



## Full paper

## Scalable fabrication of flexible thin-film batteries for smart lens applications

HyunSeok Lee<sup>a,b</sup>, Sangtae Kim<sup>a</sup>, Kwang-Bum Kim<sup>b</sup>, Ji-Won Choi<sup>a,c,\*</sup><sup>a</sup> Center for Electronic Materials, Korea Institute of Science and Technology (KIST), 39-1, Hawolgok-Dong, Sungbuk-Gu, Seoul 136-791, Republic of Korea<sup>b</sup> Energy Conversion and Storage Materials Laboratory, Department of Material science and Engineering, Yonsei University, 262 Seongsanno, Seodaemun-Gu, Seoul 120-749, Republic of Korea<sup>c</sup> Department of Nano materials Science and Technology, Korea University of Science and Technology (KUST), Daejeon 305-217, Republic of Korea

## ARTICLE INFO

## Keywords:

Flexible batteries  
Lithium-ion batteries  
Smart lenses  
Scalable fabrication  
Off-axis deposition

## ABSTRACT

The smart lens system is considered one of the ultimate wearable electronics platform, with potential applications in visual-guide or health-monitoring system. However, its development has so far been limited by the development of suitable flexible batteries. Conventional flexible battery fabrication relies on laser-based lift-off techniques, which greatly hinder scalability of such batteries. Here, we design and demonstrate the flexible thin film batteries applied to contact lens form-factor, with direct fabrication on polymer substrates and single step low-temperature annealing. The battery utilizes olivine  $\text{LiFePO}_4$  thin film cathode, fabricated with  $90^\circ$  off-axis sputter deposition. This achieves unique nanoscale microstructure required for electrochemically active  $\text{LiFePO}_4$  thin films and effectively reduces the annealing temperature of  $\text{LiFePO}_4$  down to  $400^\circ\text{C}$  for the first time. Equipped with lithium phosphorous oxynitride ( $\text{LiPON}$ ) solid electrolyte and lithium metal anodes on polyimide substrates, the battery demonstrates the energy storage capacity of  $35\ \mu\text{Wh}$  under wet condition. The storage capacity is sufficient to power glucose sensors embedded on the smart lens for up to 11.7 h. In addition, the high energy density of  $70\ \mu\text{Wh}/\text{cm}^2$  flexible batteries may enable a diverse set of micro-scale devices, with scalable and CMOS-compatible fabrication processes.

## 1. Introduction

Over the past 10 years, the research interest on flexible batteries increased by a significant amount, with a wide range of potential applications from wearable devices to bendable personal electronics [1]. One such application involves the smart lens system, one of the ultimate wearable electronics platform [2]. Smart lenses may enable artificial intelligence-driven visual guide or real-time health monitoring platform when coupled to several electronics components such as cameras, glucose sensors and displays [3–5]. One of the greatest challenges for this innovative technologies, however, lies in developing a flexible, non-toxic and durable battery system that can be integrated into the lens format by CMOS-compatible processes.

Incorporating conventional lithium-ion batteries into contact lenses features several design challenges. The strict non-toxicity requirement for contact lenses indicates that only limited electrode materials may be used. Safe and non-toxic olivine  $\text{LiFePO}_4$  is favored over cobalt-containing layered oxide ( $\text{LiCoO}_2$ ) materials [6]. Solid electrolytes must be used instead of organic solvent-based liquid electrolytes. These requirements, along with the lens form-factor, put thin-film solid-state

batteries a practical option for smart lenses [7]. With recent progress on novel solid electrolytes with high  $\text{Li}^+$  conductivity over  $10\ \text{mS}/\text{cm}$ , we may expect further research developments in solid-state thin film batteries for applications in smart lenses [8]. Yet, one major remaining challenge involves the high temperature required for annealing thin film-based cathode materials such as  $\text{LiFePO}_4$ . Thin film cathode materials require annealing at temperatures above  $500^\circ\text{C}$  [9–12], however, no flexible substrate endures annealing at such temperature. This signals that either novel processing techniques involving low-temperature crystallization [13,14] or lift-off based transfer techniques [15] must be developed for successful integration of solid-state batteries into smart lenses.

Here, we design and demonstrate a flexible battery applied on contact lens form by developing a low-temperature processed thin film batteries. Specifically, an olivine-based cathode ( $\text{LiFePO}_4$ ) thin films are deposited at  $90^\circ$  off-axis during RF magnetron sputtering to ensure that the film grows with excess surfaces. The films exhibit optimal crystallization temperature of  $400^\circ\text{C}$ , over  $100^\circ\text{C}$  lower than the reported annealing temperature required for most cathode  $\text{LiFePO}_4$  [9–12]. This allows the entire battery to be developed on flexible polyimide (PI)

\* Corresponding author at: Center for Electronic Materials, Korea Institute of Science and Technology (KIST), 39-1, Hawolgok-Dong, Sungbuk-Gu, Seoul 136-791, Republic of Korea.

E-mail address: [jwchoi@kist.re.kr](mailto:jwchoi@kist.re.kr) (J.-W. Choi).

<https://doi.org/10.1016/j.nanoen.2018.08.054>

Received 8 February 2018; Received in revised form 27 July 2018; Accepted 22 August 2018

Available online 24 August 2018

2211-2855/ © 2018 Elsevier Ltd. All rights reserved.