additionally, GPTMS was acquired from Beijing Warwick Chemical Co., Ltd. (China). Ammonia solution at 25% concentration was purchased from Fengchuan Chemical Reagents Technology Co., Ltd.

Synthesis of CNF

CNFs were obtained through TEMPO-mediated oxidation followed by high-pressure homogenization^[15]. First, 10 g of sulfate-bleached eucalyptus pulp was dispersed in deionized water to form a 1% fiber suspension. Then, 0.1 g of TEMPO and 1 g of NaBr were dissolved in deionized water at 40 °C and introduced into the suspension. A 10 wt% NaClO solution, pre-adjusted to pH 10.5 using 0.1 M HCl, was added dropwise via a peristaltic pump to initiate oxidation. Throughout this process, the pH was maintained at approximately 10.5 by supplementing with 0.5 mM NaOH as needed. After oxidation, the suspension was ultrasonicated, and the reaction was quenched by adding 20 mL of anhydrous ethanol. The obtained pulp was filtered and rinsed with deionized water to neutrality, followed by redispersion in 1 wt% solution. Finally, the suspension was passed through a high-pressure homogenizer to obtain a uniform CNF dispersion.

Bleached eucalyptus sulfate pulp (cellulose content 86%-90%, hemicellulose content 3%-4%, and lignin content 1%-3%) was used as the raw material, following the method described in a previous report^[15]. We prepared CNFs with a mass fraction of 1 wt%, a diameter range of 20-60 nm, and an average length of 68 μm . After oxidizing the pulp with 8 mmol/g NaClO, the resulting CNFs exhibited a surface zeta potential of -56.87 mV and a carboxyl group content of 0.69 mmol/g.

Preparation of MXene sheets

MXene sheets were prepared by etching the Al layer of Ti_3AlC_2 with HCl and LiF. Slowly add 1.6 g of LiF to 12 M HCl while stirring at 800 rpm for 5 min at room temperature magnetically until the mixture disperses uniformly. Then slowly add 1.0 g of Ti_3AlC_2 to the mixture. Next, the water bath temperature was raised to 45 °C, and magnetic stirring at 1,200 rpm was continued for 24 h to etch the Al layer. The obtained reaction mixture was rinsed with deionized water and centrifuged several times until the pH of the supernatant was no less than 5.5. Impurities were then removed by centrifugation for 30 min, and the deep green supernatant was collected. The MXene sheets were obtained by freeze-drying the supernatant.

Synthesis of TiO_2 @MXene

MXene was added to deionized water and stirred at 500 rpm for 5 min at room temperature to achieve uniform dispersion. Subsequently, we determined the effect of MXene oxidation time on mechanical properties. Based on the measured stress-strain curves of the aerogel, the optimal oxidation time for MXene was ultimately set at 9 h [Supplementary Figure 1]. Transfer the solution to a vacuum drying oven and oxidize at 70 °C for 9 h. After cooling, dissolve the dried TiO_2 @MXene (denoted as T@M) in deionized water to prepare a T@M dispersion (10 mg·mL⁻¹).

Preparation of G-T@M/C aerogel

We determined the influence of the T@M, CNF, and GPTMS ratio on mechanical properties. Based on the three sets of parallel stress–strain curves measured for the aerogel under each condition, the optimal composition was determined to be T@M:CNF:GPTMS = 1:2:1 [Supplementary Figures 2–5]. Unless otherwise specified in subsequent discussions, all G-T@M/C aerogels referred to in this paper were prepared using this mass ratio. The CNF dispersion (1 wt%) and T@M suspension (10 mg·mL⁻¹) were first mixed at a mass ratio of 2:1 (CNF:T@M) and stirred at 600 rpm for 30 min at room temperature. GPTMS was then added dropwise to the mixture at a mass ratio of GPTMS:CNF = 1:2. The resulting dispersion was stirred at 600 rpm and 60 °C for 2 h to promote the hydrolysis and condensation of GPTMS with both CNF and T@M. After reaction, unreacted GPTMS, oligomers, and other small molecules were removed by centrifugation. The centrifuged solution was poured into a polydimethylsiloxane (PDMS) mold positioned on a copper bridge, with both sides of the bridge immersed in liquid nitrogen (-196 °C) and ice water (0 °C), respectively, to create a temperature gradient. Following directional freezing, the sample was demolded and freeze-dried under vacuum at -60 °C for 36 h. Finally, the G-T@M/C aerogel sample was cured in a vacuum oven at 110 °C for 30 min to complete crosslinking process. For comparison, we simultaneously prepared pure CNF aerogel, MXene/CNF aerogel (without oxidation or crosslinking treatment, denoted as M/C), and G-MXene/CNF aerogel (without oxidation treatment, denoted as G-M/C) under the same conditions for subsequent comparative testing and analysis. We also analyzed their pore size distribution and density [Supplementary Figure 6].

Characterization

The microstructure of the aerogel was examined by scanning electron microscopy (SEM, JEOL JSM-IT300LV, Japan). The chemical structure was analyzed using Fourier transform infrared spectroscopy (FTIR) (Nicolet iS5, USA), while the surface chemical composition was determined by X-ray photoelectron spectroscopy (XPS, Thermo Scientific K-Alpha, USA). Crystal structure characterization was carried out through X-ray diffraction (XRD, Bruker D2 Phaser, Germany). We then conducted detailed tests on the aerogel using a static contact angle measuring instrument (VCA Optima, AST, USA), a motor control platform (DM422s, Wuhan Hongxingyang Technology Co., Ltd.), and a digital source meter (Keithley 2400, Tektronix, USA).

Mechanical property test

The compression stress–strain curves of G-T@M/C aerogels were obtained using a universal testing machine (Lishi LD23.53, China). Strain energy (e) and static cushioning coefficient (C) were calculated using Equations (1)^[16] and (2)^[17]:

$$e = \int_0^{\varepsilon} \sigma d\varepsilon \quad (1)$$

$$C = \sigma/e \quad (2)$$

where ε is the compressive strain and σ is the compressive stress.

The acceleration G 's experienced by aerogels during descent are measured by a drop test machine.

Pressure sensing test

The G-T@M/C aerogel was bonded between the compression plates of the motor control platform (MD442s, China) using two Cu electrodes. Resistance changes during compression were recorded in real time via a source meter (Keithley 2000, China), and the aerogel's sensitivity (S) was calculated according to Equations (3) and (4)^[18].

$$\Delta I/I_0 = (I - I_0)/I_0 = R_0/R - 1 \quad (3)$$

$$S = \delta(\Delta I/I_0)/\Delta \text{Strain} \quad (4)$$

where R_0 denotes the resistance without strain, R represents the resistance under strain, and ΔStrain indicates the compression size change.

