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Gallium Nitride Single-Mode Nanowire Lasers

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Abstract: We obtained single-mode lasing in GaN nanowires by using a limited number of cavity modes and a narrow gain spectra. The fabrication was achieved by a top-down technique in high quality GaN films.

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1. Introduction

Semiconductor nanowire lasers, with subwavelength diameters and lengths of a few microns, are among the smallest lasers. By using an air cladding, it is possible for the semiconductor material in nanowires to function as the gain media, waveguide, and laser resonator [1, 2]. From an engineering perspective, the realization of an extremely compact and spectrally-pure laser with small power dissipation has potential applications in spectroscopy, imaging, and data storage. We present a single-mode laser fabricated as a single nanowire using a top-down technique that gives precise control over the nanowire geometry. Previous efforts towards single-mode operation have involved complicated secondary processing [3]. The single-mode behavior presented here is achieved by reducing the dimensions of the cavity limiting the number of transverse and longitudinal modes. This limited modal distribution combined with the low damage fabrication process and the narrow gain spectrum of gallium nitride act in concert to enable single-mode performance.

2.Modeling

To explore the origin of single-mode lasing, the nanowire optical resonator was modeled by solving the transverse mode distribution using an Eigenvalue mode-solver using the material values from [4]. The results of this simulation gave the effective index dispersion and the mode confinement factors. Using the group effective index ($n_{eff\text{-}g}$) we estimated the location of the longitudinal and transverse modes with respect to the emission wavelength. The resulting modal distribution and confinement factors of a 130nm nanowire can be seen in Figure 1(a), this is contrasted with a 250nm nanowire in Figure 1(b). It is clear that the 250nm nanowire have a higher population of modes near the peak material gain [5]. A wire with a longer length would also have a higher population of modes near the gain peak due to the inverse relation between the length and the longitudinal mode spacing. Thus, single-mode lasing is enabled by the short cavity length and narrow diameter.

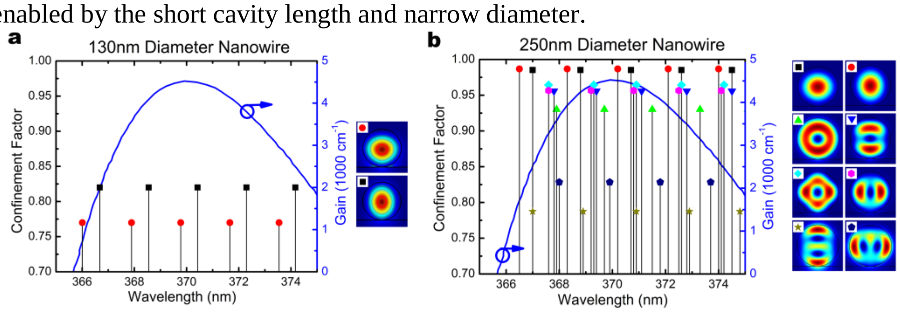

Figure 1 – The cavity mode wavelengths and their confinement factors are plotted in (a) for a 130nm diameter GaN nanowires and (b) for a 250nm diameter nanowire. Also plotted is the reported Gain [5] for a carrier density of 1.4 x 10^{19} cm^{-3}. The inset in (a) shows the mode profile for the two transverse modes supported by a 130nm nanowire. The inset in (b) shows the mode profiles for the eight transverse modes that are supported by a 250nm nanowire.

2. Fabrication

The gallium nitride nanowires used in this study were fabricated using a two-step etch process. First a monolayer of silica microspheres assembled on GaN is used as a etch mask for an inductively coupled plasma etch that creates tapered GaN nanopillars. This initial etch process creates a significant amount of damage and degrades the intensity of the photo luminescent peak at the bandedge. A scanning electron micrograph of these structures can be seen in Figure 2(a). Using a second etch step we not only remove the damaged material but also change the shape of the structures into the desired high aspect ratio, anisotropic nanowires. This final nanowire cavity structure can be seen in Figure 2(d).

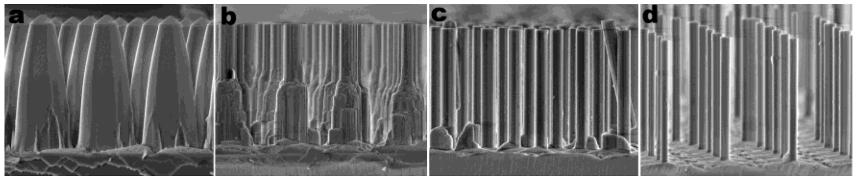

Figure 2 – Cross sectional SEM images showing GaN posts morphology transition into GaN nanowire during an anisotropic wet etch. (a) before wet etch, (b) after 2 hours, (c) after 6 hours, and (d) after 9 hours wet etch. All images have the same magnification. The scale bar in (d) represents 2 um.

