Nanofabrication Using Viral Biotemplates for MEMS Applications

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PIs: **Reza Ghodssi and James Culver**

University of Maryland, College Park

Abstract: This poster summarizes the progress achieved by the research teams of Dr. Reza Ghodssi and Dr. James Culver at the University of Maryland. In this NSF-funded work, we have developed novel techniques for the synthesis and assembly of nanostructured materials using a biological molecule, the Tobacco mosaic virus (TMV). The synthesized materials have been used as battery electrodes and sensor layers and have demonstrated a notable improvement in device performance. This approach, combined with the patterning capabilities of the viral nanostructures, provides an exciting alternative for the integration of nanostructures in functional microfabricated devices.

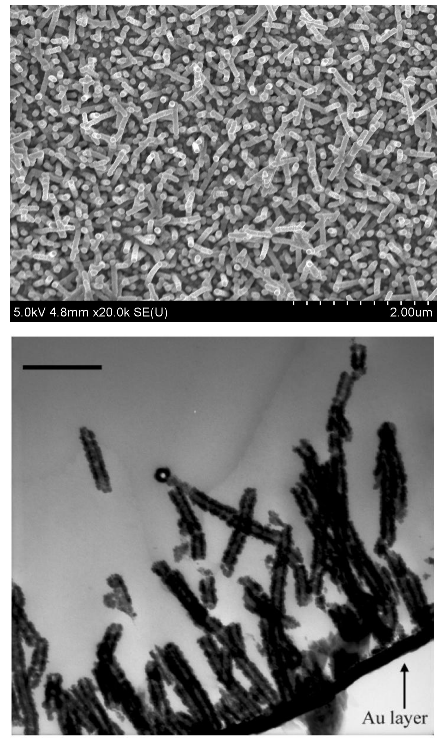

Figure 1: (a) SEM image of nickel-coated TMV assembled on a gold substrate; (b) cross-section TEM images of the virual nanostructures [1] – scale bar is 300 nm.

1. Introduction: Nanostructured materials offer significant advantages compared to their bulk counterparts such as improved mechanical stability, faster ion/electron kinetics, higher surface areas and higher sensitivities. These properties make ideal candidates for next-generation energy storage, sensors, and electronic devices. However, the ability to orderly arrange nanostructures in functional devices is often the bottleneck. Interestingly, novel functionalities that can be imparted on biological molecules such as proteins, DNA and viruses create alternative pathways for the synthesis and assembly of nano-sized materials. One such biological molecule is utilized in our research. The *Tobacco mosaic virus* (TMV) is a cylindrical plant virus measuring 300 nm in length with a diameter of 18 nm. It can be genetically modified to include functional groups with enhanced metal binding properties. As a result, TMV mutants that self-assemble onto various substrates and promote the assembly of inorganic materials can be achieved.

2. Virus-structured Materials for Battery Applications: In previous work, this process was used for the synthesis of metallic nanorod structures that can self-assemble onto gold coated substrates [1] (Fig. 1). They were also integrated in the development of a first-generation proof-of-concept nickel-zinc microbattery device [2]. In an effort to further increase the energy and power density of microbatteries, Li-ion chemistry appears as the most promising technology. However, Li-ion battery materials often include complex structures (oxides, sulfides, phosphates) or semiconductors and metals (Si, Ge, Sn) that cannot be easily fabricated with wet chemical methods directly on biological materials. In addition to the difficulty in processing, their

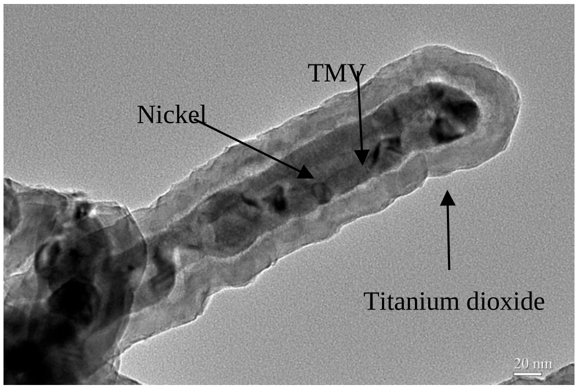

Figure 2: TEM image of a core/shell nanocomposite anode using TiO_2 as the active material.

conductivity can be a limiting factor. We have been able to address these limitations by using the nickel-coated TMV nanostructure as a scaffold for the assembly of active materials using conformal deposition methods such as Atomic Layer Deposition (ALD). ALD is in ideal technique for the uniform and controlled coating of complex three-dimensional nanostructures. As a result, a core/shell nanocomposite electrode can be synthesized (Fig. 2).

The material selected to demonstrate the concept of this novel electrode architecture was titanium dioxide (TiO_2), a promising anode due to its increased safety compared to graphite. Electrochemical tests of electrodes with and without TMV demonstrated a significant increase in capacity and faster ion kinetics for the virus-structured anodes compared to the planar thin films [3]. This is a direct result of the increased surface area of the viral nanostructures that provide more sites for electrochemical reaction as well as the existence of a conductive nickel core under the active material that allow charging and discharging of the batteries at higher current rates (Fig. 3). This method can be expanded similarly to the fabrication of cathode materials and electrolytes and lead to the production of fully virus-structured batteries.