Gas sensing test

The G-T@M/C aerogel sensor was mounted on a printed glass substrate equipped with platinum finger electrodes (15 mm × 50 mm, 3 mm spacing) using liquid metal as a conductive adhesive. Gas detection experiments were conducted at room temperature. After being equilibrated with dry nitrogen, the calibrated gas was diluted to a typical concentration with dry air via a mass flow controller at a total flow rate of 500 mL/min and then injected into a sealed chamber containing the G-T@M/C aerogel sensor. The resistance of the G-T@M/C aerogel sensor was monitored in real time using a source meter. The sensor response was defined as $\Delta R/R_0$, where ΔR represents the change in resistance of the sensor between the air (R_0) and ammonia (NH_3) environments. The response time and recovery time refer to the time required for the sensor to reach 90% of the final signal change after exposure to the gas and after the gas is removed, respectively.

The response time was defined as the time required for the sensor response to reach 90% of the maximum signal variation after exposure to ammonia. The recovery time was determined as the time for the signal to return to 10% of the maximum response after switching to pure dry air. All measurements were performed at room temperature with constant humidity and fixed gas flow rate, and the average value of three repeated tests was adopted.

RESULTS AND DISCUSSION

Preparation and characterization

Figure 1 depicts the structural design and fabrication procedure of the G-T@M/C aerogel. The preparation started from TEMPO-oxidized CNF [Figure 1A] and a uniform mixture of a pre-oxidized MXene dispersion [Figure 1B]. TiO_2 grow on the MXene surface through hydrothermal oxidation. Then, GPTMS hydrolyzes and self-polymerizes in water to generate hydroxysilanes, which further condense with rich surface hydroxyl groups distributed on CNF and MXene surfaces, forming a crosslinked network^[19,20]. Finally, the resulting solution was subjected to a two-step freeze-drying process followed by vacuum drying [Figure 1C].

The surface structure and chemical crosslinking of the CNF and MXene components were investigated using a combination of characterization techniques. The obtained aerogel [Figure 2A] has dimensions of 20 mm × 20 mm × 20 mm, a mass of 0.089 g, and a calculated bulk density of 11.11 mg·cm⁻³. It demonstrated a typical anisotropic layered porous architecture [Figure 2B]. The pre-oxidation treatment resulted in the formation of a uniform distribution of TiO_2 on the surface of MXene [Figure 2C]. Their corresponding energy-dispersive X-ray spectroscopy (EDS) elemental distribution maps revealed a uniform distribution of C, Ti, and Si across the surface [Figure 2D]. The appearance of characteristic anatase TiO_2 peaks near 23.09° in the XRD analysis pattern of G-T@M/C [Figure 2E] confirms the presence of TiO_2 on the MXene surface^[21,22]. XRD patterns of the T@M, T@M/C, and G-T@M/C nanocomposites reveal a progressive shift of the characteristic MXene diffraction peak from 7.8° to 5.7°, and further to 3.5° [Figure 2F], suggesting the intercalation of CNF and GPTMS into the MXene interlayers^[23]. XPS analysis of G-T@M/C aerogel revealed a characteristic Si–O–Ti bond at 531.2 eV in the O 1s spectrum [Figure 2G] and a C–O–Si bond at 102.2 eV in the Si 2p spectrum [Figure 2H], which also correlates with the successful crosslinking of GPTMS with CNF and MXene^[19,24]. FTIR analysis of the G-T@M/C film displays absorption peaks at 926, 1,262 and 1,171 cm⁻¹ [Figure 2I], corresponding to highly stable Si–O–Ti bond (bond energy of ~420 kJ·mol⁻¹)^[25–27] and C–O–Si

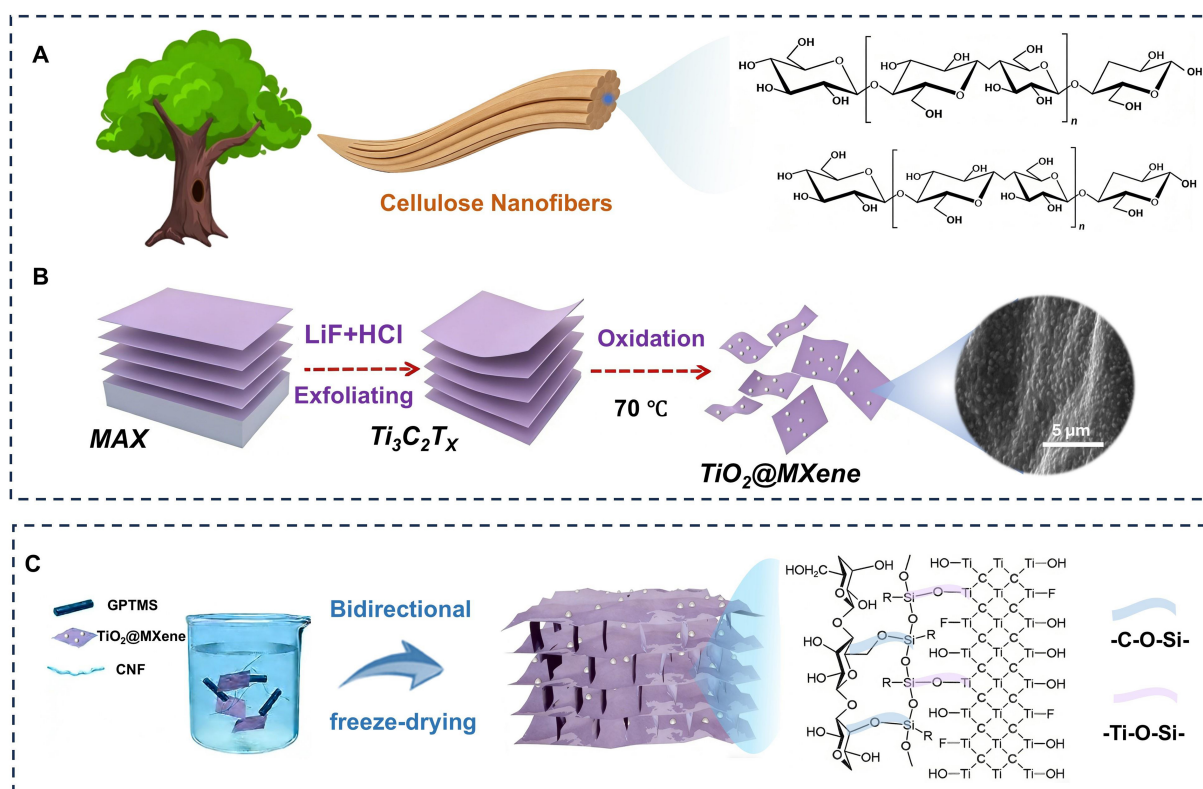


Figure 1. Preparation process of G-T@M/C aerogel. (A) Schematic illustration of preparing CNF; (B) Schematic illustration of the TiO_2 @MXene preparation process; (C) Schematic illustration of preparing G-T@M/C aerogel by crosslinking CNF and TiO_2 @MXene with GPTMS. CNF: Cellulose nanofiber; GPTMS: (3-glycidyloxypropyl) methyldiethoxysilane.

bond ($380\text{--}400\text{ kJ/mol}$)^[28], respectively, confirming the successful crosslinking of GPTMS with both CNF and MXene^[29]. The above evidence confirms the successful preparation of T@M, as well as its effective crosslinking with CNF via the GPTMS.

