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# Study on modification and electrochemical properties of $\text{CoS}_2$ -based cathode materials†

 Rongrui Xu,‡ Yicheng Wei,‡ Ling Ding, Hongliang Li, Yuezhen Hua, Yong Cao\* and Yanhua Cui \*

Thermal batteries are widely used in defense and emergency fields due to their long storage periods and high power characteristics. Among them, cobalt disulfide ( $\text{CoS}_2$ ), as a cathode material, attracts attention because of its high decomposition temperature, excellent discharge capacity, and good electrical conductivity. However, research has found that this material is prone to structural decomposition and phase transition under high-temperature working conditions and long-term storage, leading to critical issues such as electrode activity decay and battery performance degradation. This study innovatively adopts atomic layer deposition (ALD) technology to construct a nanoscale  $\text{Al}_2\text{O}_3$  coating on the  $\text{CoS}_2$  surface, and systematically analyzes it through multi-dimensional characterization methods such as X-ray diffraction (XRD) and scanning electron microscopy (SEM). Experimental results show that after an 8 days simulated storage test, the discharge specific capacity of unmodified  $\text{CoS}_2$  decreased to 70% of its initial value, while the  $\text{Al}_2\text{O}_3/\text{CoS}_2$  composite material maintained a capacity retention rate of 90%. This study confirms that  $\text{Al}_2\text{O}_3$  surface modification technology can effectively inhibit the structural degradation of  $\text{CoS}_2$ , significantly enhancing the material's environmental tolerance and electrochemical stability.

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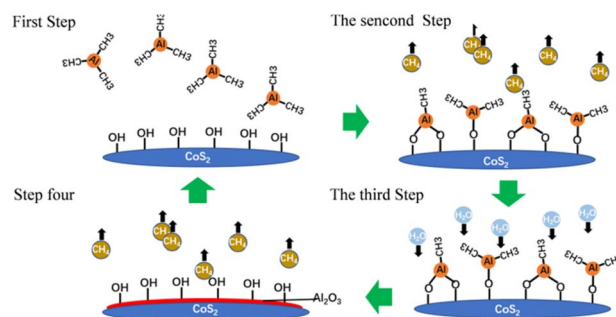
## 1. Introduction

Thermal batteries, as non-rechargeable electrochemical devices activated by heat, have become indispensable power sources for military systems such as missiles and torpedoes, as well as critical civilian applications like emergency backup and deep-well drilling, due to their exceptionally long shelf life (5 to 20 years) and instantaneous high-power discharge capability.<sup>1</sup> These batteries operate through thermally activated molten salt electrolytes (*e.g.*,  $\text{LiCl-KCl}$ ,  $\text{LiBr-LiCl-LiF}$ , *etc.*), maintaining functionality at extreme temperatures, which distinguishes them from traditional energy storage systems.<sup>2</sup>

The cathode material, as the core component of thermal batteries, directly determines the energy density and operational stability of the battery. Transition metal disulfides ( $\text{FeS}_2$ ,  $\text{CoS}_2$ , *etc.*) have emerged as promising candidates, superior to traditional oxides and halides.<sup>3,4</sup> Notably,  $\text{CoS}_2$  exhibits excellent properties, including high theoretical capacity, high decomposition temperature, and metallic-level electronic conductivity.<sup>5,6</sup> However, recent research has shown that  $\text{CoS}_2$  undergoes progressive structural degradation both during high-

temperature operation and long-term environmental storage. At high temperatures, sulfur loss due to gaseous  $\text{S}_2$  emissions leads to phase transitions (*e.g.*,  $\text{CoS}_2 \rightarrow \text{Co}_9\text{S}_8$ ), while room-temperature aging causes surface oxidation and sulfur disproportionation, collectively resulting in capacity fade and voltage fluctuation.<sup>7,8</sup> These issues stem from the inherently weak Co-S bonds and anisotropic lattice expansion during lithiation/delithiation.<sup>9</sup> Despite its technical urgency, the atomic decomposition pathways of  $\text{CoS}_2$  remain poorly understood, with limited strategies to mitigate its instability.<sup>10,11</sup>

Existing methods, such as particle size optimization or elemental doping (*e.g.*, with Ni, Cu), can only partially inhibit sulfur sublimation but fail to address interfacial corrosion mechanisms.<sup>12,13</sup> Moreover, most stability assessments neglect


 Fig. 1 Schematic of the ALD preparation  $\text{CoS}_2@/\text{Al}_2\text{O}_3$  process.

