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Review

On-chip micro/nano devices for energy conversion and storage

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ABSTRACT

The evolution of next-generation energy technologies is growing in importance as the global demand for energy skyrockets. Nanotechnology and nanomaterials are critical in the creation of next-generation energy technologies. However, it is currently highly problematic to elucidate the unique properties of nanomaterials by conventional characterization methods. Hence, tailored micro/nano devices present potentially powerful opportunities as significant proof-of-principle tools for investigating the essential structures and properties of nanomaterials. Meanwhile, these devices became increasingly sophisticated in their ability to monitor individual nanomaterials under operando conditions. This review summarizes recent progress of on-chip micro/nano devices with a particular focus on their function in energy technology. Recent studies on energy conversion devices and electrochemical energy storage devices are introduced and the special design/role of these devices are emphasized. It is expected that this review will promote further research and broaden the applications potential of on-chip micro/nano devices, thus contributing to the development of energy conversion and storage technologies.

Contents

Introduction

As society advances in terms of both growing energy needs and reducing environmental footprint, the evolution of next-generation energy technologies is becoming increasingly significant [1,2]. And given the myriad of current and looming problems associated with climate change, the scientific and engineering communities are

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striving to develop cleaner/greener energy sources that could slow the progress of global warming—while at the same time ensuring energy security and a ready supply of power [3,4]. In terms of energy conversion, most of alternative sources of energy should eventually be converted to electricity that can be conveniently used and stored [5,6]. When considering energy conversion, efficiency remains a fundamental factor that must be taken into account, and researchers are pursuing such avenues in more eco-friendly ways [7]. In terms of energy storage [8], for instance, electrochemical devices such as batteries [9–13] and electrochemical capacitors [14–17] are widely used to store energy. In order to develop high-performance devices, one needs to consider certain factors—namely, the energy density, power density, rate performance, and cycling performance [11,18–20]. However, it remains challenging to successfully address these various demands while also accommodating the growing energy requirements of the public [21–24]. Commonly, it is attributed to the slow development of key functional materials that is disjointed to the rapid increasing energy demand [25].

In recent decades, the realm of nanotechnology has been playing an ever-increasing role in advancing the energy science and technologies [26–32]. Indeed, the application of nanomaterials represents somewhat of a milestone in the development of next-generation energy conversion and storage capabilities [33,34]. As a general definition, nanomaterials feature at least one dimension that is sized between 1 and 100 nm. Depending on their size, nanomaterials are endowed with geometrical advantages for measurement and characterization under operando conditions [35,36]. Meanwhile, in practical energy devices, functional material components are fabricated by specific processing methods in order to obtain enough tap density and mechanical properties. [37,38] Undoubtedly, the unique properties of nanomaterials will be suppressed by traditional processing methods to some extent [39,40]. Although extensive of advanced nanomaterials have been developed for energy conversion and storage, the evaluation methodology has always been following the traditional methods which fabricate materials in bulk and test by practical macro devices [41]. This evaluation methodology pays more attention to the application potential and the aggregate properties while neglects the uniqueness of nanomaterial itself (*e.g.*, reduced dimensions and confined electronic properties). In physics communities, researchers have been devoted to studying the novel physical phenomena by on-chip micro/nano devices as they can detect the signal from specific low dimensional material with controlled thickness, size, crystal orientation, heterostructure, external field, *etc* [42–47]. Nevertheless, on-chip micro/nano devices haven't been widely applied in the field of energy conversion and storage. This may be attributed to the complex configurations of energy devices and the immature theoretical model. For instance, a typical lithium ion battery consists of positive electrode, negative electrode, electrolyte, current collector and membrane [48,49]. How to simplify these complex practical configurations (with electrochemical reaction) to a simple model in a micro/nano device was the first problem, especially in a single nanowire electrode system [50]. The second problem lies in how to get precise and high-quality signal of the individual nanomaterial under such complex conditions. The third problem is what important information can be achieved by on-chip devices. It is well-known that the evolution of nanomaterials has given birth to new characterization and diagnosis approaches [51–56]. Researchers have successfully addressed these three problems by well-designed on-chip devices and combing them with advanced characterization/measurement technologies. Firstly, the basic configuration of common energy conversion and storage devices is functional material-based closed circuit, which can be realized through modified on-chip physical devices fabricated by conventional microelectronics technology. Secondly, due to the high internal impedance (megohm) and small current level (picoamps or nanoamps), amplifying circuit and valid encapsulation are applied to get precise signals from individual nanomaterials. Thirdly, the importance of on-chip micro/nano devices are incarnated in the ability to focus on the specific region and materials and get real-time signal to investigate the information of materials.

This review aims to summarize the progress of on-chip micro/nano devices for energy technologies and present the fundamental methodology for designing and fabricating on-chip devices for *in situ* characterization or practical application. Herein, we focus on micro/nano devices, especially individual nanomaterial devices, which can play a critical role in investigating and determining special physicochemical properties in depth. These devices provide a platform for fully developing the natural advantages of nanomaterials, including the ability to obtain highly accurate measurements and *in-situ* monitoring of the characteristics of electrode materials in electrical/electrochemical processes. [11,50] It is worth noting that when designing the on-chip micro/nano device, the microfabrication processes are mainly depended on the detailed problems and limited by the combined characterization methods. Hence, the scope of this review is to give a systematic summary of fundamental application and architectures of on-chip micro/nanodevices, which is expected to favor the further research in energy-based materials science and technologies.

In this review, we present recent progress on advances in nanomaterial-based micro/nano devices from two perspectives: energy conversion and energy storage. The typical design and application of micro/nano devices are emphasized. In the field of energy conversion, we review photovoltaic devices, photoelectrochemical devices, thermo-electric devices, electrodialysis and blue energy devices, and electrocatalytic devices. In the field of energy storage, research on single nanowire electrochemical devices, individual nanosheet electrochemical devices, and on-chip micro-supercapacitors are presented. Finally, a brief analysis of current on-chip devices is provided, followed by a discussion of the future development of micro/nano devices. It should be noted that, we have weakened the in-depth analysis of performance data, but focus on exploiting the relationship among the device structure, the unique material properties and characterization methods.

On-chip micro/nano energy devices

As a functional material for energy conversion and storage, it should be integrated into specific device with essential configuration and structure to realize basic functions. It is necessary to make it clear that different devices have different structures and functions. The comparison of practical devices, experimental devices and on-chip devices are shown in Fig. 1a-c. Three examples, solar cell, fuel cell and Li-ion battery are compared with the corresponding experimental devices and on-chip micro/nano devices with simplified configuration. For practical application, energy devices aim for daily using, and should satisfy the requirement industrial manufacture and customer. [57,58] For basic scientific research, energy devices can be thought as prototype devices with simplified components, which facilitates the precise measurement and principle validation [59,60]. Herein, on-chip micro/nano devices should be assigned to a kind of research-oriented devices but essentially different from conventional experimental devices [61]. In a typical on-chip micro/nano device, active material is the core. That means the essence of the complex on-chip device is to extract and record the signal of specific materials and local regions, especially individual nanomaterial. The energy-based on-chip micro/nano devices initially rooted in physical devices and gradually developed into unique and significant research platform.