Mechanical protection performance

The elastic mechanical performance of aerogels is critical for their practical applicability. As shown in Figure 3A, the G-T@M/C aerogel demonstrates significant rebound recovery after being subjected to 90% compressive strain. Under the same strain, pure CNF aerogel reaches a maximum compressive stress of 100.4 kPa but suffers a severe height loss of 84.8% upon load release [Supplementary Figure 7]. This irreversible deformation arises from the inherent plasticity and viscoelasticity of CNF, in which internal fiber networks experience hydrogen bond disruption and permanent slippage under stress^[30,31]. With the incorporation of MXene, the M/C aerogel shows a reduced compressive stress of 90.1 kPa at 90% strain, along with a lower height loss of 75.8% [Figure 3B–D]. MXenes exhibit a Young's modulus as high as $0.33 \pm 0.03\text{ TPa}$ and a fracture strength of $17.3 \pm 1.6\text{ GPa}$ ^[32]. Their force-extension and retraction curves under different loads show negligible hysteresis, indicating strong elastic behavior^[33]. In contrast to flexible and plastic CNFs, elastic MXenes possess sufficient flexibility to withstand compression and demonstrate superior shape-recovery capability, enabling them to store energy during external mechanical deformation. This improvement can be attributed to the inherent elasticity of the introduced MXene itself, which simultaneously forms a stable interpenetrating structure with CNF. This facilitates efficient stress transfer from CNF to MXene nanosheets and helps mitigate stress concentration^[23]. However, the mere introduction of MXene is insufficient to achieve a significant improvement in mechanical properties. Via chemical crosslinking of 2D flexible MXene and CNFs using GPTMS, the resulting G-M/C composite achieves a

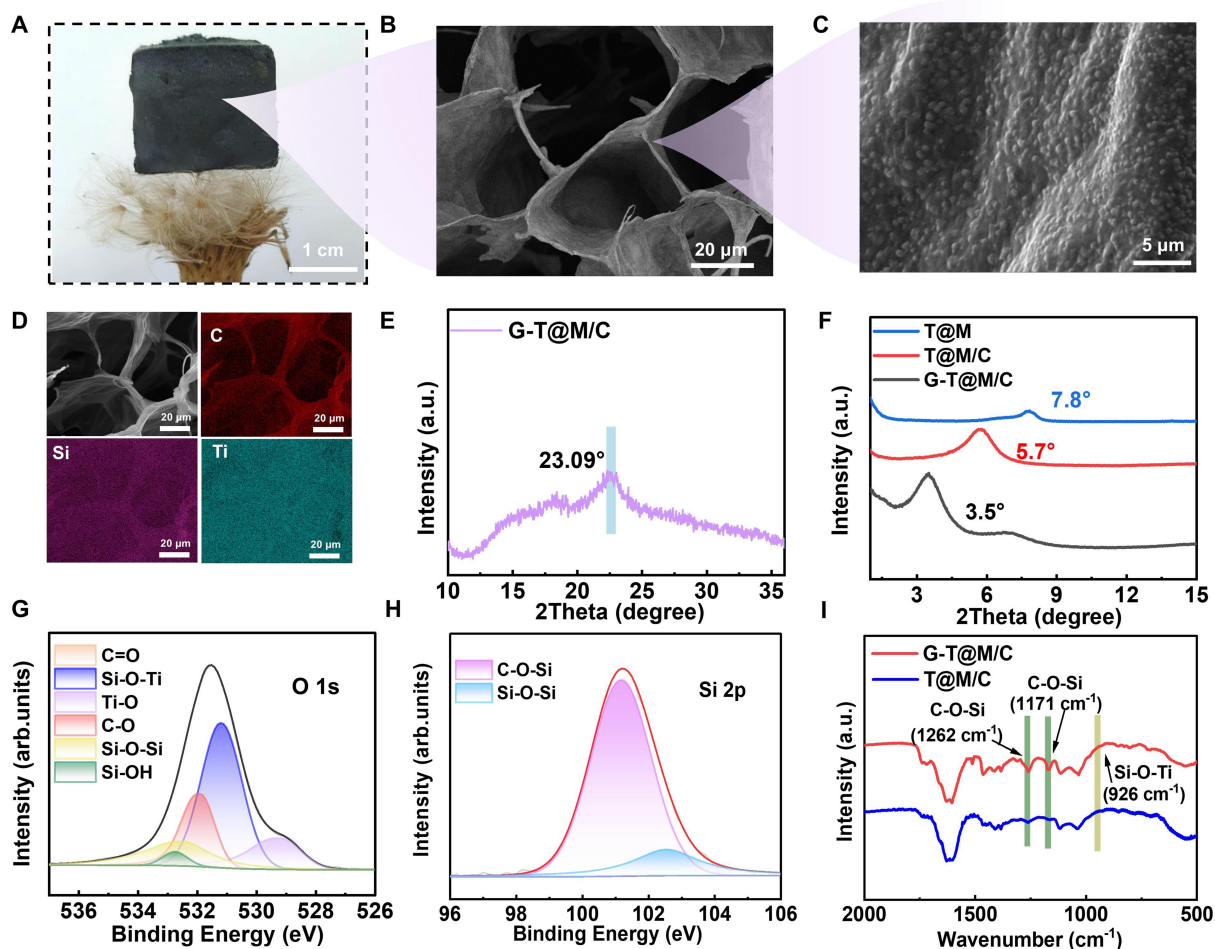


Figure 2. (A) Photo image of the lightweight G-T@M/C aerogel; (B) SEM image of G-T@M/C aerogel; (C) SEM image of oxidized MXene; (D) EDS elemental mapping of C, O, Ti, and Si for the G-T@M/C composite; (E) XRD pattern of G-T@M/C; (F) XRD patterns of T@M, T@M/C, and G-T@M/C; XPS spectra of G-T@M/C in the (G) O 1s and (H) Si 2p region; (I) FTIR curves of G-T@M/C and T@M/C. SEM: Scanning electron microscopy; EDS: energy-dispersive X-ray spectroscopy; XRD: X-ray diffraction; XPS: X-ray photoelectron spectroscopy; FTIR: Fourier transform infrared spectroscopy.

