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Towards Electrically Driven Nanowire Single-Photon Sources

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A vapor–liquid–solid (VLS) growth of microwhiskers was developed by Wagner et al. in the 1960s.[1] The recent re-examination of this method by the groups of Lieber,[2] Yang,[3] Samuelson,[4] Wang,[5] and others has resulted in the flourishing research into nanowires (NWs). Nearly all the IV, II–VI, III–V, and IV–VI semiconductor NWs can be synthesized. Ternary compound semiconductors have also been demonstrated.[6] NWs can be made with complex shapes[7,8] and form hyperbranched networks.[9] A unique characteristic of NWs is that they can transport electrons, photons, and ions by a macroscopic distance along their length while maintaining a nanoscale size effect (quantum confinement, large surface area, etc.) across the diameter dimension. NWs and their derivatives are promising in many applications such as transistors,[10] biosensors,[11,12] nanogenerators,[13] nanofluidic channels,[14] and light-emission devices.[15–20]

In the area of light-emission devices, NWs provide new exciting advantages over embedded quantum wires. First, NWs can be grown epitaxially on Si[21] due to the facile strain relaxation within the small cross section of nanowires, which allows optical functions directly integrated onto mature Si technology. Second, NWs can be assembled in the form of cross arrays, which offer the flexibility of combining different materials to realize integrated multicolor emission.[16,20] Third, NWs are not embedded in high-refractive-index substrates, which significantly increases their light-extraction efficiency.[18] With the above advantages, a new exciting opportunity would be to engineer NWs as single-photon sources (SPSs).

A SPS is a critical component for quantum information processing.[22,23] A SPS requires photon antibunching, that is, emission of a single photon at a time. To realize a SPS in NWs, it is necessary to engineering a small-sized quantum dot within a single NW. The introduction of growth techniques such as chemical beam epitaxy into the VLS mechanism allows precise control of the heterostructure down to the nanometer scale,[4,12] which opens up the opportunity to perform quantum engineering within single NWs. Recently Borgström et al.[19] have described photon antibunching in photoluminescence measurements of GaP–GaAsP–GaP linear heterostructured NWs, in which the 15 nm GaAsP segment functions as a quantum dot. Surrounded by low-refractive-index air, these NW dots show intense single-photon emission with a brightness typically an order of magnitude larger than self-assembled quantum dots. To take this a step forward, it would be highly desirable to develop electrically driven single-photon sources that do not require expensive lasers as excitation sources.

Here we highlight the work by Minot et al. on single-quantum-dot NW LEDs,[24] which show great promise towards electrically driven SPSs. A NW consisting of a narrow InAsP section sandwiched between n-InP and p-InP sections was grown by a Au-colloid-catalyzed VLS method in a metal–organic vapor phase epitaxy (MOVPE) chamber (Figure 1). The central InAsP section has a smaller bandgap, thus forming a potential well or quantum dots in the NWs, while the long InP section functions as electrical wiring for selectively injecting electrons or holes into the quantum dots. The central quantum dots need to be small enough to manifest the quantum confinement effects. Central InAsP sections as small as 12 nm have been realized by the authors.

To characterize these heterostructure NWs, the authors[24] have taken a step back to first study p–n junction InP NWs without the central InAsP quantum dot. They used different contact metals for selectively contacting with the p- and n-type InP sections, which is necessary for efficient and type-selective charge-carrier injection. They found that Ti/Al makes an Ohmic contact with n-InP, and Ti/Zn/Au is used as a contact for p-InP, but here there is a high

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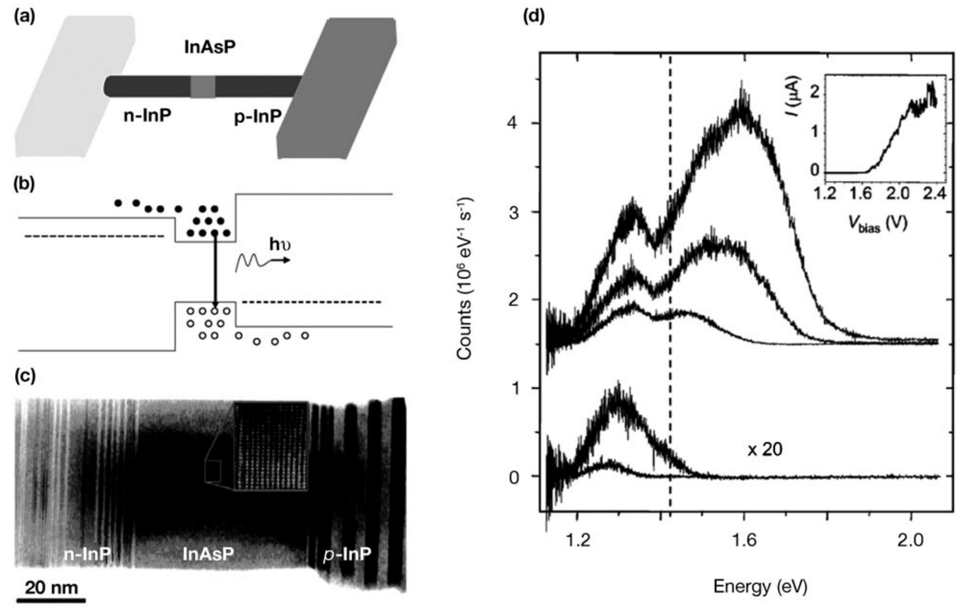

Figure 1. a) An LED device consisting of p-InP, InAsP and n-InP segments within a single NWs, in which the InAsP segment acts as a quantum dot. The p- and n-type segments are selectively contacted by different metals. b) Energy-level structure of a quantum-dot NW under forward-bias conditions. c) High-resolution transmission electron micrograph of a quantum-dot NW. d) Electroluminescence of NWs from low (bottom) to high (top) bias voltages: 1.4, 1.6, 1.8, 2.0, and 2.2 V. The inset shows data of current versus bias voltage.

contact resistance. Single-NW electrical transport shows good rectifying behavior and Kelvin probe force microscopy indicates a sharp potential drop at the p–n junction, but not at the metal–NW contact. Forward-biasing the diode causes light emission from the NWs.

With the central InAsP quantum dot within the InP NWs, the authors have carried out photoluminescence (PL) and electroluminescence measurements. In the PL measurements of intrinsic heterostructured NWs, they have shown that they can tune the phototemission wavelength corresponding to the bandgap of the InAsP section by changing the As concentration. In a NW with only a 12-nm section of InAsP, they have seen sharp emission (1 meV) suggesting a strong quantum confinement, which is favorable towards preparing SPSs. In the EL measurements on doped heterostructures, the authors have observed a single broad-peak emission under low forward bias, which corresponds to the emission from InAsP quantum dots. A second peak appears at a high forward bias, which originates from emission from the InP segments. Although it would be exciting to realize electrically driven light emission from the central quantum dots, the broad emission peak suggests that conditions for a SPS have not yet been realized. However, exploiting the electrical wiring capability of quantum dots within NWs is a significant step towards electrically driven SPS. The broad emission peak is caused by the overcharging of the central quantum dots by the doped InP segments. In the future, shielding the quantum dots with undoped intrinsic InP barriers might lead to true single-photon emission in quantum dot NWs, which opens up the opportunity of combining single-electron and single-photon control for quantum information processing.

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