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Ultra lightweight, high power density lithium ion batteries

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Abstract: Current fabrication methods for lithium ion batteries impose a limit on how light a high power battery can be made (<300 mg). The lack of lightweight, high power batteries is a significant constraint to the development of untethered micro-robots, wearable haptics, mobile computing, and biomedical applications. We have developed a laser micro-machining and assembly process which can produce batteries up to 30 times lighter than the lightest high power commercial cell, at comparable power densities (>1 kW/kg). Our process is versatile and can be adapted to make custom geometries, miniature high voltage cells, and more, all while using a broad range of starting materials. We see this technology as a path to highly versatile miniature power sources, that will enable a wide range of small scale applications.

Existing fabrication technologies cannot be used to make lightweight, high power density lithium ion batteries (<300mg). The need is increasing for these small, powerful batteries, as advances in fabrication techniques push the limits of miniaturization in robotics [1], haptics [2], wearable and biomedical technologies [3], and mobile computing for the Internet of Things [4]. Unfortunately, current fabrication methods for lithium ion cells force the end user to make a choice between high energy density and lightweight batteries (Figure 1(a)). Supercapacitors can provide even higher power density (>10 kW/kg), but have very short discharge times (0.1-5 s), which limits the range of potential applications [5]. To push the limits of performance, we have developed a hybrid manufacturing approach which uses commercially available lithium ion materials and a laser micro machining method to build lightweight (10-200 mg) high power density (>1 kW/kg) batteries.

Miniaturization of Li-ion batteries is limited by how the fabrication processes scale down [5], [6]. Conventional Li-ion electrodes are made as planar films that are stacked into prismatic or cylindrical shapes. The stacked electrodes are infused with electrolyte, then sealed into a metallized film pouch, which prevents moisture from infiltrating into the battery. The materials and processes used to prevent moisture infiltration take up a significant amount of total battery weight, and scale unfavorably as the size of the battery is reduced. Furthermore, most nickel and aluminum commercial tabs weigh hundreds of milligrams, and need large areas for reliable welding to the electrodes. For

high power devices, tabs and welds need to be oversized to avoid excessive resistive heating during fast charge or discharge. While several devices have been demonstrated to deliver high power at very small scale (1-100 mg), the fabrication processes are either long duration [7], or rely on unconventional materials [8], or are difficult to replicate [9]. In addition, the most established processes to make lightweight batteries rely on thin-film, solid electrolyte chemistries, which suffer from rate limitations at room temperature [10], [11].

To create lighter mesoscale power sources, we have developed a method to fabricate ultra lightweight, high power lithium ion batteries by applying a laser micro manufacturing process [12], [13] to commercially available materials. The laser micro machining leads to micron scale precision in cutting and alignment, as well as scalable parallel fabrication. By incorporating commercially available materials we have access to the widest range of high performance metal foils, anodes, cathodes, binders, separators, additives, and electrolytes. To minimize the battery weight, we took inspiration from lithium-air technology and reduced the inactive components [14]. Instead of a metallized pouch foil and current collecting tabs, we use a PET (polyethylene terephthalate) pouch material that can be heat bonded to itself and the metal backing on the electrodes. As a result, the only materials used in the battery are the single-sided electrodes, the separator, the electrolyte, and the thin PET pouch. Compared to conventional metallized pouch materials, our PET solution is lighter (8× less for similar areas), and making connections to the backing of single sided electrodes eliminates the need for current collecting tabs.

An expected downside of the thinner pouch material is the increased permeability to moisture, which limits the battery lifetime. We do not consider the standard cycle life performance of Li-ion to be a target for these types of batteries. Specifically, the cycle and calendar life of the batteries should be tailored to match the expected use of the final device in which the batteries are incorporated. For example, in a search and rescue operation employing multiple expendable flying drones, the expected lifetime will be on the range of hours to days. To enable unique technologies we must maximize one aspect of lithium ion performance at the expense of another, in this case trading cycle life for power density.