maximum stress of 83.9 kPa and a markedly reduced height loss of 6.42% after 90% compression. The covalent bonds formed between GPTMS and M/C are considerably stronger and more stable than hydrogen bonds^[34,35]. At the same time, the mechanical synergy between CNFs and flexible MXene enables uniform stress distribution across the three-dimensional framework under external load, thereby preventing localized structural failure. Further enhancement was achieved in the G-T@M/C aerogel prepared via GPTMS crosslinking, which exhibits a maximum stress of 79 kPa and a height loss of only 4.61% after 90% compressive strain. The retention of superior mechanical properties likely stems from the introduction of oxygen-containing functional groups onto the MXene surface via controlled oxidation. The oxygen functionalization content modifies the strength and mechanical properties of MXene^[36]. Concurrently, the orientation of interfacial bonds connecting TiO₂ to MXene also influences material strength, with tightly structured interfaces exhibiting the highest fracture resistance^[37,38]. These enhancements effectively compensate for the loss of MXene nanosheet stiffness that mild oxidation may induce^[39,40]. To characterize the reliability of the G-T@M/C aerogel, stress–strain curves were measured under compressive strains ranging from 40% to 90%. As the compressive strain increases, the curves gradually steepen, while the recovery paths nearly overlap at lower strains, indicating excellent shape memory capability of the G-T@M/C aerogel [Figure 3E]. Stress–strain behavior was also evaluated at different strain rates under compression up

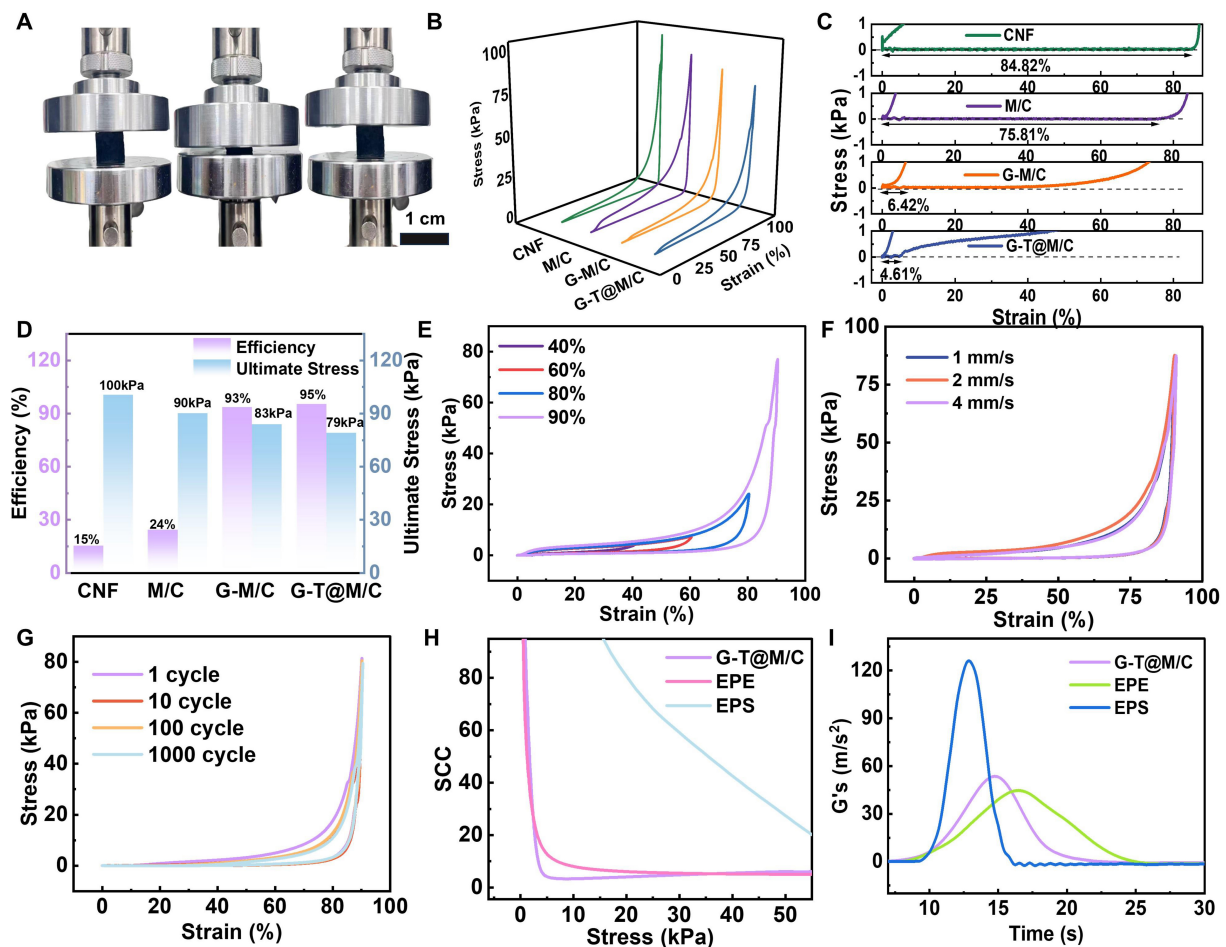


Figure 3. (A) Optical images of G-T@M/C in the initial state, at 90% compressive strain, and after full strain release; (B) Compressive stress–strain curves of CNF, M/C, G-M/C, and G-T@M/C; (C) Partial enlargement of (B); (D) Ultimate stress and height retention of CNF, M/C, G-M/C, and G-T@M/C at 90 % strain; (E) The stress–strain curves of G-T@M/C at different compressive strains; (F) Stress–strain curves of G-T@M/C compressed to 90% at different speeds; (G) Stress–strain profiles of G-T@M/C during the 1st, 10th, 100th, and 1,000th compression–release cycles at 90% strain; (H and I) The SCC and drop acceleration of EPE, EPS, and G-T@M/C foams. CNF: Cellulose nanofiber; SCC: static cushioning coefficient.

to 90%. When the strain rate increases from 1 to 4 mm/s, the peak stress remains largely consistent, stabilizing around 87.6 kPa, which reflects the functional reliability of the aerogel [Figure 3F]. Furthermore, the fatigue resistance of G-T@M/C was assessed via cyclic compression tests. Over 1, 10, 100, and 1,000 compression–release cycles at 0%-90% strain, the stress–strain curves show high repeatability with only a minor reduction in retention, confirming the superelasticity and structural stability of the G-T@M/C composite under long-term cyclic loading [Figure 3G]. After aging for 12 h under the conditions of 75% RH and 70 °C, the G-T@M/C aerogel still exhibited a compressive strength of 80.32 kPa at a 90% compression ratio [Supplementary Figure 8A] and a high rebound rate at 94.3% [Supplementary Figure 8B]. Moreover, we also tested the G-T@M/C aerogel after 100 compression cycles, and it still exhibited high resilience [Supplementary Figure 8C]. Collectively, these findings demonstrate the excellent long-term stability, durability, and reliability of our G-T@M/C aerogel.

