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Manufacturing all-polymer laminar flow-based fuel cells

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HIGHLIGHTS

- Manufactured a lightweight, all-polymer direct methanol laminar flow fuel cell.
- Bonding strategy eliminates the need for heavy metal plates and clamping.
- Developed a strategy to encapsulate fuel cell electrodes in Kapton windows.
- Designs can be scaled and stacked to achieve power requirements of portable applications.

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ABSTRACT

On the macroscale, fuel cell systems typically require heavy clamping constructions to seal layers. Here we report an alternative manufacturing approach that utilizes patterned polymer layers to yield much thinner, lighter laminar flow-based fuel cells (LFFCs). Most LFFCs reported to date have been proof-of-concept configurations. To meet the power requirements of portable electronic devices, challenges related to the design and manufacturing of scalable LFFC systems still need to be addressed. Here we report electrodes that are encapsulated between polymer layers with metallized polymer layers serving as current collectors. Assembly of a polymer-encapsulated anode and cathode yields a 1-mm thick all-polymer fuel cell, about one order of magnitude thinner than most microfluidic fuel cells. To identify performance changes associated with this alternative approach to electrode and catalyst integration, we first validated performance by analyzing the polymer-encapsulated anodes and cathodes individually, and then the complete cell after bonding the polymer-encapsulated electrodes together. This all-polymer fuel cell achieved a maximum power density of 10 mW cm^{-2} at room temperature when using 1 M methanol as the fuel. Thin, lightweight fuel cell stacks for future portable power applications could be obtained by scaling and stacking of the all-polymer cell reported here.

1. Introduction

Significant research effort has focused on developing integrated, multifunctional microchemical systems that incorporate multiple fluidic, electronic, and mechanical components and chemical processes onto a small chip [1–3]. Since their inception, a trend toward increased integration and system complexity has led to the development of highly integrated microsystems for a broad range of applications, including protein crystallization [4], genetic analysis [5,6], multistep synthesis [7], and point-of-care medical diagnostics [8]. Many of these integrated chips are fabricated from polymers, owing to polymers' wide range of material properties, such as mechanical strength, optical transparency, chemical stability, and biocompatibility, which can be tailored to specific applications [9–12]. However, to achieve commercialization of these devices, manufacturing techniques must be advanced in parallel with fluid handling and analytical/chemical capabilities [13]. Here we will address this challenge by developing polymer-based manufacturing technologies, using the assembly of an all-polymer laminar flow-based fuel cell (LFFC) as an example.

LFFCs have been investigated extensively as an alternative to membrane-based fuel cells [14–20]. Most LFFCs reported to date have been proof-of-concept unit cells [18,20]. Transitioning from proof-of-concept, single-channel cells to a multichannel system that provides sufficient power output for portable electronic applications is a present challenge. At the macroscale, fuel cells are traditionally assembled manually in layer-by-layer fashion followed by clamping the layers between metal plates. Scaling to larger systems involves the stacking of an increasing number of layers, requiring increasingly heavy clamping constructions.

Here we report an alternative approach to fuel cell manufacturing which utilizes patterned polymer layers to

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eliminate the heavy clamping structures needed in traditional fuel cell stacks. This approach will yield much smaller, lighter structures and thinner stacks, which is attractive for portable applications. In prior work with polymer-based fuel cells, Wheldon et al. developed a polyester-laminated, hydrogen/air fuel cell (>1 cm thick) that achieves a maximum power density of 57 mW cm^{-2} at room temperature [21]. Using a different approach, Tominaka et al. hot-embossed cyclic olefin copolymer (COC) to create a 200-μm thick methanol fuel cell [22]. While much thinner, the maximum power density of the COC-based cell is <0.3 mW cm^{-2}.

For the all-polymer fuel cell reported here, polyimide will be used as the substrate. Polyimide has exceptional chemical and thermal stability compared to other polymers, is well-known from IC manufacturing processes, and has previously been used to fabricate microfluidic devices [11,23]. Furthermore, polyimide can be metallized, which is needed for the integration of fuel cell electrodes. As detailed below, we aim to fabricate a thin (mm-thick) polymer-based, methanol fuel cell that achieves power levels sufficient for portable electronic applications.

2. Design

An exploded diagram of the polyimide-based LFFC reported here is shown in Fig. 1. The Kapton sheets used in fabrication of this LFFC are either 50-μm or 125-μm thick, and unless otherwise noted, each layer is 3.5 inches by 2 inches. Working from the left of the schematic, the first layer serves as an anode current collector. This 50-μm thick Kapton layer is metallized for current collection and is machined with inlet and outlet holes for the fuel/electrolyte and oxidant streams. The next layer is a ~190-μm thick carbon paper electrode that has anode catalyst deposited onto the side opposite of the anode current collector. Next, a 50-μm thick Kapton layer encapsulates the anode, leaving a window for fuel/electrolyte to flow over the anode catalyst. Fuel/electrolyte and oxidant streams pass through this layer.