The key metric for these batteries is power density per unit of battery weight, as it dictates the types of possible applications. We measured the highest power density (>1 kW/kg) in a LiMn₂O₄ (LMO) - graphite cell (Figure 1(b) and (c)) which weighed 140mg and was tested at 45°C. We present both the voltage vs. capacity curves as well as a plot of discharge power as a function of discharge duration, which may be more useful in comparing the available power with the requirements of different applications: including sensing, computation, and actuation. For reference, the reported battery weight is similar to some of the smallest and lightest micro robots (<100 mg) [1] while delivering sufficient power for autonomous locomotion (100-200mW) [15]. An example battery is shown in Figure 3(a) to demonstrate its scale. Supplemental data (Figure S1) shows the 140 mg battery can still deliver >1 kW/kg at room temperature (25° C).

The difference in performance at 25° C and 45° C suggests the batteries are limited by ion transport processes. Ionic limits are expected for these types of batteries given that the electrolyte is pipetted on the surface of the electrode. The electrolyte addition

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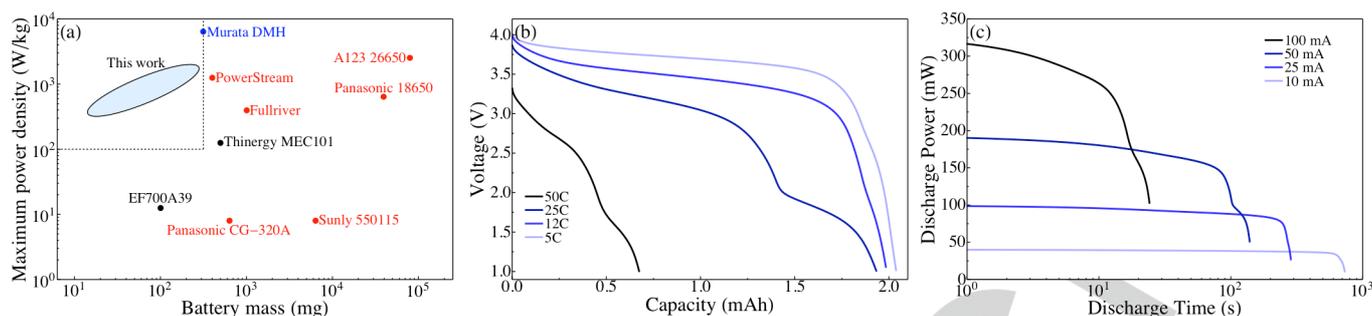


Figure 1. (a) Maximum discharge power as a function of battery mass showing the extreme regime in which our batteries operate compared to state of the art. Black dots correspond to thin film, solid electrolyte cells, red corresponds to conventional liquid electrolyte cells, and the blue dot corresponds to a supercapacitor. The dashed lines border the region of interest of low weight (<300 mg) and high power (>100 W/kg). (b) Voltage curves as a function of capacity prove the fast discharge capability of an LMO-graphite battery. The battery weights only 140 mg, has a capacity of 2 mAh, and was tested at 45°C. (c) Discharge power as a function of discharge duration for the same battery as (b) demonstrates high power density (>1 kW/kg) for fast discharge (<100 s).

process limits how much of the electrode is infused with electrolyte and therefore chemically active. Future work will target other electrolytes and assembly methods aimed at improving wetting of the electrodes.

The process is extremely versatile and can be modified to solve additional challenges. First, the laser cutting process can be easily modified to make irregularly shaped electrodes, as shown in Figure 3(b). While we were limited by linear bar sealers, custom seal profiles are possible for tailored batteries to fit their unique device geometries. Second, the process can be used to make other versatile lightweight batteries. Since the electrolyte is fully enclosed in the pouch material, two or more electrochemical cells may be stacked in a series configuration to yield a higher voltage battery (Fig. 3 (c)). A single cell output higher than 3.7 V may be useful in applications where voltage needs to be amplified, such as to drive piezoelectric actuators. In particular, a higher starting voltage may provide a significant boost to the overall energy efficiency of the system. Lastly, the size of each electrode can be reduced to squares 3 mm on a side to yield a 10 mg battery (Fig. 3 (d)). These batteries are 20 times lighter than the lightest commercially available liquid electrolyte battery, yet deliver half the power density (Fig. 3(e)).

