Imaging inside Gallium Nitride wires for next generation blue LEDs

Semiconductors are both fascinating for physicists and extremely useful to society. The best-known semiconductor is Silicon, the material at the origin of the electronics and digital revolution of the second half of the 20th century. At the present time, the nitride materials Gallium Nitride (GaN) and its alloys are beginning another semiconductor revolution due to the specific properties of their energy bandgaps that enable them to emit visible light with unparalleled efficiency. The inventions at the origin of the nitride blue LEDs (Light Emitting Diodes) that are now penetrating the mass market for lighting applications were recognized by the 2014 Nobel Prize for Physics. We focus here on a potential next generation of these nitride LEDs, based on dense arrays of nitride microwires.

In the language of nano-technology, a "wire" is a very small crystalline object having length considerably greater than its diameter. Wire-based devices are a promising new route towards improved electronic and optoelectronic devices. Compared to present-generation nitride LEDs, which are conventional planar devices, wire devices have very desirable intrinsic properties such as small footprints and improved crystal quality. With careful design of donor and acceptor doping and alloy compositions, wires offer more versatility.

The building-block of optoelectronic applications is the p-n junction. In a LED, electrons from the n-type region and holes from the p-type region recombine at the junction, emitting light. Especially promising are p-n junctions in wires grown with the "core-shell" geometry: An n-type core (doped with the donor impurity silicon) is totally enclosed by a p-type shell (doped with the acceptor impurity magnesium). The shell is deposited on the lateral walls of the core and often also on the top of the core, see Fig. 1. Thus the p-n junction at the core-shell boundary has a three-dimensional (3D) character, very different

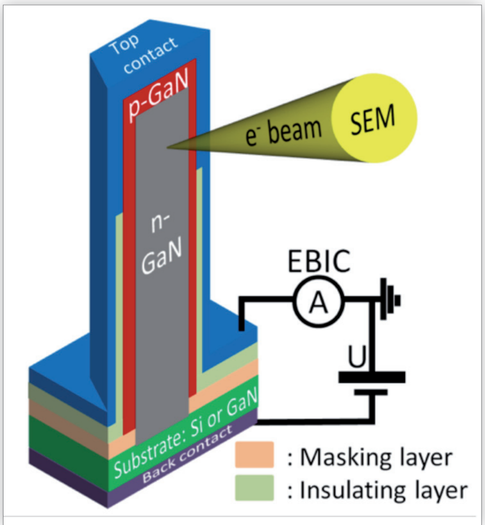

Fig. 1: A cleaved, core-shell GaN wire, and its integration into a diode device for Electron-Beam Induced-Current (EBIC) measurements. The focussed electron beam creates electron-hole pairs or excitons in the GaN semiconductor; e-h pairs or excitons created in the p-n junction region are separated by the junction's electric field, and a net electric current flows through the device.

from that of planar diodes. The wire's high ratio of surface to volume greatly increases the total area of the junction, and thus increases the proportion of active region in the device. This should alleviate the "efficiency droop" issue (a severe fall-off of efficiency at high current levels) in LEDs and will also be important for nitride-wire solar cells.

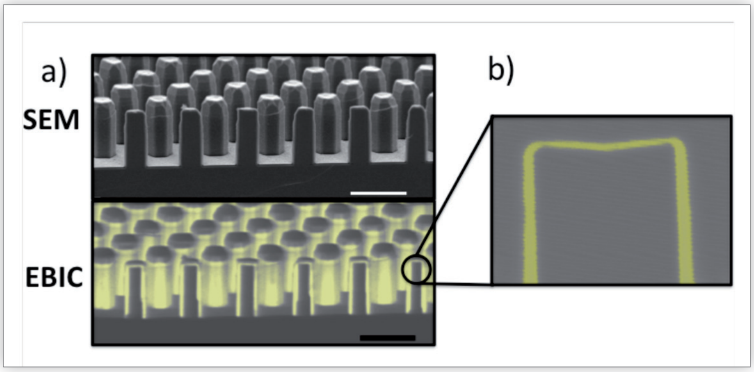

Fig. 2: ***(a)*** *Field Emission Scanning Electron Microscope (SEM) image at 10 keV for a processed, wire-based device, and the corresponding image (yellow colour) of the Electron Beam Induced Current intensity (scale bar: 10 µm). The wires in the front row were cleaved in half, so that the electron beam can probe inside them.*

(b) *A zoom onto the EBIC image shows lateral and top p-n junctions in a cleaved wire.*

Development of these nitride core-shell wire devices is hampered at present by a lack of precise knowledge about essential semiconductor properties along the buried 3D p-n junction. New, specific tools are needed to investigate the physical properties of the wire at the nanometric scale. We have now demonstrated how to image the electric field in a core-shell GaN wire and thus to determine the doping concentrations of the p-n junction.

Our diodes were wire arrays (Fig. 2) grown by the catalyst-free Metal-Organic Vapor-Phase Epitaxy technique on conducting GaN and Si substrates. The wires were grown and processed into device structures by colleagues at the CEA-LETI, Grenoble. To image the top and lateral junctions existing in the 3D diode structure, we exploited two powerful techniques available on a Scanning Electron Microscope, namely Electron-Beam Induced-Current (EBIC) and secondary-electron Voltage Contrast. We cleaved the substrates to split some of the GaN wires down their length (see Figs 1 and 2). With this cross-sectional approach and applying the scanning electron-beam techniques, we can achieve a spatially resolved analysis of the entire p-n junction, with nanoscale resolution.

The EBIC images (Fig. 2) enabled us to measure, at each point in the 3D junction, the diffusion lengths of current carriers generated by the electron beam (typically ≈60 nm on the p-type side of the junction and ≈15 nm on the n-side). The measurements also provided the width of the carrier depletion zone (40–50 nm). Under reverse bias of the diode, Voltage-Contrast Imaging provided electrostatic maps of the local electric potentials, from which we could deduce acceptor and donor impurity doping levels in the vicinity of the 3D junction (typically $N_a = 3 \times 10^{18}$ cm^{-3} and $N_d = 3.5 \times 10^{18}$ cm^{-3} in both the top and the lateral junction).

These nanoscale probing techniques provide values of the key parameters – carrier diffusion lengths, widths of space charge regions, doping levels – essential for guiding the further development of core-shell wire devices including LEDs and photovoltaic solar cells.

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FURTHER READING

"Direct Imaging of p–n Junction in Core–Shell GaN Wires"
P. Tchoulfian, F. Donatini, F. Levy, A. Dussaigne, P. Ferret and J. Pernot
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