

Abstract

Surfaces and interfaces have a key role in behavior of electronic devices. This role has never been as critically important as it is now in the era of nanotechnology, when nanostructures, being used as building blocks for electronic devices, have almost nothing but surfaces. We seek to understand mechanisms by which physical properties of nano-structured material are affected by conditions of its surface. We wish to utilize these mechanisms as part of a new approach or paradigm for electronic and photonic devices at the nanometer scale.

Our model nanostructure is the nanowire (NW), the structure with the lowest number of dimensions that still supports electrical conduction. We grow NWs of various materials (nitrides – GaN, InN, oxides – ZnO, InO, VO, and Si) by various vapor growth methods combined with metal catalysis. We also study novel catalyst-free NW growth modes.

In a pivotal study, we showed that luminescence from small structures may be dominated by trapping at surface states. The work (published in the physical review and cited 310 times) has used NW diameter dependence to resolve surface from bulk effects.

In a recent study, we have demonstrated, for the first time that activation energy of impurities, such as dopants, in NWs, is affected by the surrounding dielectric and could actually be modified by the choice of the NW embedding medium.

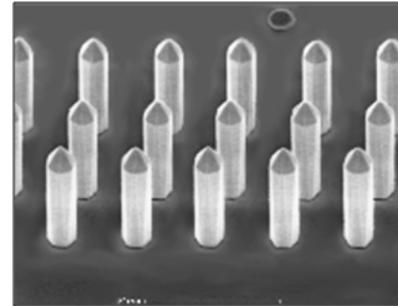
The demonstrated so called “dielectric confinement effect”, proposed by Keldysh in 1979, is a key phenomenon in doping and conduction in nanostructures. Understanding this phenomenon is fundamental to any utilization of semiconductor NWs as gas or liquid substance detectors.

Semiconductor conductivity is by far the most basic engineering parameter in electronics. It is usually defined by the concentration of a doping impurity intentionally introduced into the semiconductor. The demonstrated effect sets in as circuit dimensions shrink, which makes the material more sensitive to external conditions.

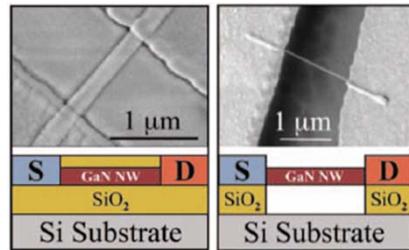
As it turns out, surfaces act like partial mirrors reflecting inner charges. An image charge in the mirror affects the energy of the real charge. When the surface is far, the mirror image is far, and its influence negligible. But as structures enter the nanometer scale, as in NWs, the mirror draws in, making it possible to manipulate the conduction from the outside.

To experiment with NW conduction, we constructed NW-channel field effect transistors and used them to measure the NW conductivity and field effect mobility. To modify the strength of the surface mirror, GaN NWs were coated and the dopant activation energy was obtained from the temperature dependence of the NW conductivity.

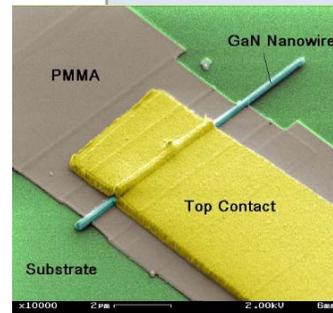
Photonic applications are another research direction where individual NWs are used to form light emitters. The most common application for NW-substrate junctions today is the light-emitting diode (LED). The key challenge in creating NW light sources lies in their assembly rather than material synthesis. One aspect of this challenge, which has received considerable attention, deals with the geometric arrangement of NWs into large-scale patterns. The other



InN nanorods grown on C-plane sapphire. The lattice mismatch of 29% is not supposed to support the observed epitaxial relations.



Nanowire-channel field-effect transistors surrounded by air (right panel) and surrounded by SiO₂ (left panel).



Our GaN LED device on the cover of Nanotechnology (top) and a detailed image (bottom)

aspect, which has received almost no attention, is the control of the interface properties resulting from making contact between NWs and planar surfaces. Semiconductor light sources derive their behavior from the properties of the interface between two semiconductors: the p-n junction LED and the so-called double heterojunction laser are the most obvious examples.

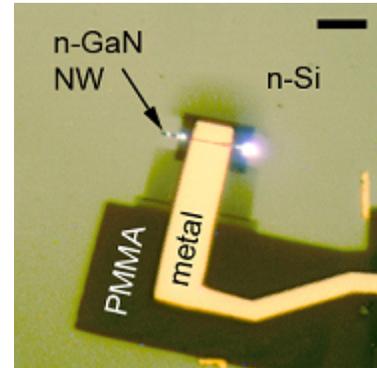
In a recent study, the issue of p-n junction formation was addressed in the NW on-substrate geometry for the purpose of creating an ultraviolet NW LED and understanding the underlying physics affecting the luminescence properties and current-voltage characteristics, an aspect so far largely neglected in previous studies of such systems. LEDs were assembled using n-type doped GaN NWs in contact with a p-type silicon substrate. The results show that, in general, junctions resulting from the intimate mechanical contact with a semiconductor substrate, due to Van der Waals type forces, are far from ideal compared with those epitaxially grown in planar systems, and practically form a tunnel junction rather than a standard p-n junction. This work however, has now shown that one of the consequences of the tunnel junction is a surprising finding that light emission also results when the n-type NW (gallium nitride) is placed on an n-type substrate (silicon). Furthermore, because of the interchangeable roles of the semiconductors forming the junction (the NW and the substrate), their device emits ultraviolet light from the gallium nitride NW for one polarity of the applied voltage, and infrared light from the silicon substrate when the polarity of the voltage is reversed.

These results provide an elegant demonstration that the details of the junction between a NW and a substrate, formed not by covalent chemical bonds (as in epitaxially grown junctions) but by van der Waals forces, critically determine the behavior of the device. Interestingly, this device structure could also be used as a novel approach for two-color unipolar LEDs.

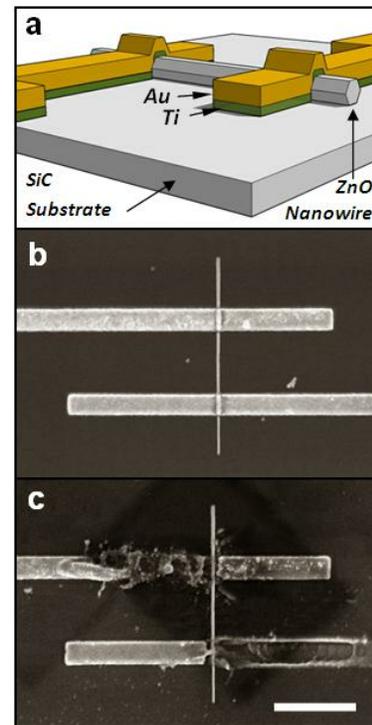
In another work, we studied the effect of metal contact structure on the ability of nanowire electronic device to survive an electrostatic discharge at the substrate-nanowire-contact junction – a common undesirable scenario in nanoelectronic devices.

The above examples outline our line of research. The beginning of nanotechnology is also the beginning of an era of applied surface science. Our understanding of the prevailing effect of surfaces and interfaces on small devices is bound to transform our approach to

device physics.



n-GaN nanowire/n-Si heterojunction bi-color light emitting diode.



Effect of contact metallization scheme on nanowire channel field effect transistor failure rate due to electrostatic discharge..