We have demonstrated a hybrid manufacturing approach that relies on conventional, commercially available materials and laser micro machining techniques to deliver high power at the mesoscale. At comparable weight our best performing batteries have a power density 100 times higher than commercial battery. At comparable power density, we demonstrate a battery that is 20 × lighter than the lightest commercial device. The process is extremely versatile and can be modified to create customized shape and weight batteries, as well as solutions for unconventional requirements, such as deformable or high voltage batteries. The process is agnostic to the electrochemical approach, allowing other high power chemistries to be incorporated [16]. We expect these high power density batteries to be useful for a broad class of lightweight applications, including wearable and biomedical devices, as well as miniature robots.

Experimental Section

Battery component preparation: The battery components were sourced from a range of suppliers, processed as received in a laboratory environment, then stored in an Argon-filled glove box until ready for battery assembly. The electrolyte liquid (1 M LiPF₆ in a 1:1 mixture of ethylene carbonate and dimethyl carbonate) was purchased from Sigma Aldrich (St. Louis, MO), the PET pouch foil material (Melinex 301H) was purchased from DuPont Corporation (Wilmington, DE), while the separator material was purchased from MTI Corporation (Richmond, CA). The single sided electrodes were: graphite anodes at 1.1 mAh/cm² and lithium nickel cobalt aluminum oxide (NCA) cathodes at 1.0mAh/cm² from Custom Cells (Itzehoe, Germany), and lithium manganese oxide spinel (LMO) electrodes at 1.5 mAh/cm² from MTI Corporation (Richmond, CA). The electrodes, separator, pouch and pouch materials were laser cut using a diode-pumped Nd:YVO₄ laser, q-switched and frequency tripled to 355nm (Oxford Laser Systems, Didcot, UK).

Laser micro machining: The electrodes are made by cutting and stacking active and pouch materials. The process uses carrier films, such as single sided adhesive (Gelpak, from Hayward, CA), to ensure precise alignment of components. A step-by-step description of the laser cutting and assembly process is given in Figure 2. Each single sided electrode is cut and adhered to a piece of PET foil. The pouch foil is laser-cut into a square piece with an opening for electrical connections, with alignment holes for stacking. An oversized piece of electrode material is laid active side down on an adhesive substrate (Gelpak, Hayward, CA). The battery contour is cut in the electrode material, and the excess material is removed. Simultaneous with the electrode cut, alignment holes are cut into the underlying Gelpak adhesive substrate. Using pins and an alignment jig, the Gelpak substrate carrying the single sided active material is laminated to the pouch foil. The lamination is done by applying 60 psi for 10 minutes at 130°C across the entire area of the pouch material. The pouch foil has an overlap of 1 mm with the metal backing of the electrode, which ensures good bonding between the two materials. The Gelpak adhesive is then removed, creating an electrode with an exposed metal connection on the back and an overhanging pouch foil, which can be sealed to itself. The preceding steps are repeated in order to manufacture the second electrode of the battery, using the anode instead of cathode material, with similar cut conditions.

