

Nondestructive sensing and failure diagnosis technologies for lithium-ion battery aging and safety

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Aging and Failure Phenomena in Lithium-Ion Batteries

During operation, lithium-ion batteries undergo complex physicochemical processes that progressively induce structural degradation and performance deterioration, thereby compromising their stable and reliable operation.

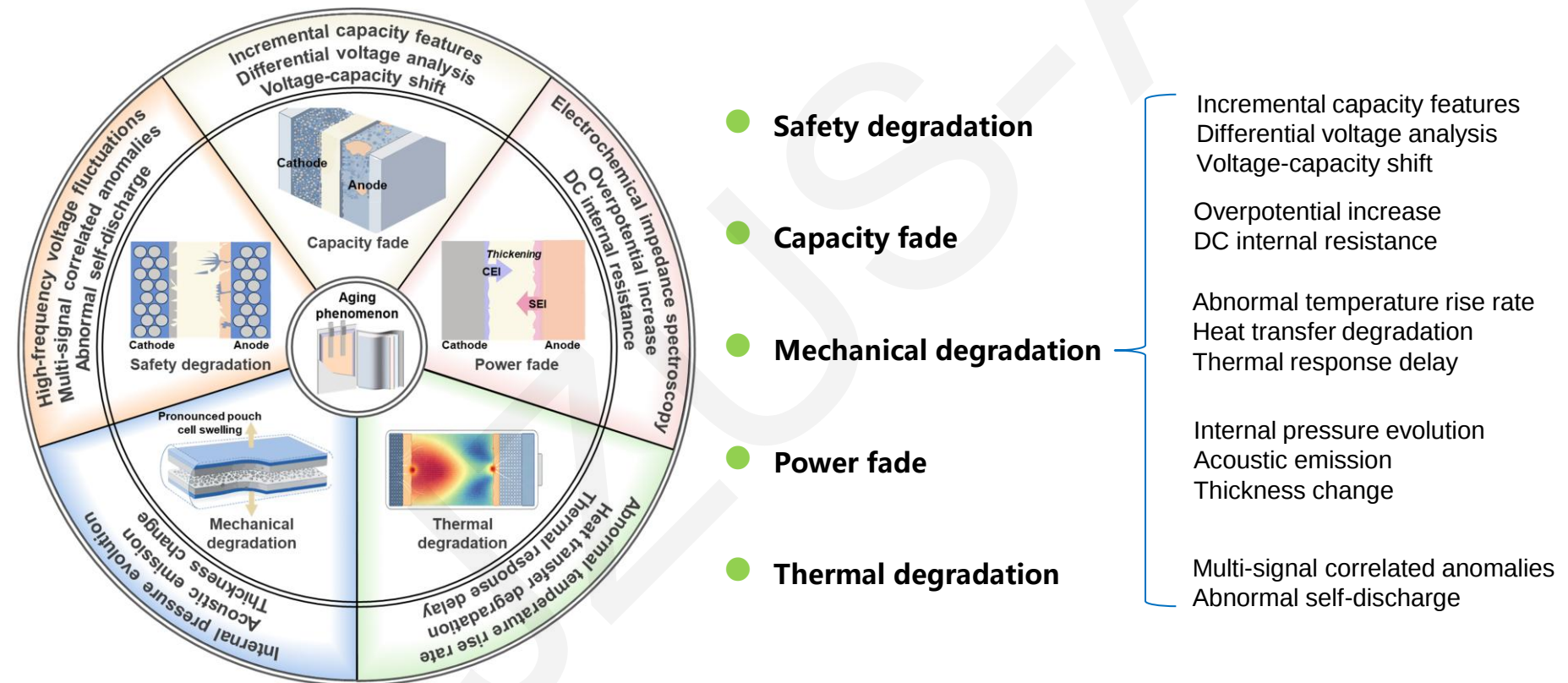


Fig. 1 Coupled aging mechanisms and detectable signal signatures in LIBs.

