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Optimized Design of the MEMS Micro-Fuel Cell System Structure

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Abstract: With the trend toward miniaturization and integration in modern electronic devices, micro fuel cells have gradually become the ideal power source for portable devices due to their efficiency and environmental benefits. However, the existing micro fuel cell stack structures exhibit certain limitations in terms of electrical connection impedance, volume optimization, and fuel distribution. This paper proposes a planar micro-fuel cell stack cascade structure based on a "twisted strip structure." The twisted strip design optimizes the arrangement of individual cells, achieving higher spatial integration and reduced electrical connection impedance. Additionally, the use of shared bipolar plates and precision microchannel design ensures uniform fuel distribution, further enhancing the power output and reaction efficiency of the stack. The paper also discusses in detail the technical implementation, manufacturing process, and performance testing methods for this design. Experimental results show that this design offers significant advantages in improving the performance of the stack and reducing manufacturing costs, with promising applications in portable electronic devices and IoT sensors.

Keywords: MEMS micro-fuel cell; Twisted strip structure; Cascading battery stacks; Electrical connection impedance; Machining

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1. Introduction

With the continuous development of modern electronic devices in the direction of miniaturization and integration, energy supply has gradually become a key bottleneck restricting the development of miniaturization technology. In the future, MEMS (microelectromechanical systems) micro fuel cells have great potential for applications in small portable electronic devices. It not only features high energy density, environmental friendliness, and quick start-up, but also facilitates integration, making it an efficient solution for microenergy supply [1,2]. In recent years, researchers have made significant progress in the basic theory, structural design, and process manufacturing of MEMS micro fuel cells. According to the working principle and fuel type, micro fuel cells mainly include micro proton exchange membrane fuel cells (μPEMFC), micro direct methanol fuel cells (μDMFC), and micro solid oxide fuel cells (μSOFC). Compared with traditional power supplies, micro fuel cells have higher power density and lower operating voltages (usually between 0.2–0.4 V), so in practical applications, multiple battery cells need to be integrated into the stack in a cascade to meet the needs of higher power output. The design and fabrication of the micro fuel cell stack structure is one of the keys to realizing the application of MEMS micro fuel cells.

2. Introduction to MEMS micro fuel cell system structure design technology

2.1. Basic structure and working principle of MEMS micro fuel cells

MEMS micro fuel cells are an innovative micro-energy device that provides high-density energy for small electronic devices through micro-scale fuel cell design. The working principle of micro fuel cells is based on an electrochemical reaction, in which a fuel (such as methanol or hydrogen) undergoes an oxidation reaction at the anode, releasing electrons and protons, which generate current through the outer circuit, while protons migrate to the cathode through the electrolyte membrane and eventually undergo a reduction reaction with oxygen at the cathode to produce water [6]. During this electrochemical reaction, the output voltage is low, and it is usually necessary to connect multiple single cells in series or parallel to form a battery stack to achieve the voltage and power required for practical applications.

2.2. Common structural design of micro fuel cell stacks

The integrated structure design of micro fuel cells is usually divided into two methods: overlapping structure and planar structure (Figure 1). Each structural design has its own characteristics and limitations in terms of space utilization, fuel transmission efficiency, and power output stability.

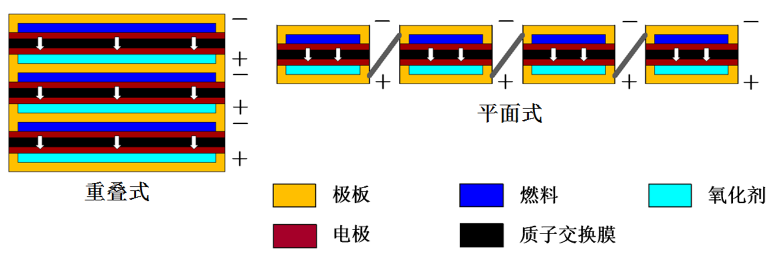

Figure 1. Schematic diagram of the cascade method of micro fuel cell stacks.

The overlapping structure uses a multi-layer stacking method to connect the battery cells in series through conductive bipolar plates, thereby effectively reducing the volume [7]. This structure achieves a high-density arrangement of single cells through upper and lower stacks, which is common in thicker cell stack designs. The overlapping structure design is characterized by reducing the plane space and increasing the current density, but due to the high resistance of the electrical connection between the cells and the long transmission path of the fuel, it can easily lead to uneven reaction and affect the overall performance. The planar structure is to distribute the battery cells in a plane manner, and the electrical connection between adjacent cells is achieved through the electrode layer [8].

In the design of MEMS micro fuel cell stacks, the fuel supply mode is crucial for the performance stability of the battery stack, and two main methods are currently used for parallel supply and serial supply (Figure 2).

