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Full paper

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

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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 $LiFePO_4$ thin film cathode, fabricated with 90° off-axis sputter deposition. This achieves unique nanoscale microstructure required for electrochemically active $LiFePO_4$ thin films and effectively reduces the annealing temperature of $LiFePO_4$ 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 μWh 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 μWh/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 $LiFePO_4$ 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 $LiFePO_4$. 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 ($LiFePO_4$) 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 $LiFePO_4$ [9–12]. This allows the entire battery to be developed on flexible polyimide (PI)

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