Multiphysics Coupling Governs LIB Aging and Failure

LIB aging and failure are governed by strongly coupled chemical, mechanical, and thermal processes spanning multiple scales, from material and interfacial degradation to cell-level performance deterioration and safety failure.

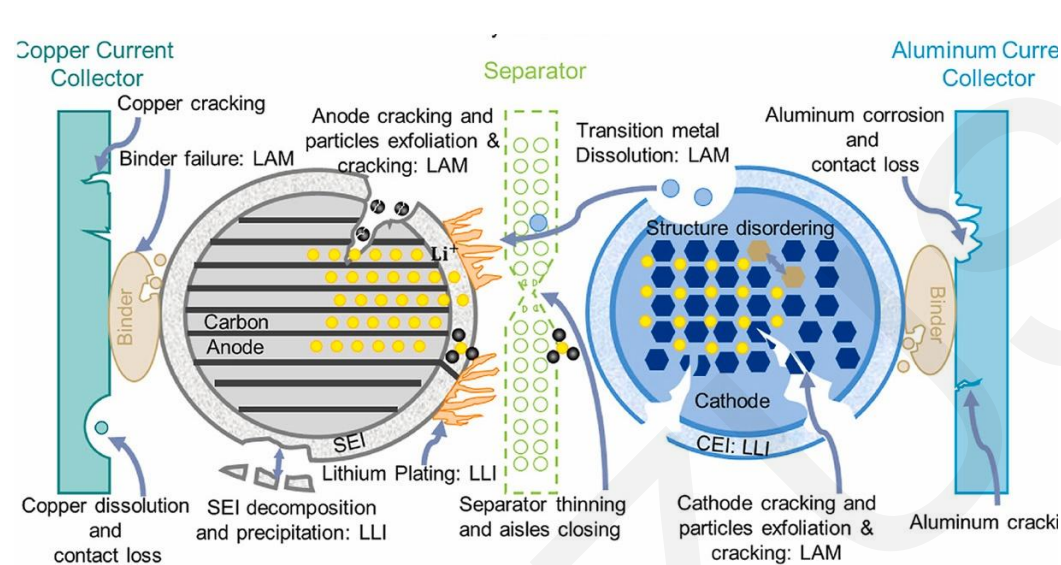


Fig. 3 Bulky and interfacial aging mechanisms in LIBs

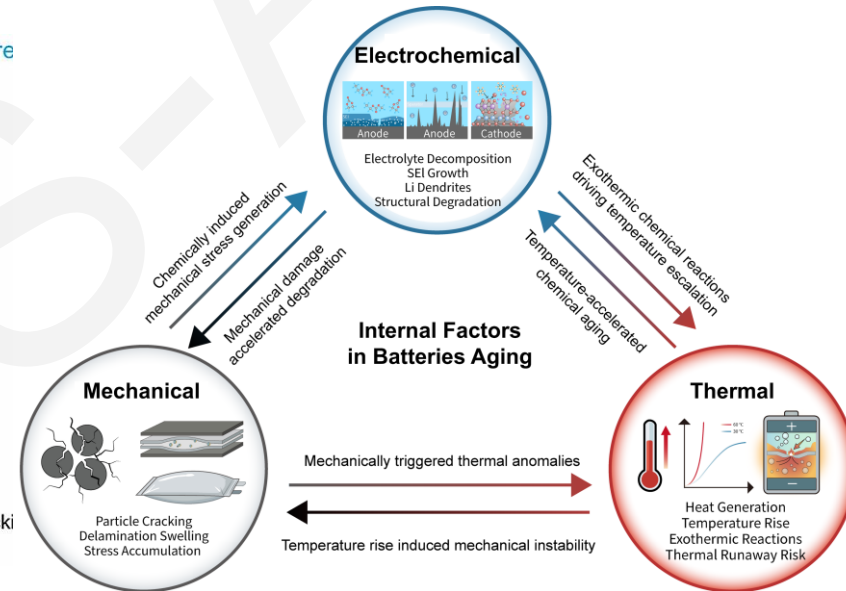


Fig. 4 Coupled chemo-mechanical-thermal aging mechanisms in LIBs

These interactions mutually reinforce one another, driving the evolution from localized degradation to system-level failure.

