SPIE Newsroom

10.1117/2.1201204.004201

Toward optoelectronic textiles

Liang Dong

Coaxial electrospinning produces a self-supporting micro/nanofiber electronic light source.

Fabric electronic light-emitting devices (LEDs) in fiber form may lead to revolutionary applications by integrating optical and optoelectronic devices into textiles. Many attempts have been made to develop electronic light-emitting fibers, which are generally fabricated by depositing multiple thin films onto a substrate fiber with a diameter ranging from several tens to hundreds of micrometers.

Smaller, more flexible light sources are highly in demand as part of an ongoing trend toward lightweight and conformable electronic and optoelectronic textile technology. Recently, light-emitting nanowires and nanotubes have been demonstrated via template-assisted synthesis,[1] vacuum sublimation,[2] and dip-pen nanolithography.[3] These techniques often suffer from a low fabrication throughput and a short device length. Electrospinning is a popular, simple, and versatile technique to generate micro/nanofibers from a good wealth of materials. It uses a high-strength electric field to draw a charged solution into a liquid jet from a nozzle. Moran-Mirabal and coworkers developed electronic light-emitting nanofibers by electrospinning ruthenium-based ionic transition-metal complex (iTMC) polymer onto interdigitated gold electrodes.[4] However, their nanofibers emit light only at discrete interelectrode intervals.[5] Pisignano and coworkers developed photoluminescent nanofibers of conjugated polymers, co-polymers, and their blends by combining electrospinning and nanoimprint lithography.[5] Unfortunately, being photoluminescent, their nanofibers require external optical excitations to emit light.

Generally, the most bulky part of a semiconductor device is its substrate, which is generally only structural and not functional. Without a substrate, a device would be more lightweight and flexible. Some researchers have used chemical methods to remove substrates after the device has been formed, but this post-processing was nontrivial and carried a risk of chemically destroying the device as well as the substrate. Our approach is to fabricate LED fibers in micro/nanofiber form with a high throughput but without a substrate.[6] We call these self-supporting light-emitting micro/nanofibers.

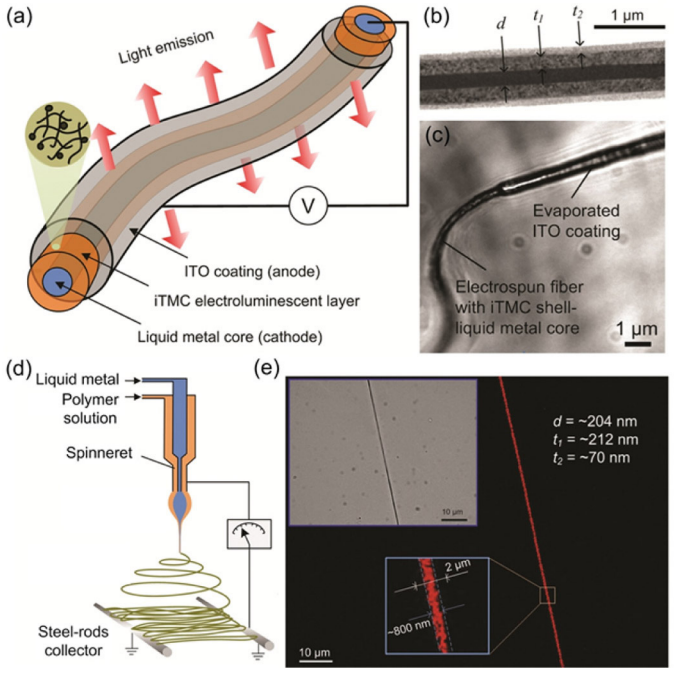

Figure 1. *(a) Schematic of a coaxial light-emitting nanofiber. (b) Transmission electron microscope image of the light-emitting nanofiber. (c) Optical image showing the ionic transition-metal complex (iTMC) shell at the end of the nanofiber. (d) Schematic setup of co-electrospinning. (e) Electroluminescence from the fabricated device captured by a CCD camera. ITO: indium tin oxide. d: Diameter of liquid metal core. t_1: Thickness of iTMC shell. t_2: Thickness of ITO coating. V: Voltage.*

The core of this idea is to integrate device layers coaxially into a single self-supporting micro/nanofiber. The three important layers include a cathode, an organic light emitting material, and an anode. As shown in Figure 1(a) and (b), the device consists of three coaxial layers within a single fiber. The innermost layer is a liquid core of highly conductive, continuous phase liquid metal Galinstan (conductivity: 3–4 × 10^6S/m at 20°C) as the cathode. (Galinstan is a metal alloy of 68.5wt% gallium, 21.5wt% indium, and 10wt% tin that is liquid at room temperature.) This liquid core is surrounded by a polymer shell

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of iTMC-based organic electroluminescent material drawn from a mixture of ruthenium(II) tris(bipyridine) and poly(ethyl oxide). The outermost coating is a highly conductive and transparent indium tin oxide (ITO) thin film as the anode, as shown in Figure 1(c). The device emits light when a voltage is applied between the cathode and anode: see Figure 1(e).

