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Flexible optoelectronic devices based on nitride nanowires embedded in polymer films

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Abstract

I will present our recent progress towards flexible nitride nanowire devices: we propose a method to combine high flexibility of polymer films with high quantum efficiency provided by nitride nanowires. The lift-off and transfer procedure allows to assemble free-standing layers of nanowire materials with different bandgaps without any constraint related to lattice-matching or growth conditions compatibility. This concept therefore provides a large design freedom and modularity since it enables combination of materials with very different physical and chemical properties, which cannot be achieved by monolithic growth.

1. Introduction

"Photonics Multiannual Strategic Roadmap 2014-2020" mentions flexible electronics, flexible light sources, displays and solar cells as key emerging technologies with high expected growth of the market share. Indeed, flexible devices offer new functionalities inaccessible with conventional technologies (e.g., rollable screens, bendable or implantable light sources, energy harvesters integrated in clothing, etc.) It is noteworthy that in the above-mentioned roadmap the notion of a «flexible device» is inseparable from an «organic device». Technologies based on organic semiconductors have indeed made a huge progress in the past 10 years, however organic devices still suffer from a short lifetime and low efficacy as compared to their inorganic counterparts. Yet inorganic semicondcutors are usually fabricated in the form of thin films and represent rigid structures, which makes fabrication of flexible devices rather difficult.

Semiconductor nanowires are characterized by a small footprint, high mechnical flexibility and long term stability. Optoelectronic devices based on these nano-objects can potentially reach high efficiencies both for light emission and for detection and at the same time enable mechanical flexibility.

2. Main results

In our work, we make use of nitride nanowires as an active material for flexible LEDs. Polymer-embedded nanowires offer an elegant solution to create flexible optoelectronic devices, which combine the high efficiency and the long lifetime of inorganic semiconductor materials with the high flexibility of polymers. Nanowire arrays embedded in a flexible film and lifted-off from their native substrate can sustain large deformations thanks to the high flexibility of individual nanowires and to their footprint much smaller than the typical curvature radius of the LED, which is of the order of a few millimeters or more.

We used self-assembled GaN nanowires grown on c-sapphire substrates by catalyst-free metal-organic chemical vapor deposition (MOCVD) [1]. These nanowires (length ~ 20 μm, radius ~ 0.5 – 1.5 μm) have a core/shell n-p junction incorporating radial InGaN/GaN multiple quantum wells. The emission color is controlled by changing the In concentration of the InGaN emitting layer. The device fabrication process of the flexible LEDs follows these steps [2]: the nanowire array is embedded into polydimethylsiloxane (PDMS), peeled-off from the sapphire host substrate and then the composite nanowire / polymer membrane is flipped onto an arbitrary holder for the metal back contacting. Then, the layer is flipped again and mounted onto a flexible substrate (metal foil or plastic) and then front-contacted by using a flexible and transparent electrode. For front-contacting, we have chosen a silver nanowire mesh, which is characterized by a mechanical flexibility, a good electrical conductivity and optical transparency.

Following this technological procedure, blue and green flexible nanowire LEDs were fabricated [2]. These devices can be bent to a curvature radius of approx. 3 mm without degrading their electrical or luminescent properties. Images of nanowire LEDs under operation are displayed in Figure 1. Contrary to OLEDs, flexible nanowire LEDs present a reasonable stability in time. Storage in ambient conditions for several months without any encapsulation does not degrade their properties.

Using this composite nanowire/polymer membrane architecture, we also realized a white flexible LED following the standard approach of down-converting blue emission with yellow phosphors to get white light by blue-yellow mixture.

To adapt this concept to flexible nanowire LEDs, we added yellow YAG:Ce nano-phosphors into the PDMS layer between the nanowires and covered the surface with an additional phosphor-doped PDMS cap [3]. The phosphor particles are smaller than 0.5 μm so that they can fill the gaps between the nanowires. The light emitted by the nanowires is partially converted by the phosphors from blue to yellow and a broad spectrum covering almost the full visible range is achieved. Flexible white LED under operation is shown in Figure 1.

The nanowire membrane lift-off and transfer procedure allows assembling free-standing layers of nanowire materials with different bandgaps without any constraint related to lattice-matching or growth conditions compatibility. This concept therefore provides a large design freedom and modularity, since it enables combination of materials with very different physical and chemical properties, which cannot be achieved by monolithic growth. We made use of this modularity to demonstrate a two-color device, combining 2 flexible LED layers containing different active nanowires as illustrated in Figure 1. A fully transparent flexible blue LED is mounted on top of a green LED. The devices can be biased separately producing either blue or green light or simultaneously producing a light mixture. The electroluminescence spectra of the different layers of the bicolor flexible LED are shown in Figure 1. As a perspective, the third red layer will be added to achieve a white flexible LED by combining red-green-blue colors. Development of pixels to move toward flexible displays in underway.

This lift-off technology can also be applied to other devices such as flexible nanowire-based photodetectors [4] or solar cells.

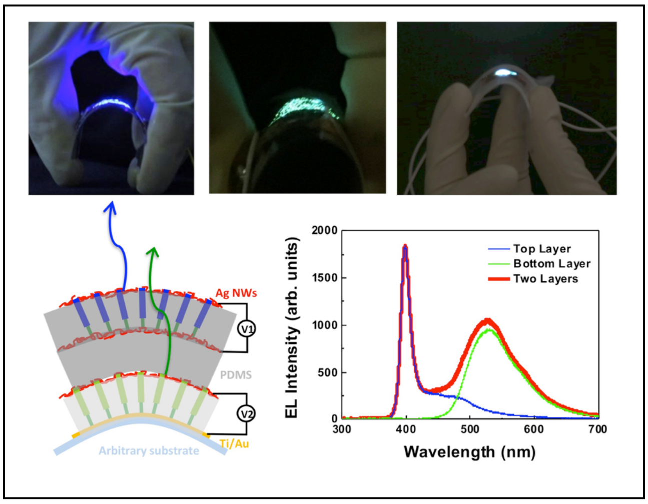

Fig. 1 Top : flexible nanowire blue, green and white LEDs under operation. Bottom : schematic and electroluminescence spectra of a two-colour LED.

3. Conclusions

In conclusion, without any top-down micro-structuring step, we have demonstrated a series of nitride nanowire based flexible LEDs: blue, green, white and two-color. These devices combine the long lifetime of the inorganic nitride semiconductor materials, the flexibility of the organic polymer and the flexibility and transparency of the Ag nanowire electrode. They show a good electronic and optical stability without any encapsulation. This technology opens new routes for efficient flexible LEDs and other optoelectronic devices, i.e. RGB tri-colored flexible LEDs or displays and flexible nanowire based photodetectors or solar cells.

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