Institute of Electronic Engineering, China Academy of Engineering Physics, Mianyang 621900, P. R. China. E-mail: cuiyanhua@netease.com

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‡ These authors contributed equally to this work.



the coupling effects between thermal cycling and environmental aging, leading to an overestimation of performance in practical scenarios.<sup>14,15</sup> In our previous study, it was demonstrated that CoS<sub>2</sub> modified with Al<sub>2</sub>O<sub>3</sub> nanoparticles synthesized *via* a facile wet-chemical method exhibits exceptional electrochemical performance. To further investigate whether analogous enhancement effects can be achieved through the deposition of Al<sub>2</sub>O<sub>3</sub> thin films *via* atomic layer deposition (ALD) or magnetron sputtering, this work systematically explores the

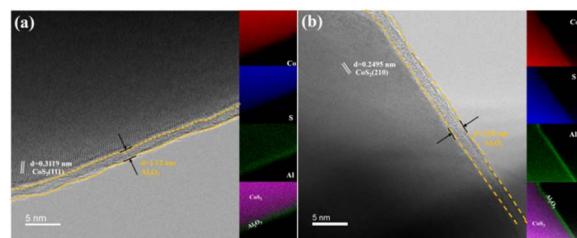


Fig. 3 TEM images: (a) Al<sub>2</sub>O<sub>3</sub>@CoS<sub>2</sub>-10s; (b) Al<sub>2</sub>O<sub>3</sub>@CoS<sub>2</sub>-30s.

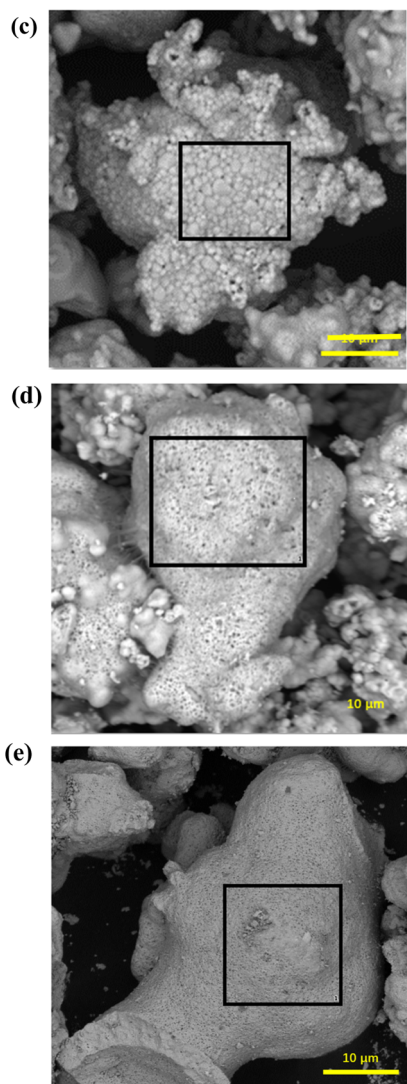
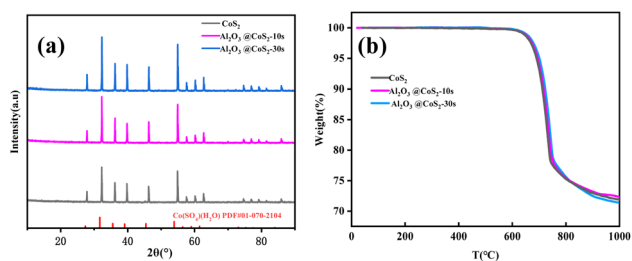