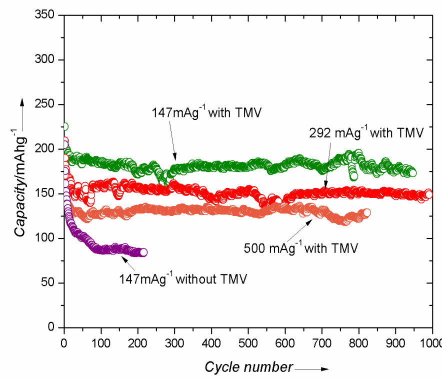

Figure 3: Capacity vs. cycle number for electrodes with and without TMV at different current rates.

3. TMV-based Receptors for Explosive Sensing: In addition to their application in energy, TMV-structured materials can be used to increase the sensitivity and selectivity of sensors for explosive detection. In this work, we have engineered a modification of the virus that combines two functional groups: 1) the surface-attaching amino acid used previously (1cys) and 2) a peptide that shows specific binding affinity to TNT. As a result, self-assembled, virus-structured receptor layers that show high sensitivity to TNT have been developed. This first-generation of functionalization nanolayers were tested in quartz crystal microbalances (QCM) that were exposed to saturated TNT vapor [4]. Devices with the engineered peptide (TNT-TMV) demonstrated a higher increase in added mass compared to both non-functionalized and

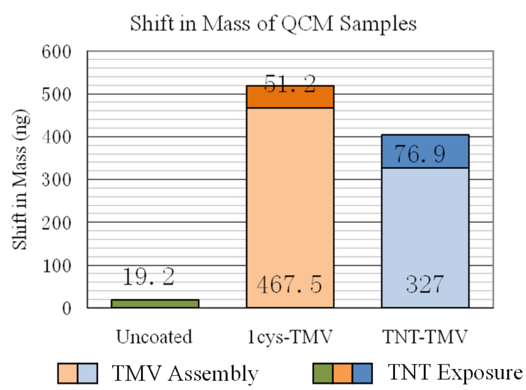

Figure 4: Mass shift for TNT sensors exposed to TNT vapor.

1cysTMV-functionalized sensors, even though the virus coverage was better in the case of the 1cysTMV. This result indicates the unique capabilities of engineered viruses as sensors for homeland security applications.

4. Patterning Capabilities of TMV: A unique characteristic of our TMV templating approach lies in the capability to photolithographically pattern both uncoated and metal-coated TMV onto hierarchical two and three-dimensional architectures [5]. The robustness of the TMV template allows its integration with standard top-down photolithography. Using lift-off or patterning and etching, nickel-coated TMV arrays can be defined onto gold-coated silicon wafers (Fig. 5(a)). This process can also be used to pattern the uncoated TMV, thus enabling fabrication of microsensors with selectively patterned receptor layers. Simultaneously, the unique feature of the self-assembly allows expansion of the surface texturing process in three-dimensions, a task often difficult using traditional nanomaterials synthesis methods. As a result, hierarchical battery electrodes with both micro and nano components can be realized and lead to a multiplied increase in surface area (Fig. 5(b)).

5. Intellectual Merit and Broader Impact: The research conducted in this project bridges the worlds of biology, nanotechnology and fabrication and leverages on expertise from interdisciplinary areas such as biology and protein engineering, materials science, electrochemistry and electrical engineering. The results that we have obtained so far provide insight into the benefits of using nanostructured materials in applications such as energy storage and explosive sensors. The materials and methodologies developed demonstrate a simple alternative solution for the integration of multi-functional nanostructures in batch-fabricated devices. In addition to the development of functional materials and surfaces for practical applications, the virus-templating processes can be used for basic science studies; for example, the study of novel phenomena at the nanoscale such as water droplet impact on hierarchical architectures that mimic the structure of plant leaves [6].

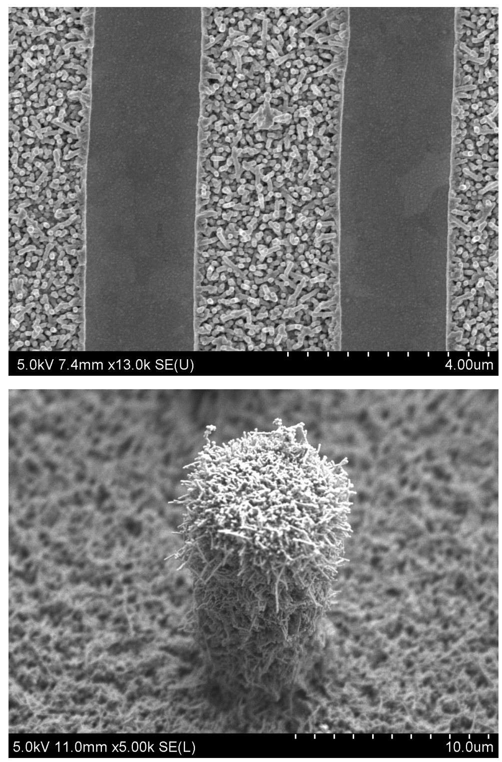

Figure 5: (a) Ni-coated TMV lines patterned on a silicon wafer; (b) polymer micropost textured with Ni-coated TMV

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