From Degradation Mechanisms to Internal Signal Perception

Understanding degradation mechanisms provides the physicochemical basis for linking internal aging processes with measurable signal signatures.

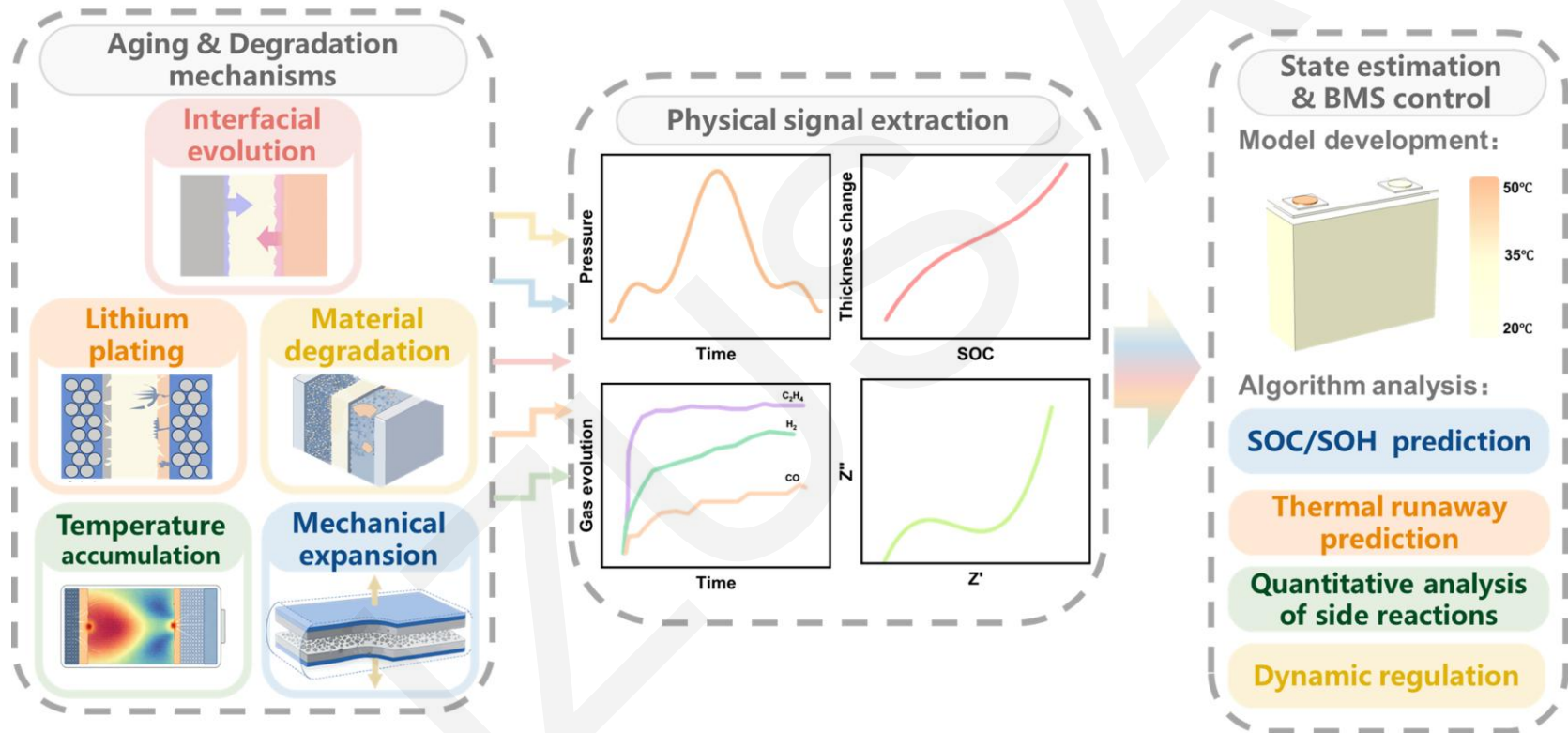


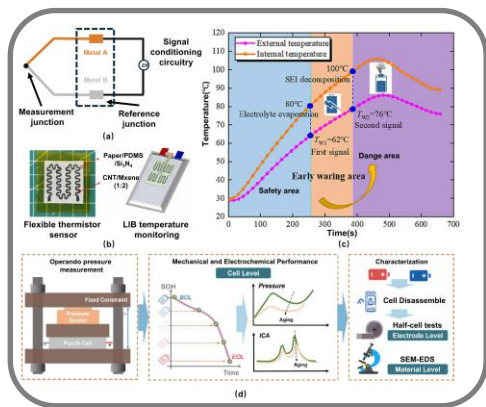
Fig. 2 Framework linking degradation mechanisms, internal signals, and state estimation in LIB aging.

Operando sensing of key physical signals enables the transition from degradation mechanism identification to internal state perception and diagnosis.