The following channel layer, machined from 125-μm thick Kapton, facilitates the transport of fuel to the anode catalyst. The oxidant stream flows through this layer, while the fuel/electrolyte stream enters this layer on one side, flows laminarly across the layer, and then exits the fuel cell on the opposite side. The next 50-μm Kapton layer encapsulates the cathode, leaving a window for the Nafion layer to conduct the protons produced at the anode. The oxidant passes through this layer. Next is a ~240-μm thick cathodic gas diffusion electrode (GDE); catalyst is deposited on the side opposite the cathode current collector and a Nafion layer is hot-pressed over the catalyst. The subsequent metallized Kapton layer (50-μm thick) is the cathode current collector, which is machined with a window for oxidant transport to the cathodic GDE. Next, a 50-μm thick Kapton layer facilitates oxidant transport to the cathode catalyst. The oxidant stream enters this layer on one side, flows across the layer, and then exits the fuel cell on the opposite side. Lastly, a 50-μm thick Kapton layer seals the oxidant flow channel. The entire 9-layer cell is ~1 mm thick.

Key to the successful assembly of these 9-layer cells is hermetic bonding of all the layers, such that no clamping structures have to be used. All bonding of the layers in these cells was accomplished by using an adhesive in combination with plasma treatment of the surfaces. The details of this step are provided in experimental Section 3.1.

This multi-layer cell design can also be used to create fuel cell stacks. In a stack, the fuel/electrolyte and oxidant streams would exit individual fuel cells in a direction opposite that shown in Fig. 1. The streams would then proceed to the following fuel cell in the stack. The exact configuration and dimensions of electrodes in such multichannel laminar flow-based fuel cell designs will affect performance. In prior work we described detailed design rules for this purpose [24]. For example, shorter and shallower channels, as well as the introduction of herringbone features along the walls in certain locations to enhance boundary layer replenishment, will lead to the desired higher current densities.

3. Experimental

3.1. Kapton fuel cell fabrication

The all-polymer fuel cell shown in Fig. 1 is manufactured using existing fabrication technologies for polymer-based microfluidics. Kapton sheets (Dupont Inc.) and metallized Kapton sheets (Dunmore Corporation or Multek Inc.) are patterned via laser ablation. Metallized Kapton sheets are coated with 300 Å of aluminum

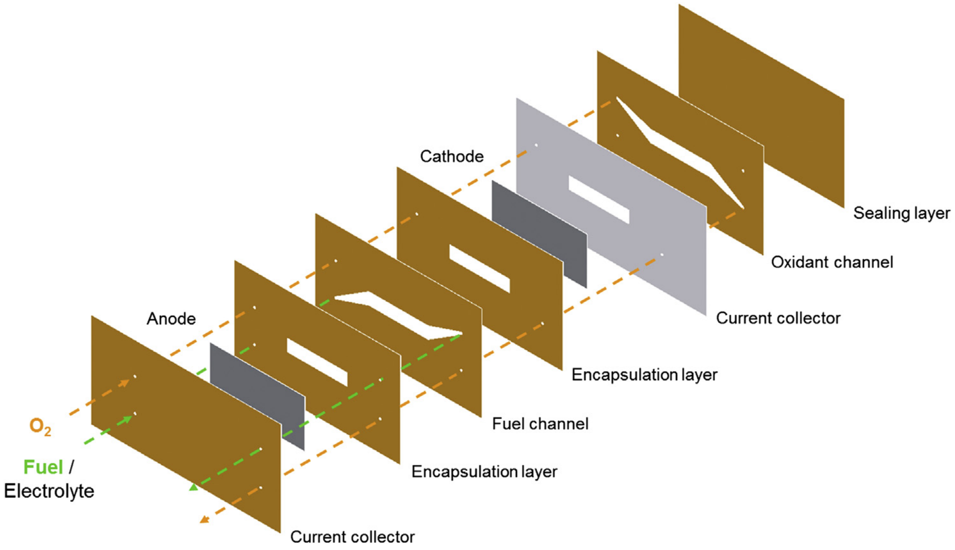

Fig. 1. Schematic of an all-polymer LFFC for manufacturing thin, lightweight fuel cell stacks. Anode and cathode layers are carbon paper, while other layers are laser-machined from Kapton (50 μm or 125 μm thick). Current collectors are Kapton layers that are metallized with aluminum to facilitate conduction of electrons. The fuel is methanol, the electrolyte is sulfuric acid, and the oxidant is oxygen.