Design, microfabrication and characterization of free form factor, lightweight thin film battery for powering bioinspired Nano-drones based on MEMS actuation

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Abstract. This paper presents the manufacturing and characterization results of biomimetic shaped thin film batteries (TFB). The final structures presented a total mass of approximately 60mg per cm² of active area, with a mean overall thickness of 100µm. Experimental results of TFB cycling at different C rates showed almost no capacity fade for current densities between 0.5 and 10mA, leading to surface energy densities as high as 0.15 mWh.cm⁻² and power densities up to 5mW.cm⁻². The achieved electrochemical results are among the highest values reported in the literature for such miniaturized energy devices, which will contribute to bring new solutions for powering MEMS actuation based micro/nanorobotics.

Introduction
Recent advances in MEMS/NEMS technology have led to an emerging industry of diverse small-scale devices that include microsensors, micromachines and drug-delivery systems. For these devices, there is a growing demand for miniaturized energy sources enabling on-board power delivery.

Among the various existing technologies, thin film batteries (TFB) are considered as the most competitive power source because of their high volumetric/gravimetric energy densities, superior power capability and design flexibility [1].

This paper will show experimental results of flying insect abdomen shaped, ultra-lightweight TFB as an integrated energy source for MEMS actuation based nanodrones. The approach described herein provides many advantages compared to previous work [2], in particular the use of high annealing steps during fabrication to decrease TFB internal resistance while keeping lightweight using substrate structuration.

Experimental
An artist view of a flying insect nano-drone and a schematic illustration of corresponding abdomen shaped TFB (as designed and realized in this work) is shown respectively in figure 1.a and 1.b.

Film deposition steps were carried out in an ENDURA PVD 200 nm tool (Applied materials) equipped with Ti, LiCoO₂, Li₃PO₄ and Si sputtering targets, and an ALCATEL SCM600 tool equipped with Pt sputtering target. Both tools were connected to Ar filled glove boxes in order to control the samples transfer and storage atmosphere. Details on TFB considered materials are reported elsewhere [2,3]. TFB layers thicknesses are selected based on numerical simulation results corresponding to the optimal trade-off between energy/power densities and lightweight, in respect to the nano-drone application.
Figure 1. Example of MEMS actuation based nanorobotics (a) artist view of a flying insect nanodrone, (b) schematic illustration of corresponding abdomen shaped TFB.

TFB were prepared by successive deposition and patterning of each layer level using UV photolithography and etching. SPR 220 photoresist was used for all photolithography steps, and UV exposure was carried out in an EVG 640 mask aligner. Wet etching of LiCoO$_2$ and LiPON were realized in HCl aqueous solution, and Pt in 1HCl:3HNO$_3$ mixture. Si/Ti top layers were etched in a CHF$_3$/Ar plasma using a Corial IL200 tool. Lightweight TFB were finally obtained after a KOH wet etch structuration of the substrate backside using a specific wafer carrier and laser ablation for singulation step.

Electrochemical measurements were carried out in Ar glove box at 25 °C, using a VMP3 galvanostat-potentiostat (Bio-Logic). Cycling was performed between 3 and 4.2 V at a typical rates between 1 and 50C. Unless stated otherwise, potentials written vs. Li correspond to potentials measured against Li/Li$^+$ redox couple.

Results

Figure 2. realized TFBs, (a) photographs of front and back side after singulation; (b) cross-sectional SEM images of TFB and (c) focus on Ti/Pt/LiCoO$_2$/LiPON/Si/Ti/Al$_2$O$_3$ active structure
Figure 2a shows back and front sides of the fabricated dragonfly abdomen shaped TFBs. The backside structuration allowed for a significant mass reduction while maintaining the overall stiffness. The final structures presented an areal density of approximately 60mg/cm², with a mean overall thickness of 100µm.

An example of SEM cross-section related to the active area of TFB is presented in figure 2. The active layer thicknesses (3.5 and 2.5, respectively for LiCoO₂ and LiPON) match very well with the intended values. Each film appears distinct and continuous, and the interfaces do not exhibit delamination or local blisters, which indicates good adhesion at the various interfaces.

Experimental results of electrochemical characterization are presented in figure 3. The variation of voltage profile during discharge with applied current is depicted in figure 3.a. For low currents the voltage profile shows a two-step decrease with two plateaus around 4 and 3.5V, the first is related to lithium ion stripping from the Si/Ti interface and the second is correlated to the lithium ion intercalation in the LiCoO₂ cathode host material. It is observed that increasing the discharge current leads to an increase of the IR drop. Moreover, voltage plateaus are lowered with increasing discharging rate and lithium stripping plateau vanishes at very high drains, indicating low kinetics related to the this electrochemical reaction.

Results of cycling stability are shown in figure 3.b. The discharge capacity decreases gradually during the first 40 cycles then tends to stabilize during next 100 cycles with an average capacity loss of less than 0.1% per cycle. Almost no capacity fade is observed for discharge currents within 1-10mA, leading to surface energy densities as high as 0.15 mWh.cm⁻² for power density up to 5mW.cm⁻².

**Figure 3.** Experimental results of TFB cycling at different C rates. (a) TFB voltage profile-capacity evolution with discharge current density (2.5cm² device) (b) discharge capacity vs. cycle number during galvanostatic discharge within [0.25, 10 mA]
Furthermore, pulsed discharge cycling have been carried out in order to investigate the electrochemical behaviour of TFBs and the compatibility with a mems duty cycle.

A constant current of 35µA was applied to fully charge the TFB. A discharging current was applied for 0.4 msec and subsequently was hold for 400 msec until a cut-off voltage of 0.5V was reached. The discharge depicted in figure 4 highlights a shift of the voltage profile during current application to the lower values with an approximately -2V, mainly due to the TFB internal resistance. Despite this IR drop, the TFB delivered full discharge when considering 0.5V cut-off, allowing an overall actuation during more than 4 hours (approximately 37K cycles) in these conditions. These results highlight the feasibility and usefulness of such biomimetic energy devices for micro/nanorobots application using electrostatic MEMS actuation.

Conclusion

Lightweight, free form factor TFBs were manufactured and tested using DC and pulsed discharge currents. The use of microfabrication techniques allowed to reach an areal density of 60 mg/cm². The TFBs showed discharges capacities around 0.15 mWh.cm⁻² for discharge currents below 10mA. Therefore, the TFBs of the present work are very promising candidates as energy storage devices for mems actuation based biomimetic nano-robots.

References

[1] R. Salot, Lithium Micro-Batteries, in Energy Autonomous Micro and Nano Systems (eds M. Belleville and C. Condemine), John Wiley & Sons, Inc., Hoboken, NJ, USA (2012).
[2] S. Oukassi, C. Giroud-Garampon, S. Poncet, R. Salot, Ultra-Thin Rechargeable Lithium Ion Batteries on Flexible Polymer: Design, Low Temperature Fabrication and Characterization, J. Electrochem. Soc., Vol 164 (9), A1785-A1791 (2017).
[3] F. Le Cras, B. Pecquenard, V. Dubois, P. Viet-Phong, D. Guy-Bouyssou, All solid state lithium-ion microbatteries using silicon nanofilm anodes: high performance and memory effect, Adv. Energy Mat., 5, 1501061 (2015).
[4] L. Le Van-Jodin, F. Ducroquet, F. Sabary, I. Chevalier. Dielectric properties, electronic conductivity and Li⁺ion motion in LiPON thin films. Solid State Ionics, Vol 253, pp.151-156 (2013).