Fig. 2 CoS<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>@CoS<sub>2</sub>-10s, Al<sub>2</sub>O<sub>3</sub>@CoS<sub>2</sub>-30s: (a) XRD Patterns; (b) TG Curves; (c–e) EDS elemental distribution maps of Al<sub>2</sub>O<sub>3</sub>@CoS<sub>2</sub>-10s, Al<sub>2</sub>O<sub>3</sub>@CoS<sub>2</sub>-30s, and CoS<sub>2</sub>.

interfacial engineering and electrochemical mechanisms of these vapor-phase fabricated Al<sub>2</sub>O<sub>3</sub>/CoS<sub>2</sub> heterostructures.<sup>16</sup> To address these gaps, we propose an innovative approach: coating CoS<sub>2</sub> particles with an Al<sub>2</sub>O<sub>3</sub> layer using atomic layer deposition (ALD) technology. The Al<sub>2</sub>O<sub>3</sub> coating is hypothesized to serve as a physical barrier that mitigates adverse interfacial reactions and structural collapse during thermal cycling and long-term storage. Systematic studies, including X-ray diffraction (XRD), thermogravimetry (TG), and scanning electron microscopy (SEM), were conducted to elucidate the structure and thermal stability of the modified material. Surprisingly, after 8 days of simulated storage testing, alumina-coated cobalt disulfide retained 90% of its initial discharge capacity, while the uncoated cobalt disulfide significantly dropped to 70%. These findings emphasize the effectiveness of alumina coating in maintaining the electrochemical integrity of cobalt disulfide, providing a material-level solution for enhancing the longevity and reliability of the next generation of thermal batteries. This work opens the path for designing robust electrode materials suitable for energy storage systems in extreme conditions.

## 2. Experimental

### 2.1 Material preparation

In this study, CoS<sub>2</sub> material was purchased from Central South University with a purity of 99.9%. An Al<sub>2</sub>O<sub>3</sub> coating was prepared on the surface of the CoS<sub>2</sub> electrode through atomic layer deposition (ALD). The deposition temperature ranged from 250–300 °C. Trimethylaluminum (Al(CH<sub>3</sub>)<sub>3</sub>) was used as the precursor for depositing Al<sub>2</sub>O<sub>3</sub>, with a pulse time of 0.06 seconds and an N<sub>2</sub> purge time of 30 seconds. After completing

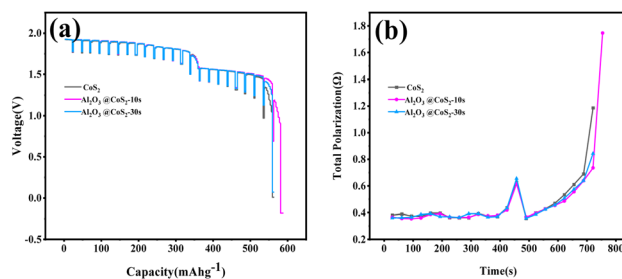


Fig. 4 Comparison of discharge performance among CoS<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>@CoS<sub>2</sub>-10s, and Al<sub>2</sub>O<sub>3</sub>@CoS<sub>2</sub>-30s: (a) specific capacity diagram; (b) polarization internal resistance diagram.



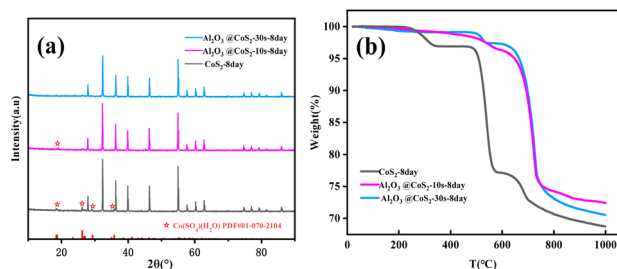


Fig. 5  $\text{CoS}_2$ ,  $\text{Al}_2\text{O}_3@ \text{CoS}_2$ -10s,  $\text{Al}_2\text{O}_3@ \text{CoS}_2$ -30s: (a) TG curves; (b) XRD patterns.