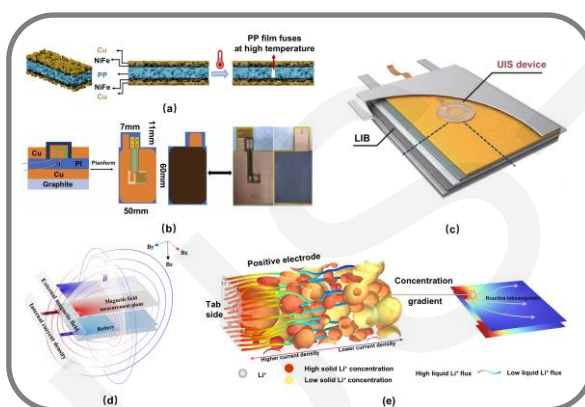
Multiphysics Sensing for Internal State Perception

Different sensing technologies provide complementary access to electrical, thermal, mechanical, acoustic, and electrochemical signatures associated with internal battery degradation.

Surface sensing technology



In situ and noncontact characterization



Implantable sensing technology

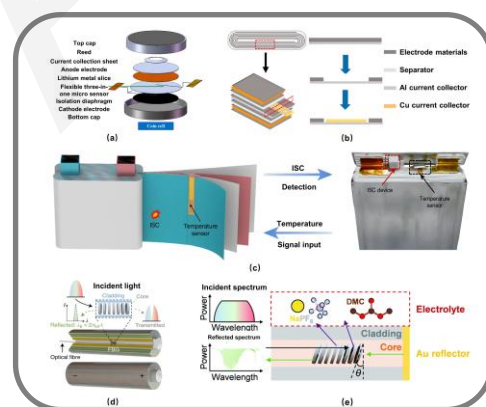
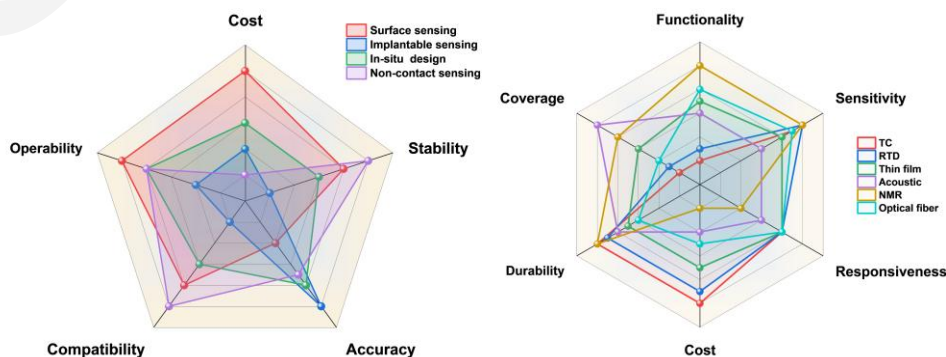


Table. 1 Comparative radar analysis of sensing strategies and sensor modalities.