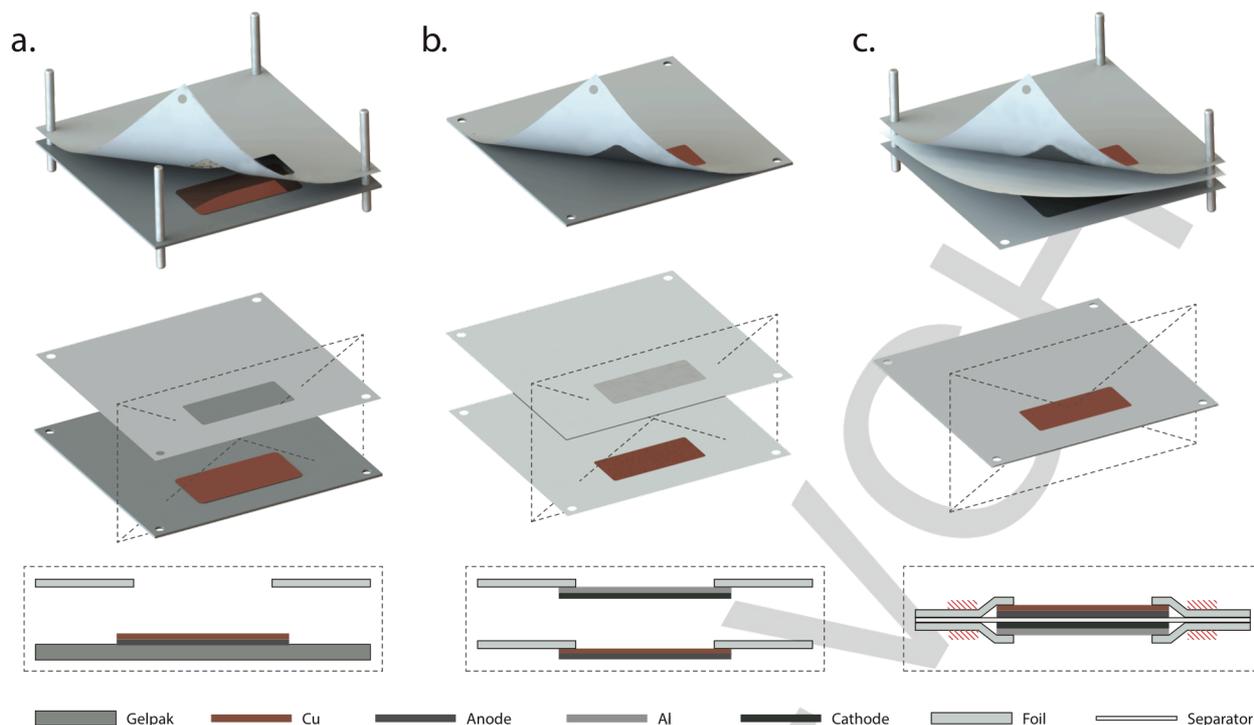


Figure 2. Illustration of the steps in the fabrication process. Dotted lines show the plane through which the cross section is taken. a. Top: laser cut pouch foil aligned with Gelpak carrying anode on copper for lamination. Middle: individual components before lamination. Bottom: cross section of foil and Gelpak carrying anode on copper. b. Top: anode being removed from Gelpak. Middle: anode and cathode electrodes after removal from Gelpak. Bottom: cross sections through electrodes before assembly. c. Top: Stacking process for anode, separator and cathode. Middle: fully assembled battery. Bottom: cross section through an assembled battery showing location of heat seals.

Battery assembly: The electrodes and separator are aligned with pins or by eye, then one side of the full battery is heat-sealed to ensure relative alignment. Electrolyte was pipetted on either side using $15 \mu\text{L}$ per mAh of battery capacity. A bar sealer (McMaster Carr, Elmhurst, IL) and vacuum sealer (Fuji Impulse FCB-200, Osaka, Japan) were used to bond the pouch layers and provide the final battery seal. We used pressure plates and layers of foam to apply 40 psi uniformly to all batteries on test.