10 cycles and 30 cycles, two types of  $\text{CoS}_2$  materials with different coating amounts were obtained, denoted as  $\text{Al}_2\text{O}_3@ \text{CoS}_2$ -10s and  $\text{Al}_2\text{O}_3@ \text{CoS}_2$ -30s, respectively.

## 2.2 Material characterization

The X-ray diffractometer (XRD) was used to collect the XRD pattern information of the tested samples at room temperature (scan range:  $10\text{--}90^\circ$ , heating rate:  $10 \text{ K min}^{-1}$ , scan speed:  $16^\circ \text{ min}^{-1}$ ; atmosphere: Ar). Scanning Electron Microscopy (SEM) was employed to observe the morphology of the  $\text{CoS}_2$  material. Elemental distribution characterization of the samples was performed using an Energy Dispersive X-ray Spectrometer (EDS). A synchronous thermal analyzer was used to collect the TG-DSC information during the thermal decomposition process of  $\text{CoS}_2$  (heating rates: 5, 10, 15,  $20 \text{ K min}^{-1}$ ; atmosphere:  $\text{N}_2$ ; gas flow rate:  $120 \text{ ml min}^{-1}$ ; temperature range:  $30 \text{ }^\circ\text{C}$  to  $1000 \text{ }^\circ\text{C}$ ).

## 2.3 The single thermal battery fabrication and measurements

All pretreatment operations for electrode materials were conducted inside a glove box filled with Ar atmosphere. The anode

(0.52 g) was LiB alloy (55 wt% Li, Ruilin), the separator (0.8 g) consisted of 50 wt% electrolyte (45 wt% LiCl-55 wt% KCl) and 50 wt% MgO and the cathodes (0.4 g) consisted of 80 wt% active material and 20 wt% electrolyte, all were stacked to form a cell of 32 mm under a pressure of 120 MPa in a drying room with a dew-point temperature below  $-50 \text{ }^\circ\text{C}$ . The single cells were discharged at  $500 \text{ }^\circ\text{C}$  with a constant current of  $100 \text{ mA cm}^{-2}$  (with a period of 30 s) and a pulsed current of  $500 \text{ mA cm}^{-2}$  (with a period of 1 s) using a Land battery test system (CT2001A, LAND). The total polarization, that is the resistance of a single thermal battery (Rb), is calculated as follows.

## 3. Results and discussion

Fig. 2a presents the X-ray Diffraction (XRD) patterns of  $\text{CoS}_2$ ,  $\text{Al}_2\text{O}_3@ \text{CoS}_2$ -10s, and  $\text{Al}_2\text{O}_3@ \text{CoS}_2$ -30s. All three samples exhibit characteristic peaks of  $\text{CoS}_2$  without the appearance of any impurity phases, indicating that the coated materials have not undergone decomposition. However, the characteristic peaks of  $\text{Al}_2\text{O}_3$  are not observable in the  $\text{Al}_2\text{O}_3@ \text{CoS}_2$  samples, which is attributed to the very thin layer of  $\text{Al}_2\text{O}_3$  deposited by ALD or the amorphous nature of the coated  $\text{Al}_2\text{O}_3$ . Fig. 1b displays the Thermogravimetric (TG) curves of the three samples, with thermal decomposition temperatures all at  $650 \text{ }^\circ\text{C}$ . The coating of  $\text{Al}_2\text{O}_3$  does not alter the thermal decomposition temperature of the material, making it suitable as a cathode material for thermal batteries. SEM (Scanning Electron Microscope) and EDS (Energy Dispersive Spectrometer) analyses were conducted to investigate the morphology and surface element composition of  $\text{CoS}_2$ ,  $\text{Al}_2\text{O}_3@ \text{CoS}_2$ -10s, and  $\text{Al}_2\text{O}_3@ \text{CoS}_2$ -30s, as shown in Fig. 2. Compared to the raw material, the morphologies of  $\text{Al}_2\text{O}_3@ \text{CoS}_2$ -10s and  $\text{Al}_2\text{O}_3@ \text{CoS}_2$ -30s coated by ALD do not change, further confirming that the thickness of the coating layer is at the nanoscale and thus not discernible in SEM images. However, EDS clearly shows the