Parameter	Sensor cost (USD)	Stability	Accuracy	Compatibility	Operability
Surface	10^0 – 10^2	★★★★★	★★★☆☆	★★★★★	★★★★★
Implantation	10^2 – 10^4	★☆☆☆☆	★★★★★	★☆☆☆☆	★☆☆☆☆
In situ	10^1 – 10^4	★★★★☆	★★★★★	★★★☆☆	★★★☆☆
Non-contact	$>10^4$	★★★★☆	★★★☆☆	★★★★★	★★★★★

Parameter	Detectability	Anti-interference	State correlation	Warning capability
Temperature	★★★★★	★★★☆☆	★★★☆☆	★★★★★
Pressure	★★★★★	★★★★☆	★★★★☆	★★★★★
Voltage	★★★☆☆	★★★★★	★★★★★	★★★★★
Gas	★★★☆☆	★★★★☆	★★★☆☆	★★★☆☆



Their complementary integration enables progressively enhanced internal state perception.

Multisource Feature Fusion for State Diagnosis and Lifetime Management

Multiphysical sensing and multisource information fusion transform fragmented signals into actionable knowledge, enabling high-fidelity state estimation, fault diagnosis, and lifetime prediction.

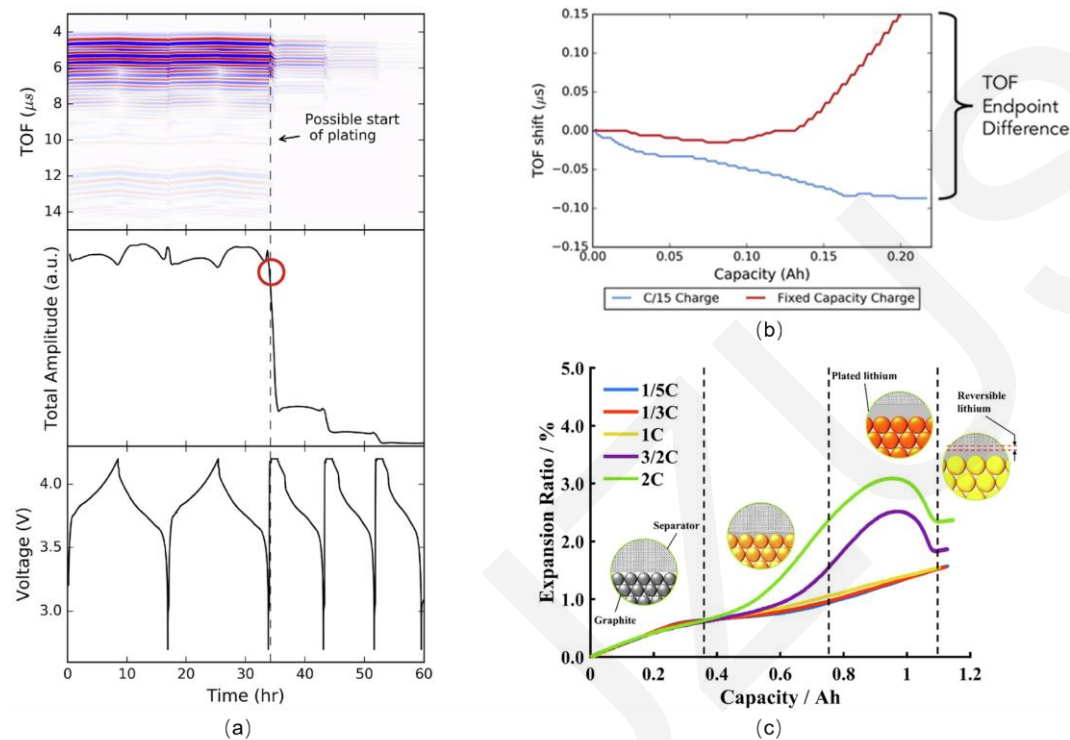


Fig. 10 Overview of sensor data and extracted features used for lithium plating detection