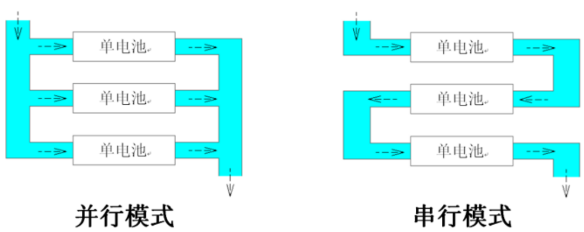

Figure 2. Supply model schematic diagram.

The parallel mode [9–12] ensures that each cell supplies fuel independently and the reactant concentration remains consistent, effectively preventing fuel leakage. However, the fuel flow rate is low in parallel mode, resulting in some fuel waste, and it is easy to swell of the monomer membrane electrode or the product blocks the flow channel, resulting in transmission resistance and affecting the uniformity of anode fuel distribution.

There are still some key technical problems in the structural design of MEMS micro fuel cell stacks:

(1) High electrical connection impedance

In series or parallel stack structures, the electrical connections between cells often lead to additional resistance, affecting the overall efficiency of the stack. High impedance can lead to power loss, reducing the actual output of the system.

(2) Structural complexity and encapsulation

The design of micro fuel cell stacks requires the integration of multiple battery cells, and the complexity of the integration structure and the packaging process puts forward high requirements for the stability and reliability of the battery stack. Improper packaging can lead to fuel leakage and incomplete reactions, affecting the durability of the battery stack.

(3) Requirements for microfabrication technology

The manufacture of micro-fuel cell stacks requires sophisticated microfabrication techniques [14], such as the fabrication of microchannels and the microfabrication of electrodes. Battery cells of different materials and structures have their own requirements in the processing process, and the processing accuracy and material compatibility must be ensured.

3. "Twisted Ribbon Structure" planar micro fuel cell stack cascade structure scheme

3.1. Design ideas and innovations

The core of the "twisted ribbon structure" planar cascade scheme is to change the linear connection method in the traditional planar cascade structure to a twisted strip design, so as to maximize the arrangement density and electrical connection efficiency of the single cell in a limited space. By introducing twisted ribbon structures into battery stacks, several innovative advantages can be achieved:

(1) Compact plane distribution

Compared with traditional flat or overlapping structure designs, the twisted ribbon design reduces the distance between battery cells, improves space utilization, and makes the entire battery stack more compact, which is conducive to meeting the stringent volume requirements of micro devices.

(2) Reduces the impedance of the electrical connection

The strip-like twist structure effectively reduces the electrical connection path. The design of the shared bipolar plate concentrates the electrical connection in the ribbon-like bipolar plate region, significantly reducing the electrical connection resistance and improving the output efficiency of the battery stack.

3.2. Physical design of the twisted ribbon structure

In the "twisted ribbon structure" design, each cell in the battery stack is arranged in a ribbon pattern, which ensures high space utilization and structural stability of the battery stack in the plane. Here are some of the key parts of the design.

(1) Bipolar plate shared design

In the traditional planar cascade structure, the battery cells need to be connected by their respective electrodes. In the "twisted ribbon structure," adjacent single cells are electrically connected by sharing bipolar plates. This design not only reduces the resistance of the electrical connection but also improves the reliability and mechanical strength of the connection. By optimizing the layout of the bipolar plates, the overall thickness of the battery stack is reduced, further improving the compactness of the structure.

(2) Microfluidic design

To ensure that the fuel flows evenly through each cell of the battery, the design uses a precise microfluidic layout. Micromachining technology is used to ensure that the flow rate of fuel is uniform between each monomer, thus avoiding the decrease in reaction efficiency caused by inconsistent flow rates.

(3) Membrane electrode structure

In battery cells, the structure of the membrane electrode is crucial, and it directly affects the electrochemical properties of the battery. In the "twisted ribbon structure," the membrane electrode adopts a combination of spraying and transfer methods to ensure the uniformity and activity of the membrane electrode, improving the overall reaction efficiency.

3.3. Manufacturing process of ribbon structure

The fabrication of "twisted ribbon" planar micro fuel cell stacks involve several key processes, such as micromachining, spraying, and transfer. Here's how each process is implemented:

(1) Micromachining technology

For the precise fabrication of bipolar plates and microfluidic devices, advanced micromachining techniques are employed. This process ensures the high-precision structure of the battery stack, which can meet the requirements of small size, micron-level processing, and ensure the stability of the structure.

(2) Spraying and transfer process

The spraying method is used to evenly coat the catalytic layer on the electrode surface, while the transfer method is used to transfer the membrane electrode to the surface of the cell. The combination of these two processes results in a uniform and stable thickness of the membrane electrode, thereby ensuring the electrochemical properties of the battery stack.