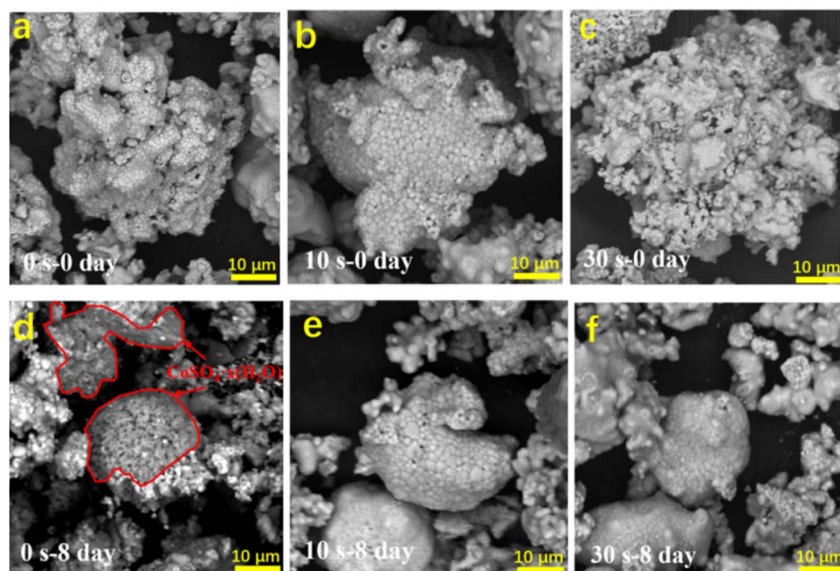


Fig. 6 Comparison of  $\text{CoS}_2$  before and after storage: (a and d); Comparison of  $\text{Al}_2\text{O}_3@ \text{CoS}_2$ -10s before and after storage: (b and e); Comparison of  $\text{Al}_2\text{O}_3@ \text{CoS}_2$ -30s before and after storage: (c and f).



uniform distribution of Al and O on the particle surface with a consistent distribution pattern, indicating the presence of an  $\text{Al}_2\text{O}_3$  coating layer on the surface of  $\text{CoS}_2$ .

To further investigate whether  $\text{Al}_2\text{O}_3$  was successfully synthesized and coated on the surface of  $\text{CoS}_2$ , we characterized the coated samples using TEM, with the results presented in Fig. 3. Through EDS scanning analysis, the upper left section of Fig. 3a and the lower left section of Fig. 3b depict  $\text{CoS}_2$  particles. Calculations reveal that the interplanar spacings are 0.3119 nm and 0.2495 nm, corresponding to the (111) and (210) crystal planes of  $\text{CoS}_2$ , respectively. A uniform layer of amorphous  $\text{Al}_2\text{O}_3$  is coated on the surface of  $\text{CoS}_2$ . The thickness of the  $\text{Al}_2\text{O}_3$  coating after 10 cycles is 1.12 nm, and after 30 cycles, it is 1.89 nm, indicating that a greater number of cycles results in a thicker  $\text{Al}_2\text{O}_3$  coating.

Three materials, namely  $\text{CoS}_2$ ,  $\text{Al}_2\text{O}_3@ \text{CoS}_2$ -10s, and  $\text{Al}_2\text{O}_3@ \text{CoS}_2$ -30s, were used to fabricate thermal battery cells for pulse discharge testing at 500 °C. The discharge conditions were as follows: a background current of 100  $\text{mA cm}^{-2}$  was applied for 30 seconds, followed by a pulse current of 500  $\text{mA cm}^{-2}$  for 1 second. Fig. 4 shows that the first discharge voltage platform for all three materials is approximately 1.9 V, with a discharge capacity of around 500  $\text{mA h g}^{-1}$  when the voltage drops to 1.5 V. The polarization internal resistance is also nearly identical. This indicates that coating with  $\text{Al}_2\text{O}_3$  has no significant effect on the discharge voltage or electrical conductivity of  $\text{CoS}_2$ .

