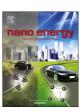


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Full paper

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



HyunSeok Lee^{a,b}, Sangtae Kim^a, Kwang-Bum Kim^b, Ji-Won Choi^{a,c,*}

- a Center for Electronic Materials, Korea Institute of Science and Technology (KIST), 39-1, Hawolgok-Dong, Sungbuk-Gu, Seoul 136-791, Republic of Korea
- b Energy Conversion and Storage Materials Laboratory, Department of Material science and Engineering, Yonsei University, 262 Seongsanno, Seodaemun-Gu, Seoul 120-749. Republic of Korea
- ^c Department of Nano materials Science and Technology, Korea University of Science and Technology (KUST), Daejeon 305-217, Republic of Korea

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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 LiFePO₄ thin film cathode, fabricated with 90° off-axis sputter deposition. This achieves unique nanoscale microstructure required for electrochemically active LiFePO₄ thin films and effectively reduces the annealing temperature of LiFePO₄ down to 400 °C for the first time. Equipped with lithium phosphorous oxynitride (LiPON) solid electrolyte and lithium metal anodes on polyimide substrates, the battery demonstrates the energy storage capacity of 35 μ 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 μ Wh/cm² 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, nontoxic 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 LiFePO $_4$ is favored over cobalt-containing layered oxide (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 Li⁺ conductivity over 10 mS/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 LiFePO₄. Thin film cathode materials require annealing at temperatures above 500 °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 (LiFePO₄) thin films are deposited at 90° off-axis during RF magnetron sputtering to ensure that the film grows with excess surfaces. The films exhibit optimal crystallization temperature of 400 °C, over 100 °C lower than the reported annealing temperature required for most cathode LiFePO₄ [9–12]. This allows the entire battery to be developed on flexible polyimide (PI)

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

^{*} 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.