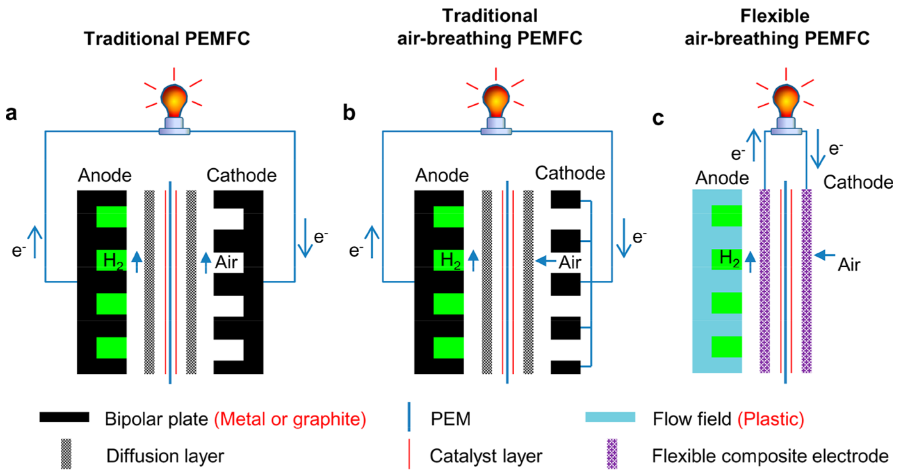
Scheme 1. Structures of Different PEMFCs.[a]



[a](a) Structure of traditional PEMFC. Air or O_2 is pumped into PEMFC. (b) Structure of traditional air-breathing PEMFC. Air naturally diffuses into PEMFC. (c) Structure of flexible air-breathing PEMFC in this research. Air naturally diffuses into PEMFC. In parts a and b, rigid, heavy, and expensive metal or graphite bipolar plates are used as flow field and current collector for both anode and cathode. In part c, the plate on the cathode side has been totally removed, and the plate on anode side has been replaced by a light, flexible, and cheap plastic plate.

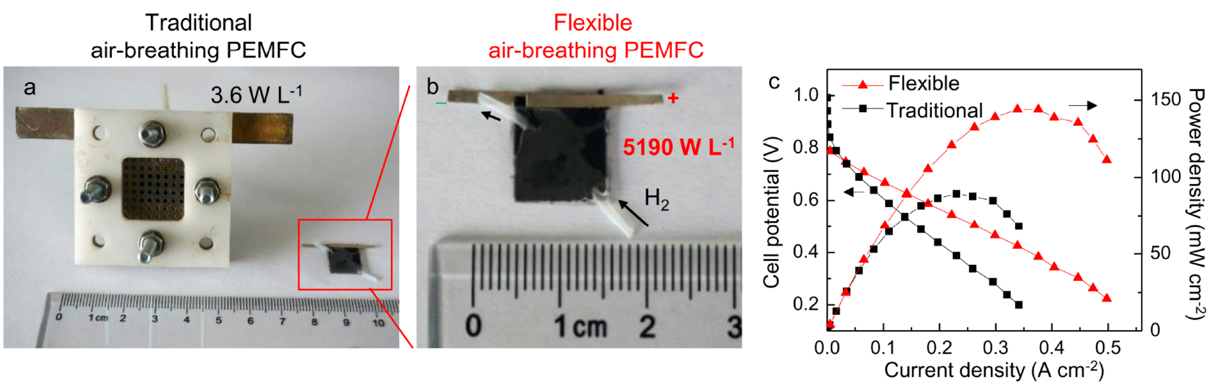


Figure 1. Performance of flexible and traditional air-breathing PEMFCs with the same working area (1×1 cm^2). (a) Photograph of traditional and flexible air-breathing PEMFCs. (b) Enlarged photograph of flexible air-breathing PEMFC. (c) Polarization curves of traditional and flexible PEMFCs. The experiments were performed with pure hydrogen at 20 °C and atmospheric pressure. Anode Pt loading (0.5 mg cm^{-2}), hydrogen flow rate (15 mL min^{-1}); Cathode Pt loading (0.5 mg cm^{-2}), air.

high energy density (39.7 kWh kg^{-1} for H_2), high conversion efficiency, environmental friendliness, and compact design.[27] Currently, the specific area power density can be up to 1570 mW cm^{-2} or higher.[28] The highest specific volume and weight power densities, 3.1 kW L^{-1} and 2.0 kW kg^{-1}, were declared for a PEMFC stack by TOYOTA company. However, traditional PEMFCs use graphite or metal plates for the flow channel and the current collector, which are usually too heavy, rigid, bulky, and expensive for flexible devices (Scheme 1a).[29] These plates are responsible for up to 80% of total stack weight, 90% of stack volume, and about 30% of cost.[30] In addition, air or O_2 needs to be pumped into the PEMFC for electrochemical reaction.

In order to make PEMFCs favorable for portable devices, the structure and operation of the PEMFCs were simplified, and a kind of air-breathing PEMFC was invented (Scheme 1b).[31] In such traditional air-breathing PEMFC (Scheme 1b), air naturally diffuses into the PEMFC and no pump for air is needed. However, the heavy, rigid, bulky, and expensive graphite or metal plates are still used in the traditional air-breathing PEMFC (Scheme 1b). Moreover, the specific area power density is usually between 100 and 200 mW cm^{-2},[32] which causes a much lower specific weight power densities (1.761 W kg^{-1}).[33] So far, there is an urgent need for a lightweight and flexible PEMFC satisfying the demands of flexible electronic devices.

On the other hand, the preparation of a flexible electrode is one of the challenges in preparing a flexible PEMFC. In conventional PEMFCs, carbon paper is usually used as the electrode, because the carbon fiber in carbon paper has high stability and proper dimension in micrometer size, which is beneficial to mass transfer and supporting catalyst. But it is not suitable to directly use carbon paper in a flexible PEMFC because of its brittleness and relatively low electrical conductivity.

In current flexible devices, carbon nanotubes (CNTs),[34,35] graphene,[36,37] conducting polymers,[38,39] Si or Ag nanowires,[40,41] and carbon cloth[42] were usually used as basic materials to prepare flexible electrodes because they have high specific surface area and high electrical conductivity.[43,44] These materials have a common feature, which is the nanometer width or thickness and micrometer length or area. This feature gives the materials high conductivity and high mechanical strength. Moreover, CNTs and graphene are currently commercially available in massive amounts, which is advantageous to the

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