After storing the three materials, namely  $\text{CoS}_2$ ,  $\text{Al}_2\text{O}_3@ \text{CoS}_2$ -10s, and  $\text{Al}_2\text{O}_3@ \text{CoS}_2$ -30s, in air at a constant temperature of 25 °C with 70% relative humidity for 8 days, they were then vacuum-dried at 100 °C for 24 hours. These samples are

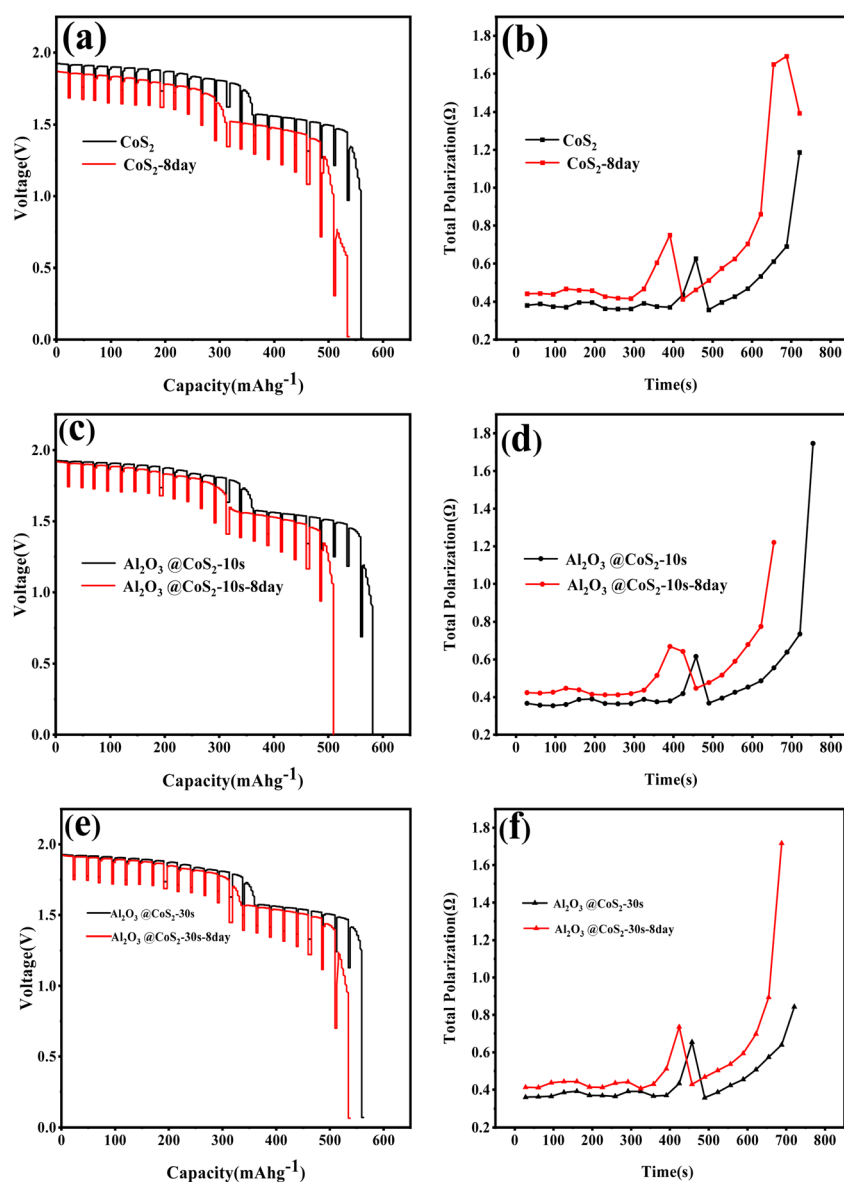


Fig. 7 (a) Fig. 6 displays the specific capacity and polarization internal resistance graphs for  $\text{CoS}_2$ -8day (a and b),  $\text{Al}_2\text{O}_3@ \text{CoS}_2$ -10s-8day (c and d), and  $\text{Al}_2\text{O}_3@ \text{CoS}_2$ -30s-8day (e and f) respectively.