Beyond elasticity, the cushioning performance of aerogels is vital for their practical use. The G-T@M/C aerogel was evaluated alongside commercial EPE and EPS foams using the SCC and the acceleration response (G's) in drop tests. The SCC represents the stress magnitude required to resist unit stress energy. As shown in Figure 3H, the G-T@M/C aerogel displays a lower SCC across the 2.4–36.2 kPa range compared to

EPE and EPS, highlighting its superior performance in low-stress scenarios. G-T@M/C aerogel exhibits optimal SCC of 3.32 at 8.3 kPa, while EPE and EPS exhibited optimal SCC values of 4.84 and 2.92 at stresses of 68 and 168 kPa, respectively. These results suggest that under identical low-pressure energy input, the G-T@M/C aerogel absorbs more energy than EPE or EPS and provides enhanced protection. G's represents the acceleration response during a vertical drop from a specific height. A smaller peak acceleration (G's value) means the outer aerogel can effectively absorb impact energy, delivering superior cushioning and protective performance for internal components. In drop tests from 30 cm height, the G's value serves as an indicator of energy absorption; a lower peak implies better cushioning and protection for the contents^[41]. The width of the G's peak reflects the cushioning duration after ground contact^[42,43]. An overly short duration may lead to rapid material rebound and potential secondary impact on the packaged object. As illustrated in [Figure 3I](#), the aerogel exhibits a peak G's value markedly lower than EPS and slightly higher than EPE, confirming its improved capacity to dissipate impact energy. This indicates that G-T@M/C aerogel significantly outperforms EPS in impact energy absorption, while exhibiting performance comparable to EPE.

The internal mechanisms underlying the superelasticity, cushioning capacity, and durability of G-T@M/C aerogel were investigated via SEM analysis. As shown in [Supplementary Figure 9](#), the aerogel possesses a regularly arranged quadrilateral layered architecture. Under 90% compressive strain, the pore walls deform through bending rather than fracture or collapse. Specifically, the walls undergo quadrilateral folding and S-shaped bending [[Supplementary Figure 10](#)], which helps to dissipate impact energy and offer sufficient space for cushioning^[44,45]. After compression recovery, the pore walls recover their original morphology. This microstructure explains how the three-dimensional network formed by GPTMS-crosslinked T@M and CNF achieves superelastic recovery cycling through synergistic material mechanical interactions and covalent crosslinking. After 1,000 compression cycles, the aerogel shows signs of incomplete rebound, decreased structural regularity, and localized fracture of pore walls [[Supplementary Figure 11](#)]. These microstructural changes account for the slight degradation in mechanical strength observed after repeated loading. We also investigate the pore size distribution, porosity, and density data of pure CNF, M/C, G-M/C, and G-T@M/C aerogels, and analyze the correlation between these structural parameters and mechanical/sensing performance. As demonstrated in [Supplementary Figure 6](#) and [Supplementary Table 1](#), the G-T@M/C aerogel exhibits the largest pore size (29.00 μm) and the lowest density (11.11 mg/cm^3). Its excellent mechanical and sensing properties can be reasonably explained by its unique structural features. The large pores provide ample space for deformation, enabling the aerogel to withstand significant compressive strain while maintaining excellent resilience^[46]. Furthermore, the well-oriented MXene/CNF network, combined with the “molecular bridging” or “hinge-like” action of GPTMS (G), effectively suppresses crack propagation and enhances the overall toughness of the composite framework^[47]. This structural design also endows the material with excellent fatigue resistance: under cyclic compression, the large-pore walls have sufficient bending space and do not collide with one another, thereby preventing permanent structural collapse^[48].

Physical pressure monitoring properties

The high electrical conductivity of MXene and the porous architecture of the G-T@M/C aerogel enable its function as a piezoresistive sensor capable of responding to external pressure. [Figure 4A](#) shows the $\Delta I/I_0$ -strain calibration curve, which can be divided into three distinct strain regions with progressively decreasing sensitivity: low strain (0%-25%), medium strain (25%-40%), and high strain (40%-80%), the corresponding sensitivities are 3.9, 1.6, and 0.96, respectively, with matching linear correlation coefficients of 0.99, 0.97, and 0.99. When retested at a high relative humidity of 75%, the $\Delta I/I_0$ -strain calibration curve showed negligible change [[Supplementary Figure 12](#)]. The pressure sensing behavior of MXene aerogels arises from the synergistic coupling between the porous scaffold architecture and the MXene conductive network. The 3D interconnected porous structure serves as a mechanically compliant framework that undergoes progressive pore collapse under compressive loading, rather than abrupt densification^[49]. This

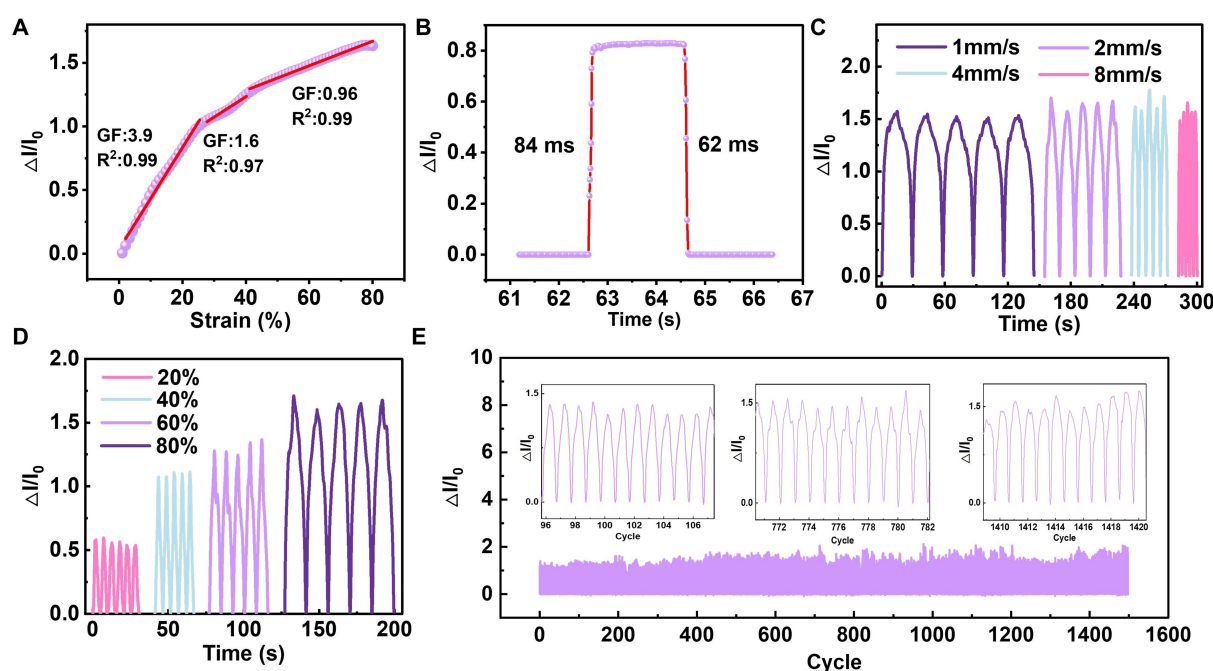


Figure 4. (A) Curve of relative current variation for G-T@M/C across a strain range of 0% to 80%; (B) Response and recovery time of G-T@M/C aerogel; $\Delta I/I_0$ value of G-T@M/C (C) at different compression rates at 80% strain and (D) under different compression strains; (E) Sensing performance stability of G-T@M/C at 80% strain for 1,500 cycles. GF: Gauge factor; R^2 : coefficient of determination.

