

A Polyimide-based In-situ Sensor and Actuator Platform for Battery Monitoring and Self-healing

Vincent Kuczius¹, Pongsak Sarapukdee¹, Emanuel Wallesch¹, Deniz Kutluay², Joe Fleming², Tazdin Amietszajew², Enric Comas³, Jagdeep Sagu⁴, Andrew Baker⁴, Lilly Gill⁴, David Johnson⁴, Ian Manfren⁴, Kevan Parkes⁴, Gavin Brown⁴, John McClean⁴, Frances Tait⁴, Sam Chan⁴, Louise Evans⁴, Stefan Palzer¹

¹Technical University Dortmund, Professorship for Sensors, Otto-Hahn-Straße 8, 44227 Dortmund, Germany

²Coventry University, C-ALPs building, Coventry University, Cheetah Road, CV1 2TL

³IDNEO Technologies, Career Rec de Dalt 3, Barcelona, Spain

⁴Centre for Process Innovation, The Coxon Building, John Walker Road, Sedgefield, TS21 3FE United Kingdom
stefan.palzer@tu-dortmund.de

Summary:

This work introduces a 30 µm-thick flexible array for in-situ battery monitoring and triggering of self-healing mechanisms. By combining temperature sensing with localized thermal actuation, the polyimide-based platform is able to trigger healing mechanisms at specific locations inside the battery without heating the entire cell. Simulations and experiments confirm spatial heat confinement. This enables a shift from pure diagnostics to active, closed-loop battery management capable of autonomously detecting and mitigating battery failure mechanisms.

Keywords: in-situ sensors, battery monitoring, battery, self-healing, battery system

Introduction

Next-generation battery systems employ high-energy materials and complex architectures that exhibit stronger thermo-mechanical coupling accompanied by higher safety sensitivity. This necessitates real-time monitoring to provide direct insight into internal processes to enable early detection of degradation and more precise control of battery operation [1, 2]. Embedded flexible sensors including thin-film thermocouples, piezoresistive sensors, and strain gauges, allow for real-time monitoring of corresponding internal battery parameters. They may be integrated on flexible substrates such as polyimide for in-situ, multiphysics monitoring within electrode stacks or separators with minimal impact on cell performance [3, 4]. While these technologies significantly improve diagnostics and battery management, they remain largely passive monitoring tools.

Here a sensor-actuator platform tailor-made for batteries that incorporate self-healing materials is presented. In this scenario detection alone is insufficient, since many healing mechanisms such as bond reformation require thermal activation [5]. Heating the entire cell is inefficient and may accelerate degradation or introduce safety risks. Therefore, the array enables localized heat deposition to deliver heat only at damaged regions and initiate healing processes within safe

limits. By combining in-situ sensing with localized thermal actuation, this approach extends current flexible battery sensor technologies towards active self-healing battery systems capable of both detecting and autonomously mitigating degradation.

Processing

The fabrication process for the sensing platform starts with a glass wafer used as a temporary support substrate. A photosensitive polyimide (PIM) layer is first deposited by spin coating to form the flexible base layer. The electrical structures are produced via physical vapor deposition (PVD) of Aluminium (Al) metallization using maskless photolithographic patterning. The fabrication of resistive temperature detectors is achieved using a serpentine structure and array of 3x3 temperature sensors with a respective area of 149.47 mm².

Electrical insulation and chemical protection to prevent corrosion and electrolyte interaction from the battery environment is achieved by a second spin-coated polyimide layer. Finally, the devices are singulated using wafer sawing and released from the glass carrier by laser ablation resulting in a free-standing flexible sensor structure with a total thickness of ~30 µm. The process flow is shown in Figure 1 including a photograph of the finished device.

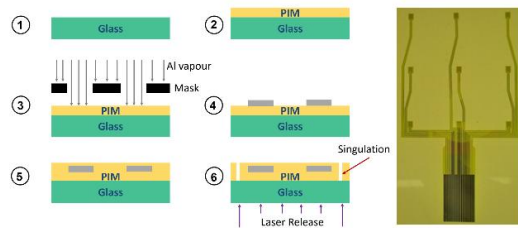


Fig. 1. Fabrication process for the sensing platform. The photograph on the right shows the finished device.

Experimental

The thermal behavior of the system has been modelled to understand heat generation and dissipation within the sensor structure and battery. To this end, the spatio-temporal behaviour is simulated using the finite-element method (FEM) and material parameters and dimensions for a single Pouch cell using a Li-S chemistry. The sensor array is calibrated to establish the relationship between the electrical resistivity of each temperature sensing area and the actual temperature. The heating performance is then experimentally characterized by analyzing both the temporal evolution of temperature and the spatial temperature distribution across the device to ensure localized heat deposition.

Results

The simulation results indicate that the generated heat remains strongly confined around the active heating element, with a spatial spread of approximately 15 mm (FWHM) as shown in Figure 2.

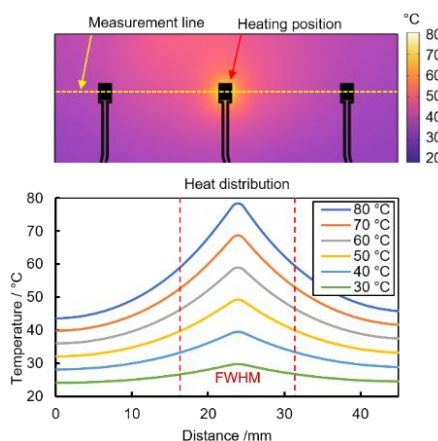


Fig. 2. COMSOL simulation of the micro-heater array (top) and the corresponding lateral temperature distribution profiles (bottom) at various setpoints from 30 °C to 80 °C.

The vertical temperature decreased by approximately 1.7°C at the aluminum current collector interface and 2°C at the sulfur layer relative to the peak heater temperature.

This confirms that the device design enables highly localized thermal actuation. Experimental

validation was conducted by heating a single temperature sensing site to 51.8 °C. The measured temperature response agrees well with the simulation results, confirming localized heat deposition without significantly affecting neighboring sites. Based on the calibrated sensor signals, the temperature distribution across the array was reconstructed during operation. The reconstructed heat map in Figure 3 visualizes the thermal profile and demonstrates controlled, localized heating within the flexible sensor structure.

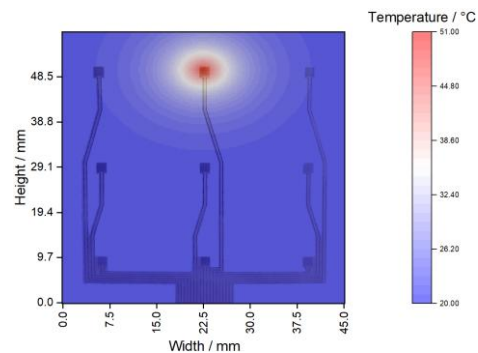


Fig. 3. Interpolated temperature distribution on an aluminum foil substrate with a 3x3 resistor array.

Conclusion

This work introduces a flexible, quasi-2D microsensor for in-situ temperature monitoring and localized heating in batteries. Experiments and simulations confirm precise thermal control with minimal spread. By combining embedded sensing with targeted actuation, this platform offers a pathway for self-healing battery chemistries. Future integration with management systems will enable responsive, intelligent energy storage through closed-loop thermal control.

References

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