The optical properties of single GaN nanowires fabricated by this method were characterized by optical pumping using a micro-photoluminescence setup. Single GaN nanowires were individually pumped with a spot size of ~5µm achieved using a 50X UV objective. Light emitted by the nanowire was analyzed using a high resolution spectrometer and a CCD camera. The emission spectra of GaN nanowires with diameters of 130nm and 250nm and with increasing pump intensities are shown in Figure 3(a) and (b). For a 130nm diameter GaN nanowire, and when the pump power intensity is below 320kW/cm^2, the emission spectra are featureless with a broad spectral width of ~ 6 nm. When the pump power is increased above 320kW/cm^2, the emission spectra shows a single sharp peak. The FWHM of this sharp peak is only 0.12nm. Figure 3(c) and (d) show the peak intensity as a function of pump power and indicates lasing action in the nanowire above a threshold of 300kW/cm^2. As the pump power intensity is gradually increased to 1300kW/cm^2, the emission remains single-mode with the peak intensity increasing linearly and with a constant FWHM peak width of 0.12nm. Single-mode lasing behavior was consistently observed in GaN nanowires with diameters ~130nm and lengths of 4.7µm.

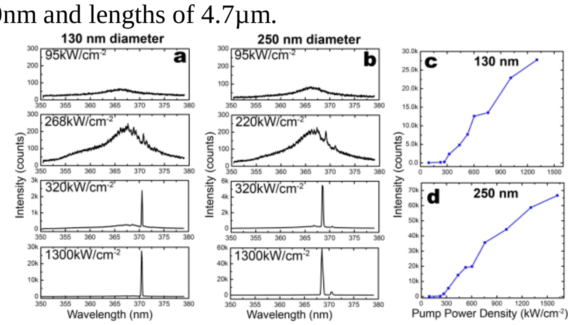

Figure 3 –PL spectra acquired from a 130nm diameter (a) and a 250nm diameter (b) GaN nanowire as the optical pump power increases from 95 to 1300kW/cm^2. The linewidth of the 250nm is significantly broader than the 130nm indicating multi-mode emission. The onset of stimulated emission can be seen above a threshold of 300kW/cm^2 the 130nm wire (c) and the 250nm wire (d) in the plot of peak intensity as a function of the pump power density.

4. Conclusions

We have shown a single-mode nanowire laser created by a top-down fabrication technique in GaN. Our model predicted in order to realize a single-mode laser without the use of secondary fabrication techniques it is necessary to sufficiently reduce the dimensions of the nanowire. Employing a novel top-down fabrication technique that allowed for precise control of the nanowire geometry, we were enabled to create a cavity with the necessary dimensions for single-mode behavior.

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5. References

[1] Johnson, J. C., Yan, H. Q., Schaller, R. D., Haber, L. H., Saykally, R. J., and Yang, P. D., "Single nanowire lasers," *J. Phys. Chem. B,* vol. 105, pp. 11387-11390 (2001).

[2] Johnson, J. C., Choi, H. J., Knutsen, K. P., Schaller, R. D., Yang, P. D., and Saykally, R. J., "Single gallium nitride nanowire lasers," *Nat. Mater.,* vol. 1, pp. 106-110 (2002).

[3] Xiao, Y., Meng, C., Wang, P., Ye, Y., Yu, H. K., Wang, S. S., Gu, F. X., Dai, L., and Tong, L. M., "Single-Nanowire Single-Mode Laser," *Nano Lett.,* vol. 11, pp. 1122-1126 (2011).

[4] Tao, Y., Goto, S., Kawata, M., Uchida, K., Niwa, A., and Gotoh, J., "Optical properties of GaN thin films on sapphire substrates characterized by variable-angle spectroscopic ellipsometry," *Jpn. J. Appl. Phys. 2, Lett.,* vol. 37, pp. L1105-L1108L1108 (1998).

[5] Renzoni, F., Donegan, J. F., and Patterson, C. H., "Optical gain and linewidth enhancement factor in bulk GaN," *Semicond. Sci. Technol.,* vol. 14, pp. 517-520 (1999).