sequential deformation - initiated from larger macropores and extending to smaller mesopores - ensures a gradual increase in the contact area between adjacent MXene-coated pore walls, thereby extending the linear sensing range and preventing premature signal saturation. Simultaneously, the MXene nanosheets assembled on the pore walls form a continuous conductive network whose electrical resistance is highly sensitive to compressive strain. Upon pressure application, two distinct contributions govern the resistance decrease: (i) the formation of additional conductive pathways as neighboring pore walls come into contact; and (ii) the reduction of inter-sheet tunneling barriers as the distance between MXene nanosheets decreases. These coupled mechanisms enable MXene aerogel-based sensors to achieve both high sensitivity and a wide detection range^[50]. Notably, the hierarchical nature of the porous structure allows for pressure discrimination across a broad spectrum: subtle pressures are detected through initial contacts at isolated pore wall junctions, while higher pressures involve extensive pore collapse and near-complete conductive network percolation^[51]. The sensor also demonstrated rapid response and recovery times of 84 and 62 ms [Figure 4B]. Moreover, when the compression rate rose from 1 to 8 mm/s, the peak $\Delta I/I_0$ stayed nearly constant at approximately 1.6. Figure 4C indicates that the sensing performance of the G-T@M/C aerogel is stable and unaffected by speed. Under a constant strain rate of 2 mm/s, Figure 4D shows the $\Delta I/I_0$ values measured at 20%, 40%, 60%, and 80% strain were 0.83, 1.25, 1.47, and 1.63, respectively, consistent with the calibration curve in Figure 4A. Moreover, G-T@M/C aerogel can distinguish between different objects and different masses of the same object [Supplementary Figure 13]. The sensor's long-term reliability was confirmed through 1,500 compression-release cycles (0%-80% strain), during which it exhibited consistently stable resistance. Steady performance across magnified views of cycles 98-106, 772-782, and 1,410-1,420 further attests to its high durability [Figure 4E].

Gas sensing performance

The sensing performance toward NH_3 is essential for the practical application of the G-T@M/C sensor. The selectivity of the G-T@M/C sensor was evaluated against several common interfering gases. As shown in Figure 5A, the sensor displays a markedly stronger response to 1 ppm ammonia than to typical reducing

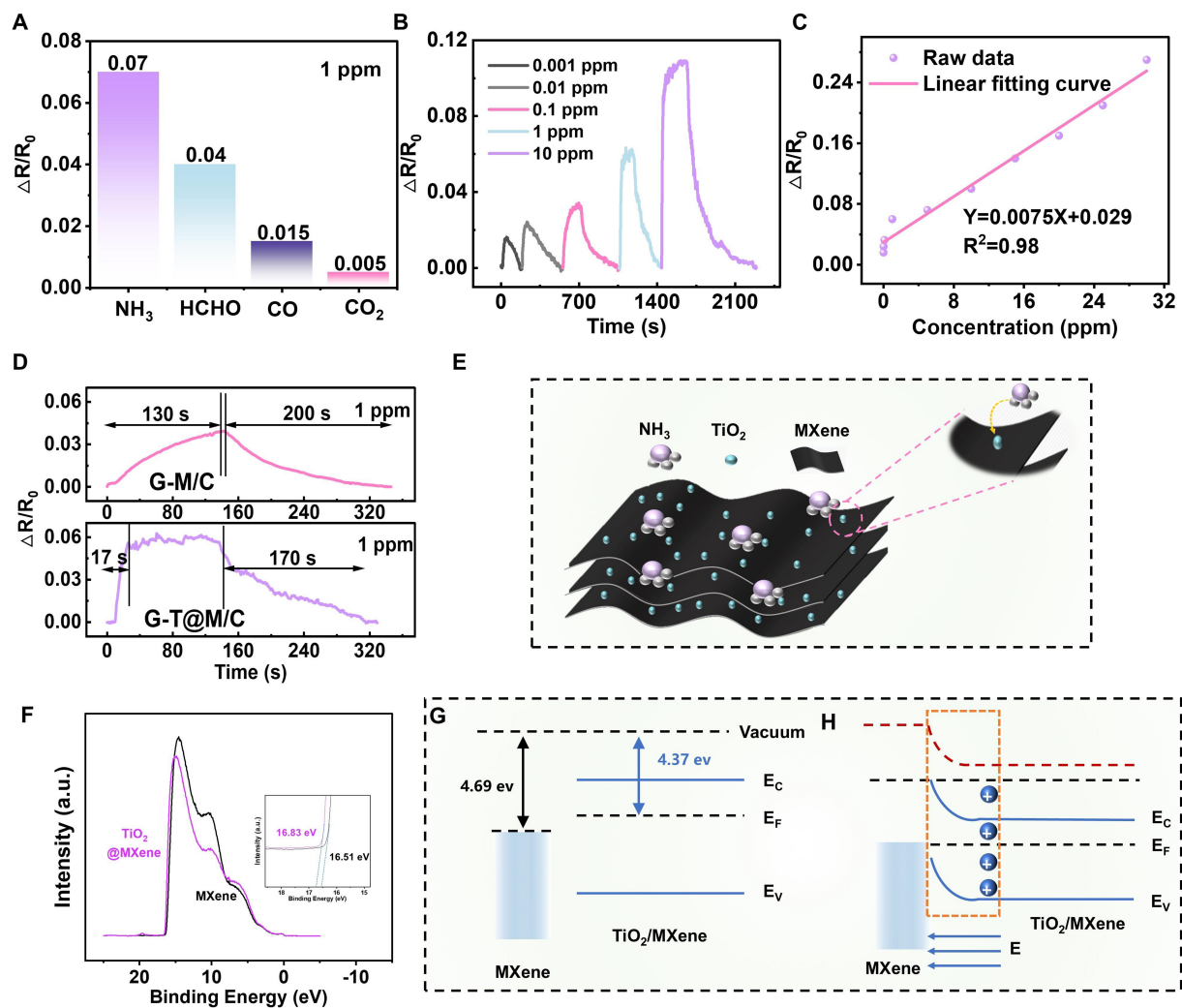


Figure 5. (A) Response values of the G-T@M/C sensor to different gases at the same concentration (1 ppm); (B) Response-recovery curve of the G-T@M/C sensor at different NH_3 concentrations; (C) Resistance response curve of the G-T@M/C sensor at different NH_3 concentrations; (D) Response-recovery curves of the G-M/C sensor (upper) and G-T@M/C (lower) sensor at 1 ppm NH_3 concentration; (E) Schematic diagram of the gas response mechanism of the G-T@M/C sensor; (F) UPS spectra of MXene and TiO_2 @MXene; (G) The alignment of MXene energy levels before and after oxidation demonstrates the formation of a TiO_2 @MXene Schottky barrier; (H) Schematic illustration of charge transfer and band bending mechanisms when G-T@M/C aerogel comes into contact with ammonia gas. UPS: Ultraviolet photoelectron spectroscopy.