hereafter referred to as CoS<sub>2</sub>-8day, Al<sub>2</sub>O<sub>3</sub>@CoS<sub>2</sub>-10s-8day, and Al<sub>2</sub>O<sub>3</sub>@CoS<sub>2</sub>-30s-8day, respectively. Fig. 5a presents the XRD patterns of the stored samples. The uncoated raw material exhibits obvious characteristic peaks of CoSO<sub>4</sub>·H<sub>2</sub>O after storage, indicating decomposition of the material. Although Al<sub>2</sub>O<sub>3</sub>@CoS<sub>2</sub>-10s-8day also shows characteristic peaks of CoSO<sub>4</sub>·H<sub>2</sub>O, the intensity of these peaks is very weak. In contrast, Al<sub>2</sub>O<sub>3</sub>@CoS<sub>2</sub> does not exhibit any characteristic peaks of CoSO<sub>4</sub>·H<sub>2</sub>O, suggesting no decomposition or minimal decomposition. Both observations demonstrate that coating CoS<sub>2</sub> with Al<sub>2</sub>O<sub>3</sub> using ALD technology can significantly enhance the storage stability of CoS<sub>2</sub>.

Fig. 5b displays the TG curves of the three materials after storage. All three materials undergo decomposition after 8 days of storage; however, compared to the raw material, the degree of decomposition of the Al<sub>2</sub>O<sub>3</sub>@CoS<sub>2</sub> coated samples is greatly reduced, with Al<sub>2</sub>O<sub>3</sub>@CoS<sub>2</sub>-30s exhibiting the lowest degree of decomposition. The mass percentages corresponding to the thermal decomposition platform of CoS<sub>2</sub> are 78 wt%, 95 wt%, and 97 wt%, respectively. The comparison of storage stability under the same conditions is as follows: CoS<sub>2</sub> < Al<sub>2</sub>O<sub>3</sub>@CoS<sub>2</sub>-10s < Al<sub>2</sub>O<sub>3</sub>@CoS<sub>2</sub>-30s. The atomic layer deposition (ALD)-engineered nanoscale Al<sub>2</sub>O<sub>3</sub> coating on the CoS<sub>2</sub> surface consists of an ultrathin protective layer, which accounts for the nearly identical final residual mass percentages observed in thermogravimetric (TG) analysis. In contrast, the uncoated pristine CoS<sub>2</sub> exhibited an earlier decomposition temperature due to the absence of this protective barrier, rendering it more susceptible to thermal degradation. This observation further demonstrates that the Al<sub>2</sub>O<sub>3</sub>-coated CoS<sub>2</sub> significantly enhances the stability of thermal batteries, as evidenced by the delayed decomposition behavior and improved electrochemical performance.

Fig. 6 presents comparative SEM images of CoS<sub>2</sub>-8day, Al<sub>2</sub>O<sub>3</sub>@CoS<sub>2</sub>-10s, and Al<sub>2</sub>O<sub>3</sub>@CoS<sub>2</sub>-30s before and after 8 days of storage. After storage, decomposition products (CoSO<sub>4</sub>·H<sub>2</sub>O, highlighted in red regions) were observed on the surface of uncoated CoS<sub>2</sub> particles. In contrast, comparative analysis of images e and f reveals no significant degradation for the Al<sub>2</sub>O<sub>3</sub>-coated samples under identical storage conditions, further confirming that the ALD-deposited Al<sub>2</sub>O<sub>3</sub> layer significantly enhances the storage stability of CoS<sub>2</sub>. Supporting high-magnification SEM images (provided in the ESI†) unambiguously verify the presence of CoSO<sub>4</sub> on the CoS<sub>2</sub> surface, corroborating the role of the Al<sub>2</sub>O<sub>3</sub> coating in mitigating degradation.

