Fabrication of highly ordered vertical GaAs nanowires by inductively coupled plasma etching and their modal analysis

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ABSTRACT

Highly ordered vertical gallium arsenide (GaAs) nanowires are fabricated by dry etching using various metal mask combinations. A great control on length, diameter, pitch and facet tapering of the nanowires is achieved. Diameters ranging from 30 nm to 250 nm with pitch ranging from 200 nm to 1100 nm and length up to 2 μm are fabricated using this process. The highest diameter to pitch ratio is ~68%. The reflection measurements are performed on the samples and the diameter dependent strong absorption peaks due to optical modal excitations are observed from the refection measurements. Finite difference time domain (FDTD) analysis is used to validate the measurements and the absorption characteristics are understood. The modal analysis is also performed from the same simulations. The hybrid cylindrical waveguide modes as the function of nanowires diameter are identified to be linear. Also the near field coupling between the nanowires is absent even at the small pitches.

KEYWORDS: gallium arsenide, nanowire etching, nanowire photonics, reflectance, absorptance.

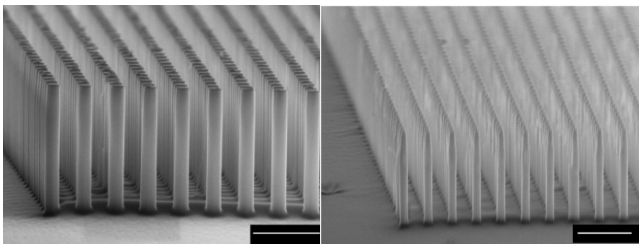
1 INTRODUCTION

Gallium arsenide nanowires are the subject of interrogation for various applications like lasers, field effect transistors, solar cells, light emitting diodes etc. The most popular approach to achieve the one dimensional nanowire morphology is the bottom up approach in which a metallic catalyst is used as a precursor to grow the nanowires. But this approach has its limitations as it is still challenging to control the diameter, crystal orientation, lattice arrangement, doping concentration, facet shape, length and position of the nanowires. This is a serious roadblock in the path of integrating one-dimensional nanostructures into optoelectronic devices.

To overcome the issues faced by the nanowires fabrication in bottom up approach we have resorted to the top down approach. Dry and wet etching is the most effective method to create the nanowires with high aspect ratio. Since the etched nanowires carry all the properties of the bulk material, it is inevitable that doping, crystal orientation, lattice arrangement can be controlled very well with this approach. In our work, using inductively coupled plasma reactive ion etching (ICP-RIE) we have managed to control the diameter, pitch, facet shape, position of gallium arsenide nanowires too. We have fabricated the cylindrical nanopillars with different diameters, pitches and lengths and studied their optical properties using reflection measurements and simulations. We also did the modal analysis of the nanowires from the measured and calculated data and presented a comprehensive model to understand the optical properties of gallium arsenide nanowires.

2 FABRICATION

Gallium Gallium arsenide nanowires were fabricated using e-beam lithography, patterned on polymethyl methacrylate (PMMA) followed by chlorine based Inductively Coupled Plasma Reactive Ion Etching (ICP-RIE). Different combinations of metal masks were tested to achieve the high aspect ratio vertical nanowires. An immense control on diameter, pitch and length was achieved with smooth sidewalls as shown in figure 1. A thin layer of aluminum below chromium as a mask rendered the reduction in whisker formation combined with the high selectivity in chlorine based etching [1]. Moderate etch selectivity was achieved by depositing oxidized titanium layer on the top of thin chromium layer. It leads to the radial etching of the mask resulting in the top half of the nanowires starting to get etched away in the latter stages of the etching to give tapered end points.



(a) (b)

Figure 1. (a) SEM image of GaAs nanowires with diameter 185 nm and 1.9 μm length (b) 170 nm diameter and 1.6 μm length**.** Scale bar for both cases is 1μm.

3 OPTICAL PROPERTIES

The optical properties of the nanowires were understood by performing the reflection measurements by shining light, in the wavelength range of 400 - 850 nm, normal to the sample. The reflection spectra matched well with finite difference time domain analysis under periodic boundary conditions in the transverse directions as shown in figure 2(a) and (b). The effects of length, pitch and diameter were studied.

