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## Application Note

### Introduction

Semiconductor nanowires display fascinating optical effects associated with their large aspect ratio (length-to-width ratio) and high refractive index at optical frequencies ( $n \approx 3.5$ ). Typical nanowires have diameters of 20-300 nm and lengths of 1-10 microns. These dimensions are much shorter and longer, respectively, than the free-space wavelength of light. The above factors enable nanowires to support various types of optical resonances which can assist in designing the emission, absorption, and guiding of light at the nanoscale. In some cases, it is desired to enhance the light emission and absorption from a large area. Nanowire arrays are particularly suited for this purpose. In an array, nanowires can couple with a strength depending on their mutual separation. Inter-wire coupling effects can modify the resonances of the individual nanowires, or even lead to new resonances associated with spatially extended optical states. Therefore, semiconductor nanowire arrays have attracted much attention for large area light absorption and emission. Recent developments in nanowire arrays have shown their potential to improve the performance of light-harvesting devices, e.g. solar cells [1] and light-emitting devices (LEDs) [2]. An important issue that these arrays face relates to the polydispersion in the optical properties of the constituent nanowires. Structural and/or material variations in the nanowires often degrade the collective response of the ensemble, thereby limiting the maximum device efficiencies that can be attained. It is therefore important to study these spatial variations by optical means. In this report, we present measurements taken with a Neo sCMOS camera from Andor Technology of the spatially-resolved photoluminescence from semiconductor nanowire arrays. The measurements illustrate typical variations in light intensity emitted by different nanowires. Arrays of different periodicities are shown, and the high resolution of the Neo camera allows us to observe the finest details in dense nanowire arrays.

### Sample fabrication and measurement technique

The nanowires are made of indium phosphide (InP), which is known to be optically active and is strongly absorbing visible light. The cores are grown using the bottom-up vapor-liquid-solid (VLS) method in a metal-organic vapor-phase epitaxy (MOVPE) reactor. Gold catalyst particles with a diameter of 50 nm were positioned in square arrays on an InP substrate using electron-beam lithography. The arrays consist of 25x25

particles of which the lattice constant varies from 1.2 to 5  $\mu\text{m}$ . After the core growth, the diameter of the nanowire is increased by radial growth of an InP shell at higher temperature. Both the axial and radial growth rates are determined by the period of the array, which causes different nanowire diameters for the different arrays, ranging from 180 to 295 nm. Figure 1(a) and 1(b) show scanning electron micrographs of arrays of nanowires arranged in a square lattice of constant  $a = 5 \mu\text{m}$  and  $a = 2 \mu\text{m}$ , respectively.

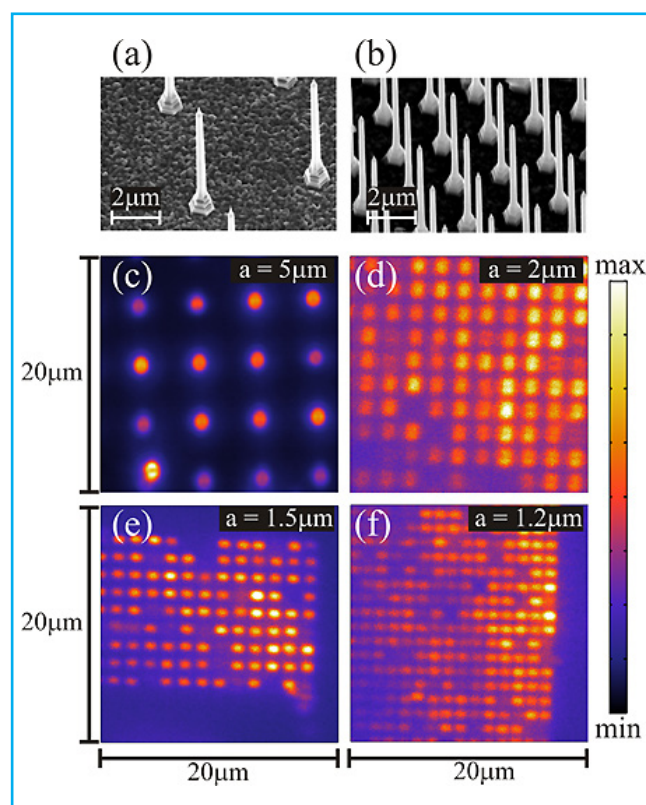


Figure 1: Nanowire imaging. (a-b) scanning electron micrographs of nanowire arrays taken under an oblique angle of 30 degrees. (c-f) Fluorescence maps of the sample under plane wave excitation recorded with the Andor Neo sCMOS camera. Array lattice constant  $a$  is shown in the top right corner of each map.

The nanowires are grown in mixed zincblende-wurtzite crystal phase. Due to a difference in electronic band gap between InP in wurtzite and InP in zincblende phase (1.43 eV and 1.34 eV respectively at room temperature [3]), the peaks of substrate emission (around 920 nm) and nanowire emission (around 870-880 nm, due to mixed crystal phase growth) can be spectrally



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distinguished. To filter out the substrate emission and detect only the nanowire emission, we placed a band pass filter centered at 880 nm with a full width at half maximum (FWHM) of 40 nm in front of the Neo camera.

To generate the nanowire photoluminescence (PL), we excited the sample with a 532 nm laser through a 100x microscope objective with a normal incident plane wave. Plane-wave excitation is realized by illuminating with a focused beam the centre of the back focal plane of the objective [4]. This allows us to excite the nanowires with a well-defined angle of incidence rather than with a broad angular range as it normally occurs through large numerical aperture (NA) objectives. The light emitted by the nanowires is collected through the same objective and directed to the Neo sCMOS camera. Spatial maps of the nanowire light emission are shown in Figs. 1(c-f) for arrays of various lattice constants  $a$ , as indicated on the top right corner of each plot.

## Results

Figures. 1(c-f) show spatially-resolved PL maps from arrays with increasing nanowire density. The PL intensity is normalized for each plot in order to distinguish intensity variations within each array. The most dilute array (Fig. 1c) displays relative small variations in intensity. These variations are likely attributed to size variations of the nanowires. As the density increases, more pronounced light emission intensity variations are observed for the various nanowires within each array. In particular, notice that the number of defective nanowires (emitting little or no light at all) is proportional to the nanowire density or inversely proportional to the lattice constant. This effect is likely due to the mutual influence that the nanowires exert onto each other during the growth phase, which leads to structural defects that quench the light emission. There is also a small chance of missing nanowires, due to a distorted start of the growth. Note that in Fig. 1e-f, the plotted range includes the edges of the nanowire array.

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### Conclusion

Fluorescence microscopy measurements of nanowire arrays with varying lattice constant were presented. For dilute arrays, small variations in fluorescence intensity across the nanowires were attributed to size variations. For dense arrays, larger variations in fluorescence intensity were attributed to structural defects in the nanowires affected by the local growth conditions. The high pixel density and high sensitivity of the Neo camera allowed us to perform far-field measurements with a high spatial resolution.

### References

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