1. Multiphysical signals provide complementary insights

- Complementary multiphysical information
- Early degradation signatures
- Enhanced internal state perception
- Mechanism-specific fault detection

2. Multisource fusion enables high-fidelity state diagnosis

- Feature engineering
- Multimodal information fusion
- SOH/RUL prediction
- Mechanism-informed fault diagnosis

3. Practical deployment requires sensing–algorithm–system codesign

- Low-intrusion sensing
- Efficient feature reduction
- Sensing–data–BMS integration
- Cost-effective and scalable deployment

Conclusions: Toward Intelligent Battery Systems

The future of LIB diagnostics lies in the evolution from minimally intrusive sensing to intelligent multisource perception and ultimately to autonomous, system-level optimization and control.

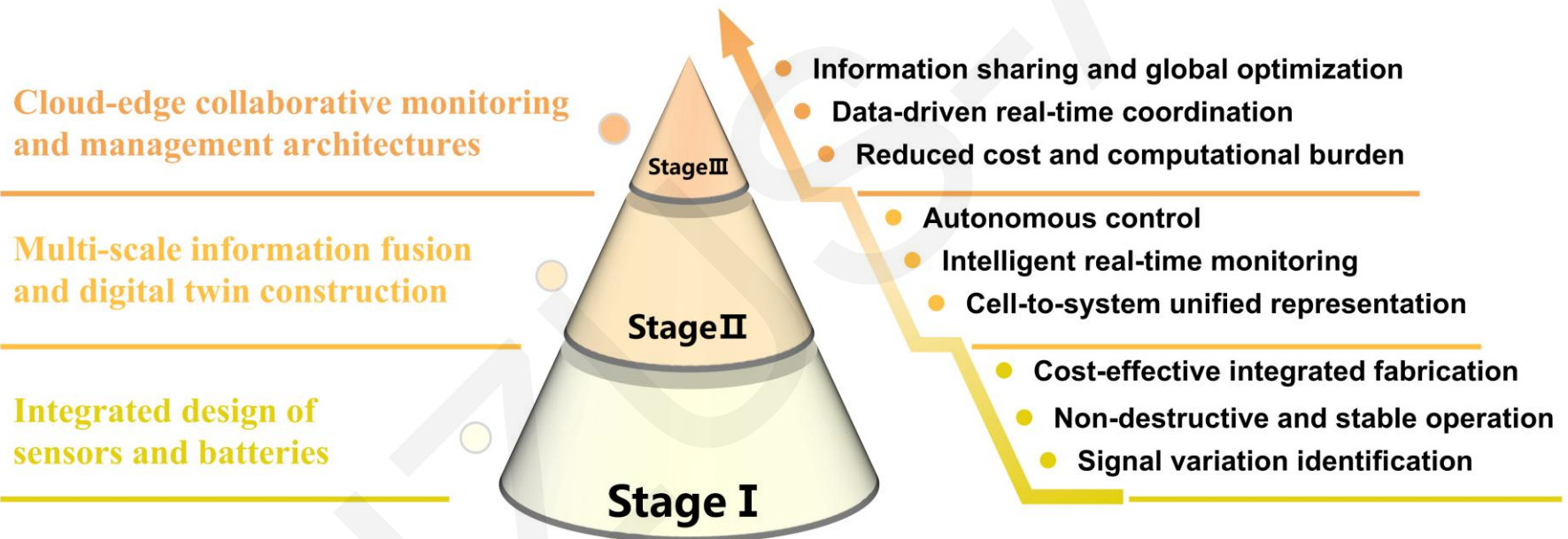


Fig. 11 Staged roadmap for system-level optimization of nondestructive diagnosis in LIB aging