The increase in length effectively reduced the reflection, going down below 5% for large diameters and absorption features are broadened due to the exponential dependence of Beer-Lambert law as shown in figure 2(a). The absorption was also calculated using the same simulations. From the absorption analysis it was observed that at 60 nm diameter HE_{11} modes [2] begin to excite and red shift in the position of resonant modes was seen with the increase in diameter, as shown in Figure 2(c). The bright patch of high absorption from wavelength 400 nm to 800 nm corresponding to the diameters ranging from 50 nm to 175 nm suggest the HE_{11} modes are excited. The higher order HE_{12} modes were also excited at lower wavelength for larger diameters larger than 125 nm resulting in much lower reflection than smaller diameters despite of having larger surface facing the incident beam. The relation between the resonant wavelengths as a function of diameter is turned out to be linear for both HE_{11} and HE_{12} modes.

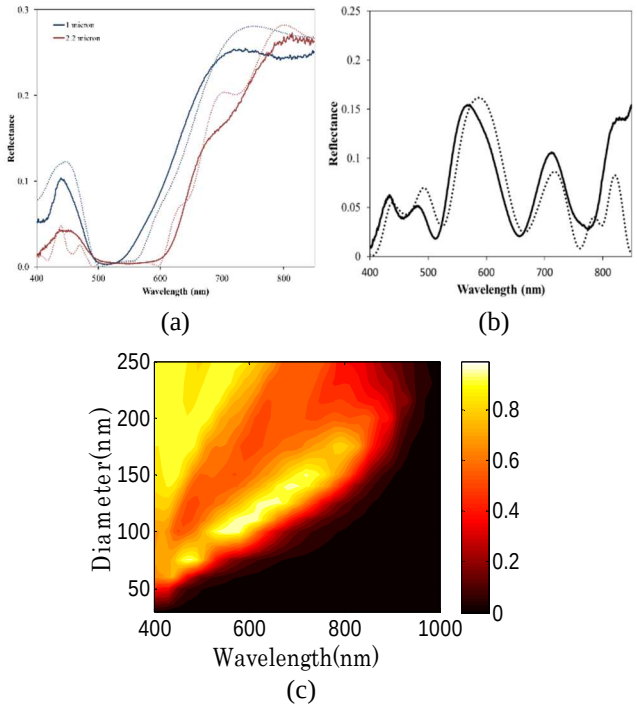


Figure 2. Measured and simulated reflection spectra for (a) 100 nm diameter nanowires at two different lengths 1 μm and 2 μm (b) 175 nm diameter for 1 μm length. (c) Simulated absorptance spectra for nanowires at a fixed pitch of 400 nm and different diameters.

3.1 Optical Modes

The previous discussion helps one understand the absorption using the measured reflectance spectra, but it does not give any physical understanding of why such peaks are observed. To remove the Fabry-Perot resonances from the analysis and to understand only the transverse modal properties of the nanowires, simulations were done on semi-infinite nanowires. Nanowires with perfect matching layer (PML) on the bottom were simulated. Figure 3 plots the absorptance spectra as the diameter is increased. As in figure 2(c), an absorption peak shifts to longer wavelengths with increase in diameter.

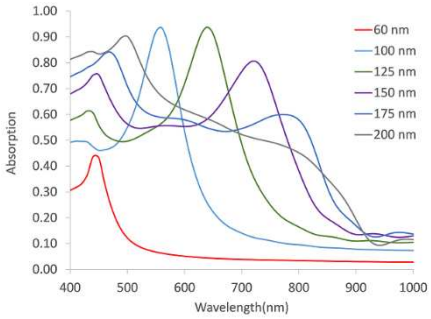


Figure 3. Absorptance inside 450 nm length of nanowires with perfect matching layer (PML) boundary at the bottom of the nanowire for varying diameters and pitch of 400 nm. Resonant peak absorption due to excitation of the HE_{11} mode and HE_{12} mode for larger diameters is observed.

For diameters of 125 nm and larger, a second peak appears at smaller wavelengths. At those diameters, the nanowires are multi-mode waveguides where, the longer wavelength absorption peak corresponds to the excitation of the HE_{11} mode and the second peak at smaller wavelengths corresponds to the HE_{12} mode. The HE_{11} peak is not observed above 200 nm diameters as it has moved into the transparent region for the GaAs material. This results in reduced absorption for this diameter as seen in figure 2(c). It is also observed that resonance wavelength shifts linearly with increase in diameter. For the fundamental HE_{11} mode, the shift is ~3.5 nm per 1 nm change in diameter while for the HE_{12} mode, it is ~1 nm per 1 nm change in diameter.