gases (formaldehyde, carbon monoxide), or oxidizing gases (carbon dioxide). We also tested typical gases produced during the explosion, such as sulfur dioxide (SO_2) and nitrogen dioxide (NO_2). SO_2 is an acidic, weakly oxidizing gas. On the TiO_2 surface, adsorption is primarily physical, with minimal charge transfer and no significant change in electrical resistance [Supplementary Figure 14A], in line with previous literature. TiO_2 grows *in situ* on the MXene surface, forming a metal–semiconductor heterojunction: the MXene provides high electrical conductivity and an electron reservoir, while TiO_2 (n-type semiconductor) provides adsorption sites. NO_2 (a strong oxidizing agent) captures electrons on the TiO_2 surface, while interfacial charge transfer occurs from MXene to TiO_2 , significantly altering the material’s electrical conductivity (increased resistance) and generating a strong sensing signal [Supplementary Figure 14B]. Figure 5B presents the resistance and response curves of the sensor upon exposure to NH_3 at concentrations ranging from 0.001 to 10 ppm at room temperature. A noise analysis was conducted on the response to 1 ppb of ammonia, confirming the accuracy of the 1 ppb reading [Supplementary Figure 15]. A linear relationship between the

resistance response and NH_3 concentration is observed from 0.001 to 30 ppm [Figure 5C], with a high correlation coefficient ($R^2 = 0.98$), indicating a broad sensing range and excellent response linearity (The 0.001–10 ppm range consists of a set of arbitrarily selected concentration points intended to demonstrate the sensor's step response characteristics at various typical concentration levels (as shown in Figure 5B). Because there are too few data points in the 0.001–10 ppm range, the 0.001–30 ppm range was specifically designed to evaluate the sensor's linear response behavior). Subsequently, the transient response of G-T@M/C to 10 ppm NH_3 gas was investigated under various humidities, ranging from dry air to 85% relative humidity [Supplementary Figure 16]. In all cases, the aerogel's resistance increased as NH_3 was adsorbed. NH_3 is highly soluble in water; it is rapidly absorbed by the water film on the material surface and reacts with water to form ammonium ions (NH_4^+). The mobility of NH_4^+ is much lower than that of H^+ ^[52], resulting in a significant decrease in the efficiency of the ionic conduction pathway. Furthermore, the generated NH_4^+ ions react with pre-adsorbed O_2^- and OH^- ions on the material surface, consuming a large number of conductive ions ($\text{H}^+/\text{H}_3\text{O}^+$). The ionic conduction pathways are severely disrupted, causing a sharp drop in carrier concentration and a substantial increase in resistance. The presence of moisture effectively provides ammonia with an efficient "reaction platform", resulting in a much greater increase in resistance compared to dry conditions^[53]. Figure 5D compares the response–recovery profiles of G-M/C and G-T@M/C sensors to 1 ppm NH_3 . The G-T@M/C sensor exhibited a $\Delta R/R_0$ value of approximately 0.062, about 1.58 times higher than that of G-M/C (0.039), along with a more stable baseline resistance. Furthermore, the response/recovery times for the G-M/C and G-T@M/C gas sensors were approximately 130 s/200 s and 17 s/170 s, respectively. The response/recovery time of the G-T@M/C gas sensor was 0.12 times that of the G-M/C sensor for response and 0.85 times for recovery. According to the experimental findings, we propose a sensing mechanism to explain the enhanced sensitivity of the G-T@M/C sensor [Figure 5E]. To verify whether a Schottky barrier forms at the TiO_2 /MXene interface, ultraviolet photoelectron spectroscopy (UPS) measurements were conducted [Figure 5F]. The work function of pristine MXene was determined to be 4.69 eV, which decreased to 4.37 eV after oxidation. This reduction of approximately 0.32 eV indicates the formation of an interfacial Schottky barrier heterojunction, attributed to the intrinsically lower work function of TiO_2 and the resulting band alignment. The built-in electric potential at this heterointerface introduces a depletion layer, thereby modulating carrier transport. Upon exposure to electron-donating NH_3 molecules, the barrier height is dynamically reduced, enhancing interfacial conductivity and amplifying the resistive response of the sensor. When n-type TiO_2 is deposited on the MXene surface, electrons transfer from the TiO_2 conduction band to MXene, establishing an internal electric field at their interface^[54]. Upon air contact, oxygen molecules capture electrons according to Equations (5) and (6)^[55] to form oxygen anions, reducing the electron density on the TiO_2 surface^[56].



Conversely, in an NH_3 environment, NH_3 molecules interact with adsorbed O_2^- anions via Equation (7)^[55], capturing electrons and enhancing the electric field, thereby increasing resistance. Relevant investigations reveal that the adsorption energy of small molecules on the TiO_2 surface presents a positive linear relationship with their HOMO energy levels^[3,57]. Figures 5G and H illustrate the proposed ammonia sensing mechanism. Partial oxidation of MXene leads to the *in-situ* formation of TiO_2 nanoparticles on the MXene surface, thereby constructing a Schottky barrier heterojunction. As shown in Figure 5G, the Fermi level of MXene lies below the conduction band of TiO_2 , which drives electron transfer and induces upward band bending of TiO_2 at equilibrium. In this heterostructure, the TiO_2 -rich regions serve as the main NH_3