3.4. Advantages of the scheme

The "twisted ribbon" planar micro fuel cell stack offers significant advantages.

(1) High spatial integration

The ribbon design improves the integration of the battery stack and effectively reduces the size of the battery stack, making it suitable for miniaturized electronic devices.

(2) Low electrical connection impedance

The electrical connection impedance is greatly reduced, improving the efficiency and output power of the battery stack.

(3) Fuel distribution evenly

The ribbon structure ensures performance fluctuations caused by unreasonable supply patterns in traditional structures.

4. Technical route and feasibility analysis

The technical route is a key step in the entire project from theoretical research to experimental verification, ensuring the feasibility and efficiency of the proposed scheme through effective modeling, design and experimental verification. This paper conducts an in-depth analysis of the equivalent modeling, manufacturing process, and testing methods of the battery stack to ensure the feasibility of the design scheme in theory and practice.

4.1. Technical route

The technical route of this project is shown in Figure 3. Based on the previous research of micro fuel cell experiments, an equivalent circuit model of the structure of the micro fuel cell stack is established based on the existing monomer mathematical model, and the influence of fuel concentration, flow rate, and temperature on the polarization characteristics of the battery stack is analyzed. The equivalent model is used to simulate and analyze the influence of the cascade mode and fuel supply mode on the performance of the stack, so as to realize the optimal design of the micro fuel cell stack structure. According to the design results, the cathode and anode plate structure of the micro fuel cell stack is realized on PDMS or silicon substrate by micromachining technology. The membrane electrode, fuel supply system, collector plate, and reaction chamber are encapsulated to form a miniature fuel cell stack. A test system platform is established to test the polarization performance of the battery to verify the correctness of the model and optimized design.

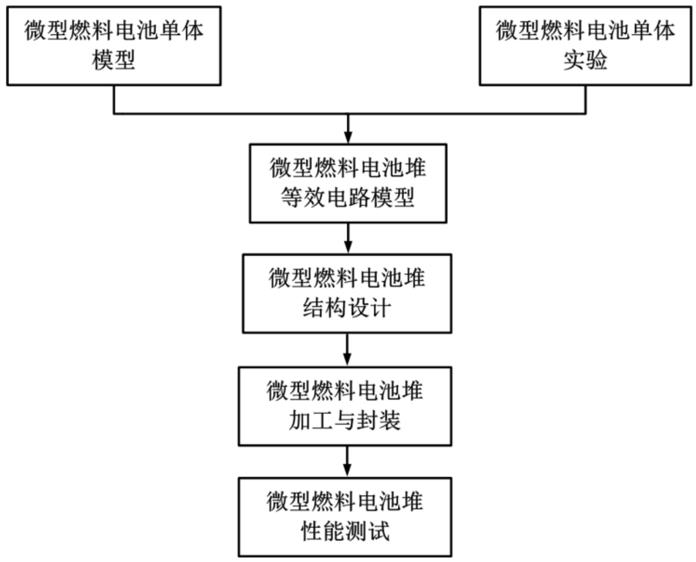

Figure 3. Design scheme diagram.

4.2. Feasibility analysis

4.2.1. Equivalent modeling

An equivalent circuit model of a micro fuel cell stack is established to provide theoretical support for subsequent design and optimization. According to the working principle of MEMS micro fuel cell stacks, the gray box model method is used to establish the equivalent circuit model of the battery stack by combining the existing single fuel cell model, as shown in Figure 4. The influence of fuel cell operating parameters (such as fuel concentration, flow rate, temperature, etc.) on the output performance of the battery stack is studied through this model. Meanwhile, in this model, the working performance of the battery stack is described by parameters such as voltage, current, and resistance. The model can realize the optimization and analysis of different design schemes.

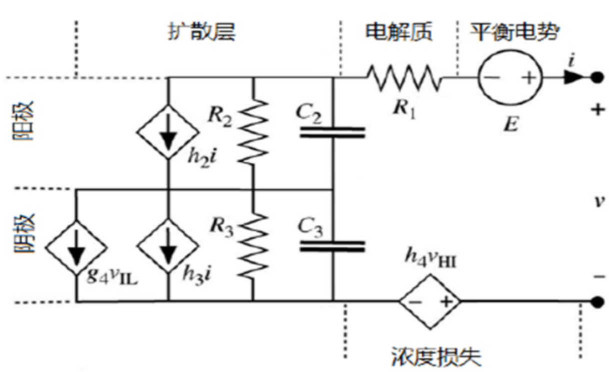

Figure 4. Battery stack circuit schematic diagram.

