Nanowire lasers and solar cells

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***Abstract* — The high refractive index of III-V semiconductors results in strong waveguiding of light in nanowires, despite their small cross-section dimensions. We will discuss how these waveguiding properties can be used to design nanowire lasers and solar cells with functionalities not possible in conventional, planar devices.**

Keywords—III-V semicondcutors, nanowire, laser, solar cell, dieelctric waveguide

I. INTRODUCTION

Nanowires are quasi one-dimensional structures with base dimensions of the order of few 10-100s of nms and length or height of few microns. The shape anisotropy of nanowires enables their growth on lattice mismatched substrates as strain relaxation could, in principle, occur through the large free facets of the nanowire, not bound to the substrate. This opens up the possibilities of integration of III-V compound semiconductors with Si for integration of electronic and optoelectronic devices, and growth on cheap substrates like glass for reducing the cost of optoelectronic devices.

The high refractive index of III-V compound semiconductors means that the nanowires act as waveguides for light close to the band gap of the semiconductor, despite their small cross-section dimensions. These waveguiding properties affect the interaction of semiconductor material in the form of nanowires with light [1-3]; and can be used to design optoelectronic devices that perform very different to planar devices fabricated from the same semiconductor. We will discuss the design of nanowire optoelectronic devices: lasers and solar cells; and present experimental results.

II. NANOWIRE LASERS

The end facets of the nanowire or the nanowire-air interfaces act as reflectors for the waveguide modes supported in the nanowire, with non-zero propagation constant along its axis ($k_z \neq 0$). The semiconductor nanowire thus acts as a Fabry-Perot cavity, and integrates the semiconductor gain medium with a cavity. This eliminates the need for any post-growth fabrication needed for achieving photon confinement in the active medium.

The reflectivity at the nanowire-air interface is different for different waveguide modes, and also varies with the nanowire diameter [4]. The cavity quality factor, Q, for different waveguide modes, as a function of nanowire diameter is shown in Fig. 1. The data shown is for a fixed wavelength of 870 nm, for a nanowire with refractive index ~3.6 and length of 5 µm, suspended in air. The threshold gain, g_{th}, for lasing is inversely proportional to the cavity quality factor, as shown in Eqn. 1, where Γ is the mode confinement factor, k_0 is is the free space wave vector and n_g is the group index of the mode.

$$\Gamma g_{th} = \frac{k_0 n_g}{Q} \tag{1}$$

Lasing occurs via the waveguide mode with the lowest threshold gain requirement. The diameter of the nanowire can simply be varied to select the lasing mode. For example, nanowires with diameter between 200-300 nm are expected to lase from TM_{01} mode, while nanowires with diameter larger than 300 nm are expected to lase from the fundamental HE_{11} mode. Each waveguide mode has a characteristic far-field emission pattern and polarization response. The ability to control the lasing mode by simply changing the diameter of the nanowire, thus provides an opportunity to control the far-field emission pattern and dominant polarization of emission from nanowire lasers. We have experimentally demonstrated this ability in InP nanowire lasers [5].

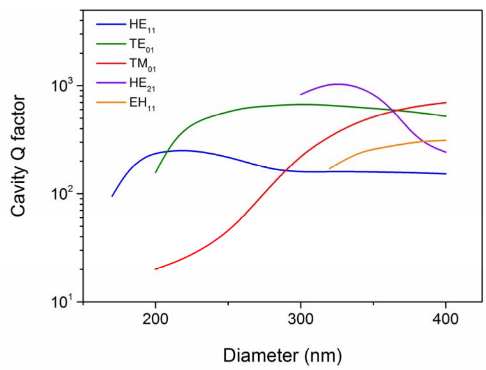

Fig. 1. The nanowire cavity quality factor, Q, for waveguide modes with non-zero propagation constant along the axis of the nanowire as a function of nanowire diameter. The nanowire is suspended in air and has refractive index of ~3.6 and length of 5 µm. Light with wavelength of 870 nm is considered.

III. NANOWIRE SOLAR CELLS

Light incident on a nanowire, in a direction parallel to the nanowire axis can couple to the waveguide modes supported in the nanowire. The coupling efficiency of incident light to nanowire waveguide modes can be maximized by maximizing the overlap integral between the field components of the incident light and the field profile of the waveguide mode. Light coupled to waveguide modes confined in the nanowire is efficiently absorbed in the nanowire, resulting in large absorption cross-sections [6], as shown in Fig. 2.

Due to the large absorption cross-section, III-V semiconductor nanowires are efficient light absorbers, despite their small volumes. In planar solar cell configurations that aim at reducing the volume of absorbing semiconductor layer (thin film solar cells), photon management strategies or light trapping strategies become critical to enhance light absorption in the semiconductor. For nanowires, the high absorption cross-sections eliminate the need for external photon management strategies. The nanowires integrate the light trapping strategy with the absorbing material due to their unique geometry.

IV. CONCLUSIONS

The shape anisotropy of nanowires offers the possibility of design and demonstration of optoelectronic devices with several advantages compared to conventional devices. We have demonstrated that the far-field emission pattern and dominant polarization in nanowire lasers can be controlled by simply changing the diameter of the nanowire. For solar cell applications, large absorption cross-section in nanowires maximizes light absorption in small volumes, eliminating the need for external photon management strategies. Both these advantages are a consequence of the waveguiding properties of semiconductor nanowires.

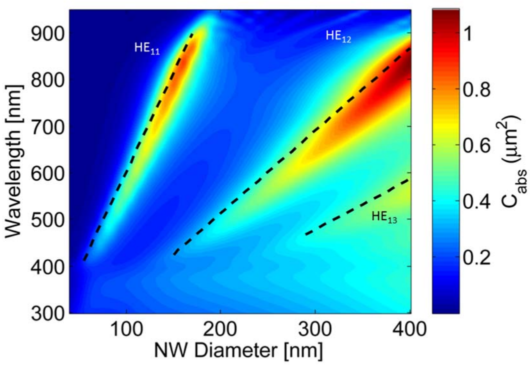

Fig. 2. Absorption cross-section, C_{abs}, as a function of nanowire diameter and incident wavelength for a 2 μm long InP nanowire.The dashed lines are the maxima of product of overlap integral between incident field and the waveguide mode and the waveguide confinement factor for HE_{11}, HE_{12} and HE_{13} modes.

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