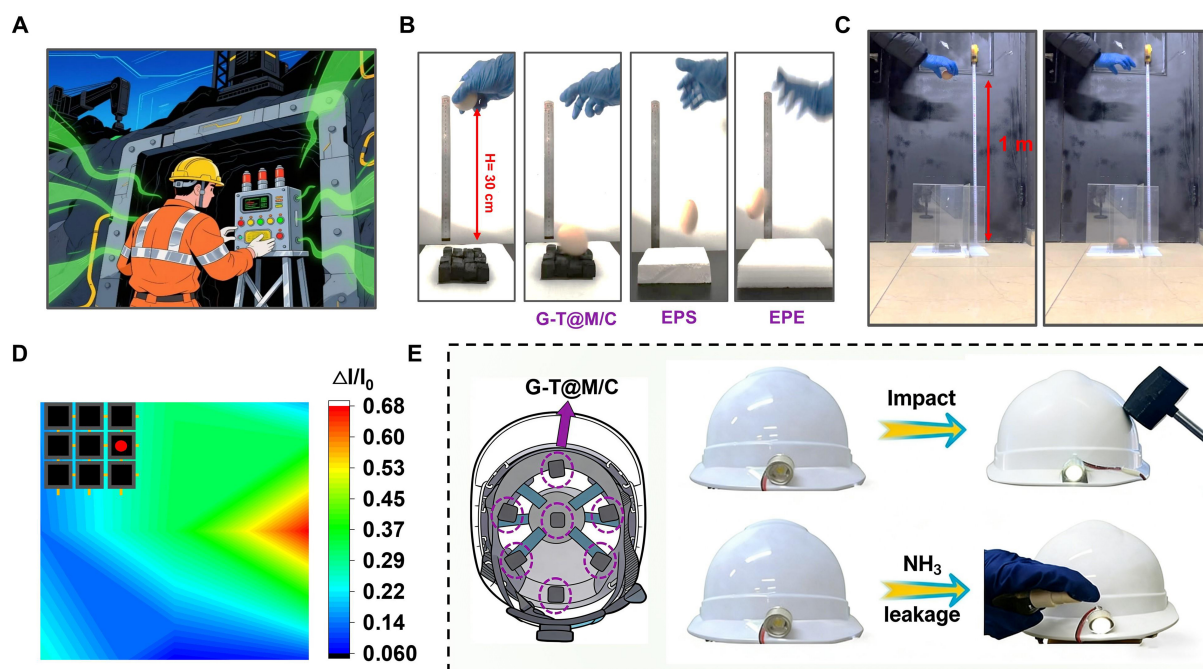


Figure 6. (A) Schematic diagram of the intelligent protective safety helmet structure based on G-T@M/C aerogel; (B) Photographs of eggs after drop tests using G-T@M/C aerogel, EPE and EPS as cushioning liners; (C) An egg drop test from a height of 1 meter was conducted using G-T@M/C aerogel as a cushioning pad; (D) Photograph of a sensor array detecting a 100 g weight and the corresponding pressure distribution relative to the change in electric current; (E) Integrated circuit display system for monitoring pressure and ammonia gas. Variation in LED bulb brightness within integrated circuits under pressure. Variation in LED bulb brightness within integrated circuits in ammonia gas conditions. LED: Light-emitting diode.

adsorption sites^[3], while the remaining MXene network provides a conductive pathway. Accordingly, electron donation from adsorbed NH_3 on TiO_2 effectively modulates the TiO_2 /MXene barrier and amplifies the resistance change across the junction network. Under exposure to NH_3 , the adsorbed electron-donating molecules neutralize the holes in MXene and reduce the hole concentration. Consequently, the built-in electric field is enhanced, the Schottky barrier is strengthened, electron transport becomes more difficult, and the overall resistance increases. Therefore, introducing TiO_2 onto the MXene surface to create a heterointerface promotes effective charge separation, which amplifies the electrical signal change upon NH_3 adsorption. This mechanism enhances the material's responsiveness to NH_3 , thereby improving the sensitivity of ammonia gas detection. Evaluated by the key performance metrics of rebound rate, Compression ratio, piezoresistive sensitivity, gas detection limit, and response time, this work shows distinct advantages over state-of-the-art CNF/MXene dual-mode aerogels [Supplementary Table 2 and Supplementary Figure 17]^[23,46,58,59].

Application

Owing to its mechanical properties and multifunctional sensing capabilities, the G-T@M/C aerogel can be integrated into the inner structure of safety helmets to provide both impact protection and gas leakage warning [Figure 6A]. Designed for blasting personnel, these helmets not only shield wearers from physical hazards such as falling rocks but also continuously detect ambient ammonia levels. The cushioning performance of the G-T@M/C aerogel was evaluated against common materials (EPE and EPS) using a drop test with eggs. When dropped from a height of 30 cm, eggs impacting the EPE and EPS surfaces rebounded and sustained secondary damage. In contrast, eggs dropped onto the G-T@M/C aerogel exhibited no rebound and remained intact, demonstrating its superior energy absorption [Figure 6B]. To visually evaluate the cushioning protection performance of G-T@M/C, raw eggs were dropped from a height of 100 cm onto

surfaces of G-T@M/C aerogel. As shown in the two sequential images in [Figure 6C](#), eggs dropped onto G-T@M/C exhibited no rebound and remained intact, clearly demonstrating the aerogel's superior energy absorption in practical scenarios [[Supplementary Video 1](#)]. Additionally, a flexible 3×3 G-T@M/C aerogel array was assembled, with a 2×2 cm² active pixel region and an overall device dimension of 8×8 cm² [[Figure 6D](#)]. When a 100 g weight was placed within the pressure testing zone (with a schematic at top left), the output resistance signals from the sensing pixels accurately reconstructed the pressure distribution at the contact area. Furthermore, this aerogel was uniformly distributed inside the safety helmet, with each aerogel unit connected in series to a light-emitting diode (LED) to provide a visual indication of external mechanical pressure and ammonia concentration. External impacts are simulated through hammer strikes: when either side of the helmet is struck, the corresponding warning LED on that side immediately turns on. For gas detection, a leak is simulated by evaporating a 10 ppm ammonia solution, triggering the corresponding indicator light to illuminate and thereby providing an effective early warning [[Figure 6E](#) and [Supplementary Video 2](#)].

CONCLUSIONS

In summary, this study successfully developed a multifunctional composite aerogel for intelligent safety protection in hazardous environments. This aerogel exhibits high mechanical resilience, retaining 95% rebound capacity at 90% strain along with superior cushioning performance. It also realizes dual pressure and gas sensing, with a detection limit of 1 ppb for ammonia. These properties allow seamless integration into safety helmets to provide impact protection, pressure sensing, and real-time toxic gas warning. This work offers a promising strategy for designing next-generation intelligent protective equipment that combines physical safeguarding with environmental monitoring.

DECLARATIONS

Authors' contributions

Conceptualization, methodology, formal analysis, investigation, writing - original draft, writing - review and editing, visualization: Mao, N.

Conceptualization, methodology, validation, formal analysis, investigation, data curation, writing - original draft, visualization: Yuan, J.

Conceptualization, methodology: Li, X.

Validation, investigation, resources, data curation, writing - review and editing, visualization: Ren, G.

Visualization: Jia, C.

Data curation: Huang, J.; Song, Y.

Supervision: Liu, H.; Yang, S.

Conceptualization, investigation, writing - review and editing, supervision, project administration, funding acquisition: Liu, Y.

Supervision, funding acquisition: Cheng, B.

Availability of data and materials

The data that support the findings of this study are available from the corresponding author upon reasonable request.

AI and AI-assisted tools statement

During the preparation of this work, the authors used AI tool ChatGPT (version 5.4, released 2026-03-05) due to language polishing and the generation of schematic illustrations ([Figure 6A](#) and the plant elements in [Figure 1A](#)). The authors reviewed and edited all AI-generated content and accept full responsibility for the published material.

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Conflicts of interest

Huang, J. and Song, Y. are affiliated with the Electric Power Research Institute of Yunnan Power Grid Co., Ltd. The other authors declare no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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Supplementary Materials

[Supplementary Materials](#)

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