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Synchrotron-based Characterization of Nanowires and Nanowire Devices

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Abstract

We use the unparalleled brightness and coherence of modern synchrotron X-ray sources to study semiconductor nanowires for next generation LEDs, photovoltaics and high speed/low power electronics. We measure nanowire chemistry, electronic properties, structure and strain from micrometers to the atomic scale. In addition we explore new methods for in-situ and in-operando measurements of both complete devices and during steps of device manufacturing.

1. Introduction

Already today, the circuits in the chips driving our computers and mobile devices have reached the nanoscale – quickly moving towards atomic scale levels. This development is only accelerating, and in the future atomic scale controlled electronic and photonic components will be ubiquitous in consumer electronics, renewable energy devices, energy storage, LEDs and much more. Synchrotron based techniques are playing a significant role in the development of future electronics as it is possible to directly investigate many aspects of device processing/synthesis, operation and structure that is not available by other techniques.

Despite the many III-V nanowire (NW) technologies under current development, be it solar cells and light emitting diodes or high speed/low power electronics [2], there are still many outstanding questions on their function as they are incorporated into devices. In particular their surfaces and interfaces remains quite unexplored as well as how their structure and strain changes when they are incorporated into larger devices structures. These issues have to be understood in detail if we are realize nanowire (or any other nanostructure) electronic/photonic devices that are really superior to current technology; trial-and-error design will not suffice.

In this presentation three prominent examples will be given demonstrating the use of different synchrotron based techniques, often in combination with complementary lab based methods. All these methods will be available at the unprecedented levels at the next generation synchrotron [1] MAX IV inaugurated June 2016, which will also briefly be introduced.

1. Fast Strain Mapping of Nanowire Light-Emitting Diodes Using Nanofocused X-ray Beams

Nanofocused X-ray beams are nondestructive probes that uniquely allow direct measurements of the nanoscale strain distribution and composition inside the micrometer thick layered structures found in many electronic device architectures [2]. While the method has generally been considered time consuming, we demonstrate that by special design of X-ray nanobeam diffraction experiment we can (in a single 2D scan with no sample rotation) measure the individual strain and composition profiles of many structures in an array of upright standing nanowires[3-5]. We make use of the observation that in the generic nanowire device configuration, which is found in high-speed transistors, solar cells, and light-emitting diodes, each wire exhibits very small degrees of random tilts and twists toward the substrate. Although the tilt and twist are very small, they give a new contrast mechanism between different wires. In the present case, we image complex nanowires for nanoLED fabrication and compare to theoretical simulations, demonstrating that this fast method is suitable for real nanostructured devices. We then go on to discuss the use of the new highly coherent synchrotrons such as MAX IV for microscopy [6].

2. Nanowire surface chemistry and electronic properties from microns to the atomic scale

The atomic scale structure and morphology of NW surfaces are central in determining their functionality, due to the inherently large surface to bulk ratio[7]. Using synchrotron based Spectroscopic Photo Emission and Low Energy Electron Microscopy (SPELEEM) we have characterized III-V nanowire surface chemistry and electronic properties, investigated ultra-thin dielectrics, native oxides and epitaxial shells[8-10]. Combining this with several types of Scanning Probe Microscopy a complete picture of surface chemistry, effects on bandbending and information on axial and radial doping is obtained[7,11-16]. We will demonstrate recently developed concepts that allows us to study nanowire devices during operation using both focused X-ray beams X-ray spectroscopy, SPELEEM and STM.

3. Studying surface chemistry during Atomic Layer Deposition.

We will discuss dynamic studies of surface chemistry and dynamics using X-ray Photoelectron Spectroscopy (XPS) and ambient pressure X-ray Photoelectron Spectroscopy (AP-XPS). We show how the chemistry of technologically important processes such as Atomic Layer Deposition (ALD) of HfO2 can be directly investigated using AP-XPS. This gives us new insights into the growth processes and demonstrate that the simple picture of the ALD growth is not quite true when the process can be followed while it is happening. Unexpected details are revealed about the correlation of initial precursor molecular adsorption, native oxide removal, and high-k layer formation [17], which will help to further optimize the high-k deposition and minimize the formation of unwanted defects at the interface. We strongly believe that this type of investigations of the initial interface control will be essential to attain surface and interface control crucial to future nanowire devices.

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