Electrochemical characterization: The batteries were characterized on a battery tester (BSC- 815, Bio-Logic, Sessynet-Pariset, France). The electrochemical characterization was performed either at room temperature, or in a VWR incubator set to 45°C . For power characterization, the batteries were charged for 4 h at C/4 rate based on capacity specifications from the electrode supplier, then discharged at rates of up to 50 C. The voltage safety limits were: 4.4 V upper limit during charge and 1 V lower limit on discharge. For cycle life testing the same voltage limits were used while the charge and discharge rates of the battery were set to C/4

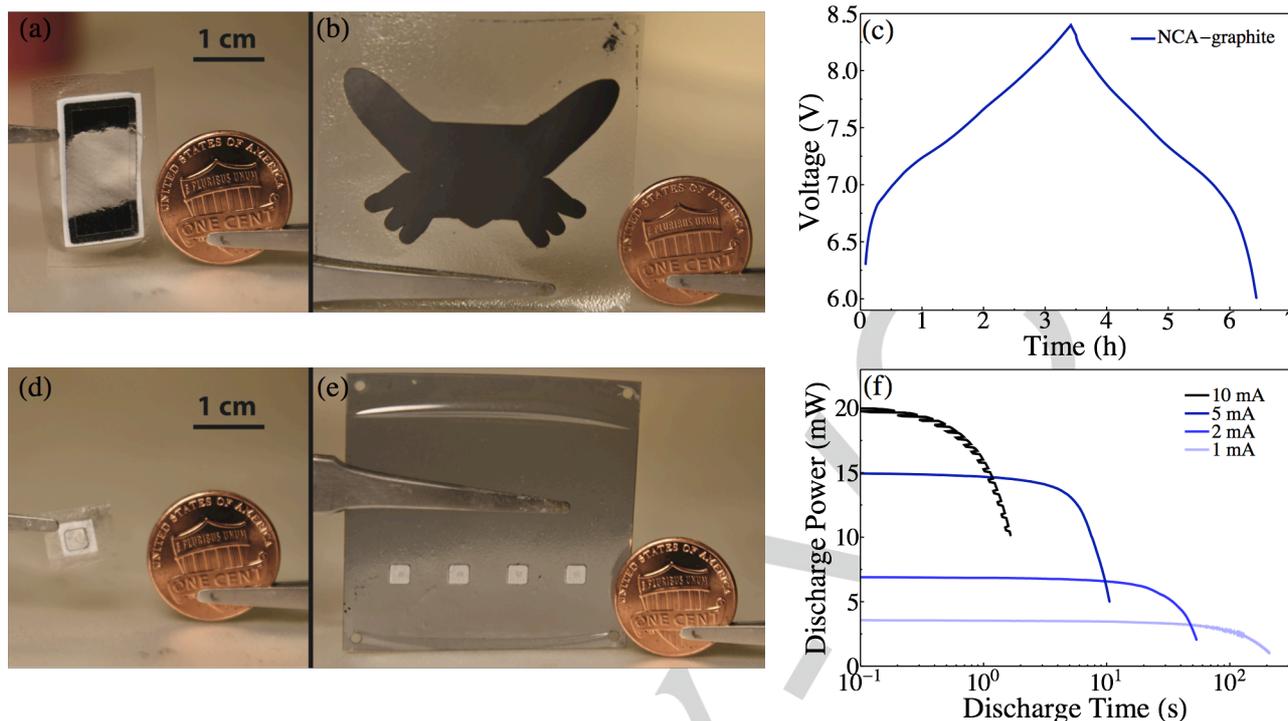


Figure 3. (a) Example of a battery used to establish high power density. The active materials cover 2 cm×1 cm and the battery weighs less than 140 mg after electrolyte addition and heat sealing. (b) Example of an irregular shaped anode electrode for custom shape batteries. (c) Voltage vs. time profile over charge and discharge of a 7.4 V battery made from two single cells connected in series. The high starting voltage may boost the energy efficiency of miniaturized power electronics. (d) Examples of a small (3 mm side squares) battery after assembly. The miniaturized battery weighs 14 mg and approaches the limit of manual assembly capability. (e) Set of cathodes (3 mm squares on a side) on Gelpak demonstrating parallel fabrication capability. (f) Discharge power as a function of time for an example 0.1 mAh battery shown in (d), tested at 45° C. The battery weighs only 14 mg but can deliver more than 1 kW/kg for short durations.

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Keywords: batteries, high power, laser micromachining, lightweight, power density

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