As shown in Fig. 7, a comparison of the discharge performance of the three materials after 8 days of storage reveals the following: the first platform voltage of CoS<sub>2</sub>-8day, Al<sub>2</sub>O<sub>3</sub>@CoS<sub>2</sub>-10s-8day, and Al<sub>2</sub>O<sub>3</sub>@CoS<sub>2</sub>-30s-8day decreased by approximately 0.1 V, 0.03 V, and 0.01 V, respectively, compared to before storage. The discharge specific capacities at 1.5 V decreased by about 30%, 16%, and 10%, respectively. The polarization internal resistances increased by approximately 0.07 Ω, 0.05 Ω, and 0.05 Ω, respectively. These results indicate that coating with Al<sub>2</sub>O<sub>3</sub> significantly enhances the storage stability of CoS<sub>2</sub>.

The reasons why coating CoS<sub>2</sub> with Al<sub>2</sub>O<sub>3</sub> using ALD improves its storage stability without compromising its discharge performance and thermal stability may be as follows: the ALD coating method results in a uniform and very thin (nanoscale) protective layer of Al<sub>2</sub>O<sub>3</sub> on the surface of CoS<sub>2</sub>. This layer effectively reduces the contact between H<sub>2</sub>O and CoS<sub>2</sub>, thereby lowering the rate of decomposition of CoS<sub>2</sub> when exposed to water and oxygen, and ultimately enhancing storage stability. At high temperatures, due to thermal expansion and contraction or the insertion of lithium ions into Al<sub>2</sub>O<sub>3</sub>@CoS<sub>2</sub>, the particles of the Al<sub>2</sub>O<sub>3</sub>@CoS<sub>2</sub> cathode material expand, causing the surface Al<sub>2</sub>O<sub>3</sub> layer to crack. This allows lithium ions to normally insert into CoS<sub>2</sub> during discharge, thus not affecting the discharge performance of CoS<sub>2</sub>. Additionally, since the thermal decomposition temperature of Al<sub>2</sub>O<sub>3</sub> is much higher than that of CoS<sub>2</sub>, the thermal stability of the Al<sub>2</sub>O<sub>3</sub>@CoS<sub>2</sub> composite material remains unchanged.

## 4. Conclusions

Addressing the issue of insufficient stability in CoS<sub>2</sub> materials, this study employed Atomic Layer Deposition (ALD) to uniformly coat a thin layer of Al<sub>2</sub>O<sub>3</sub> on the surface of CoS<sub>2</sub>, successfully fabricating a protective layer that is both uniform and of minimal thickness. Experiments revealed that this composite material maintains a high degree of consistency with the original CoS<sub>2</sub> material in terms of micromorphology, thermogravimetric analysis, and discharge performance, indicating that the Al<sub>2</sub>O<sub>3</sub> layer does not compromise its excellent properties. Furthermore, storage tests found that the unprotected CoS<sub>2</sub> material exhibited a significant decrease of 30% in discharge specific capacity and an increase of 0.07 Ω in polarization internal resistance after being stored for 8 days, demonstrating notable performance degradation. In contrast, the CoS<sub>2</sub> composite material coated with 30 layers of Al<sub>2</sub>O<sub>3</sub> on its surface showed only a 10% decrease in discharge specific capacity and a smaller increase in polarization internal resistance of just 0.05 Ω under the same storage conditions. This suggests that the Al<sub>2</sub>O<sub>3</sub> protective layer effectively isolates CoS<sub>2</sub> from direct contact with moisture in the air, thereby substantially enhancing the material's storage stability. Therefore, the Al<sub>2</sub>O<sub>3</sub>@CoS<sub>2</sub> composite material outperforms bare CoS<sub>2</sub> in terms of storage stability.

## Data availability

The data supporting this article have been included as part of the manuscript.

## Author contributions

Rongrui Xu and Yicheng Wei: data curation, formal analysis, investigation, writing-original draft, writing-review & editing; Ling Ding: writing-original draft; Hongliang Li: formal analysis; Huazhen Hua: supervision; Yong Cao: supervision, project administration; Yanhua Cui: Supervision, project administration, funding acquisition.



## Conflicts of interest

There are no conflicts to declare.

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