We used coaxial electrospinning, or 'co-electrospinning,' to enclose the Galinstan in the Ru-metal complex polymer shell. Co-electrospinning is a modified electrospinning method for making core-shell nanofibers. A co-electrospinning setup includes a high-voltage source, a fiber collector, and a concentric spinneret that allows delivery of Galinstan and Ru-metal complex polymer solutions independently by two individual syringe pumps: see Figure 1(d). Uniquely, fabrication of our light-emitting fibers did not need any initial substrate. Instead, the cathode (core) and the organic electroluminescent polymer (intermediate) were drawn out of the concentric spinneret into a nanofiber in air, and then fell onto a collector. We subsequently coated the nanofiber surface with the ITO anode layer, using a conventional evaporation technique. This method can render 1D light sources that are more flexible, lightweight, and conformable. Additionally, because the device fabrication process can start in air with co-electrospinning, we can choose a wide variety of materials (e.g., glass, metal, clothing, plastic) to collect the devices, reducing restrictions on the surface conditions and material properties of candidate collector materials.

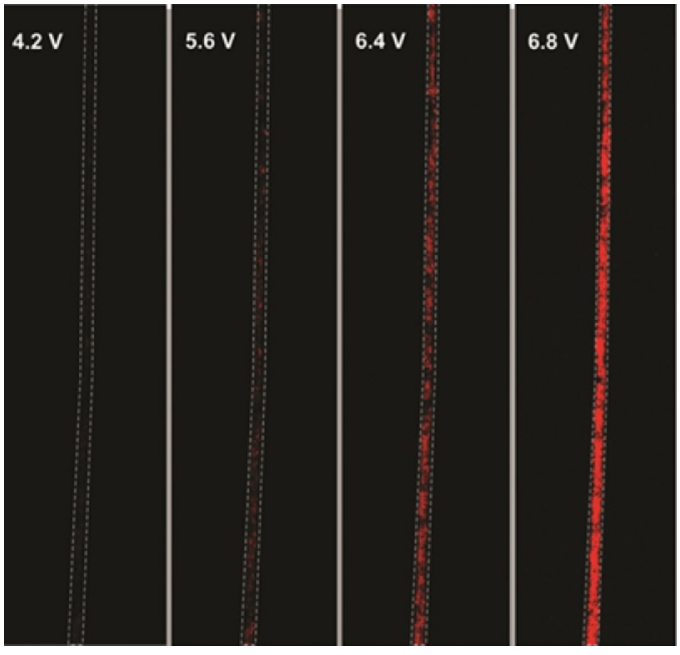

Figure 2. *Luminescence responses of the fabricated nanofiber to different voltages applied.*

Light emission from the fabricated nanofiber was detectable by a CCD camera at 4.2V applied under a nitrogen atmosphere, and could be seen by naked eyes at 5.6V: see Figure 2. We found that, as the applied voltage increased, electric current first increased with a gradual reduction in its rate of increase before subsequently increasing exponentially with rising applied voltage. The luminescence threshold voltage or turn-on voltage V_{th} was found to be around 4.2V. After the device was lit, its emission intensity followed a trend of exponential increasing with the voltage applied. The external quantum efficiency of the device was found[6] to be approximately 0.277% with a corresponding luminance of 23cd/m^2.

Electrospinning has been used in many textile applications, and so our self-supporting light-emitting nanofibers could be integrated into textile products. We are now working to optimize the lifetime and threshold voltage of the light-emitting nanofibers to improve performance and also to develop better ways to connect the fibers to external circuits for optoelectronic and electronic textile applications. We are also examining the potential use of electrospun multilayered coaxial nanofibers in other devices such as biosensors, actuators, high-resolution microscopy, and energy-harvesting devices.

Author Information

Liang Dong
Department of Electrical and Computer Engineering
Iowa State University
Ames, IA

Liang Dong received a PhD from Tsinghua University, Beijing, China, in 2004. From 2004 to 2007, he was a postdoc at the University of Wisconsin–Madison. Since 2007, he has been an assistant professor at Iowa State. His research focuses on developing lab-chips, micro-electromechanical systems, and nanotechnology.

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