4.2.2. Research on microfabrication methods for MEMS micro fuel cell stack structures

Based on the previous research on the processing method of micro fuel cell monomer, it's proposed to use micromachining technology to realize the patterning of the flow field structure of the negative and yang collector plates of the micro fuel cell stack on a silicon substrate or a PDMS substrate. Considering the cascade method, this paper proposes a planar micro fuel cell stack structure based on the “twisted ribbon structure”. The series connection between adjacent cells of the battery stack is not completed by the electrical connection between the electrode layers of the cell membrane, but by using a common bipolar plate with a gold-plated layer between adjacent cells, which is conducive to the miniaturization and integration of the battery stack.

4.2.3. Research on test methods for MEMS micro fuel cell stacks

The characteristics of voltage-current, power-current, and other characteristics of micro fuel cell stacks are tested by various methods, such as constant current (voltage) discharge, and key parameters such as output power and work efficiency are evaluated. The impedance measurement of the fuel cell stack is proposed to use the AC impedance method, and the numerical fitting method is used to quantitatively interpret the spectrum to obtain a more specific and quantitative polarization loss analysis. The micro fuel cell stack working condition test is planned to use the multi-parameter orthogonal test method (including fuel concentration, inlet flow rate, pressure, temperature, cathodic oxygen pressure, and other parameters) to test the power, life, stability, and other performance. In addition, the test will also draw on the currently widely used battery power supply test standards to test the battery stack in terms of short-circuit.

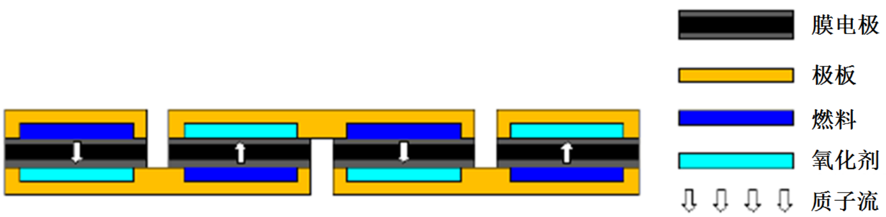

Figure 5. Planar micro fuel cell stack structure.

5. Simulation experiments

In order to verify the performance of the “twisted ribbon structure” planar micro fuel cell stack cascade structure, the method of computational fluid dynamics (CFD) combined with circuit simulation is adopted. CFD simulation is used to simulate fuel flow, reactant concentration distribution, and temperature field, while circuit simulation is used to evaluate the performance of electrical connection impedance and power output. Among them, CFD simulation uses ANSYS Fluent software to simulate the fluid dynamics of fuel cell stacks to simulate fuel flow, gas exchange, and reaction efficiency. Circuit simulation uses the electrochemical module and circuit simulation module in COMSOL Multiphysics software, combined with the simulation modeling method, to calculate the current-voltage characteristics, electrical connection impedance, and power output characteristics of the micro fuel cell stack, and analyze the steady-state and dynamic response characteristics of the battery stack.

5.1. Simulation steps

(1) Simplified models of traditional structure, twisted strip structure batteries are modeled and configured in ANSYS Fluent software.

(2) An electrochemical model is established in COMSOL software to simulate the current-voltage characteristics of the fuel cell stack, and the electrical connection impedance and power output are calculated.

5.2. Simulation results and analysis

Table 1 shows the simulation results of electrical connection impedance, power output, and reaction efficiency. Twisted structures exhibit distinct advantages in electrical connection impedance. The lower electrical connection impedance effectively reduces energy loss, which is about 15% lower than conventional structures, thereby improving the overall efficiency of the battery stack. At the same time, under the same operating conditions, the power output of the twisted structure is significantly higher than that of the traditional structure, which is about 20% higher than that of the traditional structure, indicating that the design can effectively improve the power density and reduce the power attenuation.

Table 1. Simulation results

Electrical connection impedance (Operating current density: 0.5 A/cm²)		Power output		Reaction efficiency	
Structure	**Distorted structure**	**Traditional structure**	**Distorted structure**	**Traditional structure**	**Distorted structure**
12.5 Ωcm2	10.5 Ωcm2	35 mW/cm2	42 mW/cm2	85% (Fluctuates under high-load conditions and decreases significantly when fuel concentration distribution is uneven)	92%

6. Conclusion

The “twisted strip structure” planar micro fuel cell stack cascade structure scheme proposed in this paper shows significant advantages in improving the integration of battery stacks, reducing the impedance of electrical connections, and optimizing fuel distribution. By introducing an innovative design with a ribbon structure, the connection path between battery cells is reduced, improving the power output and energy density of the battery stack. At the same time, the existing micromachining, spraying and transfer processes are used to make the design have strong manufacturing feasibility and meet the energy supply needs of microelectronic devices for compact and efficient energy.

Disclosure statement

The author declares no conflict of interest.

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