To affirm the fact that it is the excitation of optical modes, which results in the peak absorption, electric field distributions were simulated at different wavelengths. Nanowires were excited with a plane wave with electric field polarized along the x-direction. The diameter and corresponding wavelength chosen for the simulations are the peaks corresponding to the resonant modes in figure 3. In figure 4(a) the HE_{11} mode distribution for 100 nm diameter nanowire at the wavelength of 560 nm is shown. Similarly to show HE_{12} mode, we have chosen 175 nm diameter nanowire at wavelength of 460 nm. As can be clearly seen, the bull's eye shaped HE_{11} mode and donut shaped HE_{12} mode validate our theory.

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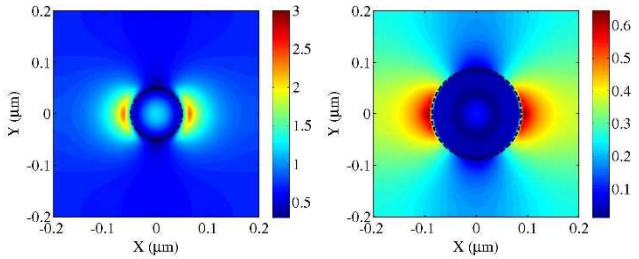

(a) (b)

Figure 4. Cross-sectional distribution of the E_x field for (a) 100 nm diameter nanowires at HE_{11} resonant wavelength 560 nm (b) for 175 nm diameter at HE_{12} resonant wavelength 460 nm. The excitation is a plane wave with electric field polarized along the x-direction. The scales are normalized to the input amplitude of the plane wave. The outline of the nanowire is shown in dashed line.

3.2 Effect of Pitch

The effect of pitch was analysed for semi-infinite nanowires using FDTD simulations. Simulations were done where the pitch was varied while keeping the diameter constant and the results are plotted in figure 5. There was no shift observed for resonant peak position with the increase in pitch [1]. The overall absorption is reduced due to the decreasing fill factor with increasing pitch.

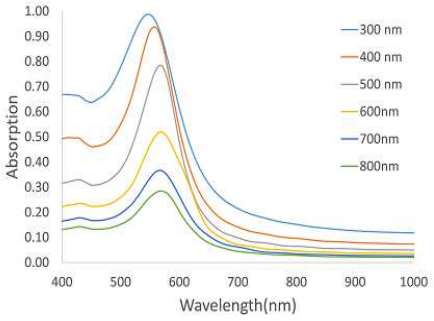

Figure 5. Simulated absorption spectra for 100 nm diameters at different pitches. The absence of peak shift shows a weak dependence of resonant peak on the pitch.

This effect can also be seen in the reflected colors, as there is no change in hue of the color with change in pitch as shown in figure 6(b). The results were contrary to what was seen in silicon nanowires [3] where the resonance absorption peak, hence the bright-field reflected colors shifted in wavelength as the pitch was changed. This could be explained by the absence of near-field coupling in direct band gap GaAs nanowires due to high absorption coefficient. But different diameters do give off wide range of colors due to the shift in resonance peak as shown in the figure 6(a).

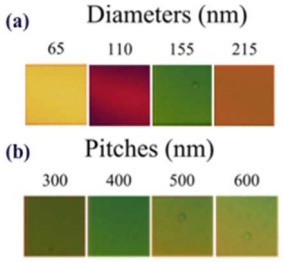

Figure 6. Reflected colors from nanowire arrays at different diameters (above) and pitches (below)

4 CONCLUSION

We have demonstrated ICP-RIE based etching of highly ordered GaAs nanowires. The fabrication method developed allows significant control on diameter, length, pitch and facet shape of the nanowire arrays. The reflectance measurements demonstrate diameter dependent absorption occurring due to excitation of optical modes within the nanowires. At these absorption peaks, light is highly concentrated into the nanowires and even short length nanowires absorb light very efficiently. These tunable absorption peaks can be used to fabricate spectral photodetectors. Further, by increasing the length, the absorption features broaden due to the exponential dependence of Beer-Lambert law resulting in specific diameters for optimized absorption of solar energy. For larger diameters, the fundamental HE_{11} mode is excited in the transparent region of the material and as such, they do not absorb light as efficiently. Also the near field coupling between the nanowires is absent even at the small pitches.
Our work provides an alternate method to growth for fabricating III-V nanowire based devices. The work done here paves the way towards achieving high efficiency solar cells, lasers, single photon emissions and tunable photodetectors using III–V nanowires.

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