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Quantum wires by direct laser fabrication

Anahita Haghizadeh[1] and Haeyeon Yang[1, 2*]
[1]Nanoscience and Nanoengineering, South Dakota School of Mines and Technology, Rapid City, SD 57701, U.S.A.
[2]Center for Security Printing and Anti-Counterfeiting Technology, South Dakota School of Mines and Technology, Rapid City, SD 57701, U.S.A.

ABSTRACT

For optoelectronic device applications, quantum wires can be used as active media due to their unique physical properties. However, conventional approaches such as the self-assembly via the Stranski-Krastanov (S-K) growth technique have a limited success in their applications toward optoelectronic devices including photovoltaics and solar cells. A novel fabrication mechanism for quality quantum wires has been discovered. The laser fabricated nanowires semiconductor surfaces can have width and height as small as 30 and 5 nm, respectively while the density is one per 200 nm.

INTRODUCTION

Fabrication of nanowires has been studied for the last three decades due to their unique properties stemming from the carrier confinement in two dimensions. Lateral semiconductor nanowires are typically fabricated by the Stranski-Krastanov growth technique, so called self-assembly process, which is driven by the strain-relaxation mechanism.[1] However, the dimensions (width, height, and length) of self-assembled nanowires are difficult to control.[2] Vertical nanowires have been studied rather intensively last few years. However, use of vertical nanowires for optoelectronic devices has a problem of integration into the well-established planar processing technology.[3, 4] Recently planar nanowires have been reported to realize nanowire MOSFETs that are grown directly on a semi-insulating GaAs(001) substrates by the selective lateral epitaxy.[5] These nanowires are grown by the vapor-liquid-solid (VLS) technique. Typically vertical nanowires are observed from VLS technique. Lateral nanowires can be grown by the VLS technique when growth parameters are adjusted properly.[6] In this study, we report observation of nanowires on the (001) orientation of GaAs and Si surfaces when they are interferentially irradiated by laser pulses (IILP). Nanowires fabricated by applications of IILP show base width down to 20 nm from GaAs substrates while it is 26 nm from Si substrates. Analysis of surface images obtained by atomic force microscope (AFM) indicates wider and taller nanowires are possible. The analysis suggests that morphology of nanowires can be controlled by controlling the laser intensity.

EXPERIMENT

In order to fabricate nanodots, transient thermal grating was created on the surfaces by overlapping two laser pulses on the surface, which creates a laser intensity modulation on the surface due to the interferential irradation of laser pulses (IILP). A sinlge high power laser pulse is split into two pulses at a 50:50 ratio, one passed through the beamsplitter and the other is reflected. The reflected beam is directed onto the sample surface by a dichroic mirror and the other, pass through beam, is reflected by a dichroic mirror, which direct the beam into the surface as well. The two pulses are eventually overlapped on the surface, which interfere each other to create an intensity modulation on the surface.

The in-air experimental setup is similar to that used to produce nano trenches and nano hills from GaAs(001).[7] Although there are complications in interpreting the surface images due to interaction with ambient gas molecules during the heating and relaxation processes (albeit short due to the short pulse width (7 ns)), in-air patterning is easy and straightforward. The gained insights can be used to determine the sets of interference parameters such as the intensity and wavelength for a particular interference angle for other environments such as vacuum.[8] A schematic diagram is shown in **Figure 1** for IILP. The setup is similar to the report on interference laser crystallization[9] as well as interferometric lithography (IL),[4] where two continuous wave (cw) laser beams, instead of pulses, of wavelength λ intersect at an angle of 2α on a resist-coated substrate, where α is incident angle of laser pulse measured from the surface normal. The interferometric lithography was used to produce an array of nano pyramids that have heights of 40 nm and widths of 30 nm via double exposures,[10] where a second exposure at 90° to the first produces a grid pattern in the resist. Chemical etching after the exposures results in these nanostructures. In our IILP experiments, the chemical etching is replaced by laser ablation when a laser power is large enough.

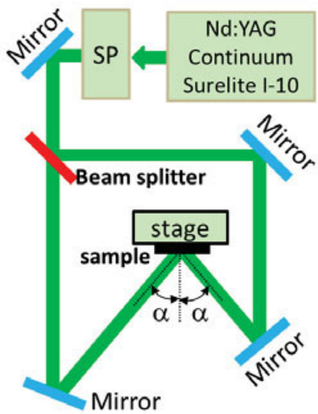

Figure 1. A schematic diagram for in-air IILP for direct fabrication of nanowires. A laser pulse from a Nd:YAG laser passes through the separation package (SP), which separate the intensity of other wavelengths by dichroic mirrors. The pulse is then split by a beam splitter, colored red. The split pulses are directed onto the sample surface by the three mirrors, colored blue. The interference angle or the incident angle of laser pulse into the surface is designated as α, which is measured from the surface normal.

The laser pulses are from an Nd-YAG laser (Continuum Surelite I-10) with an injection seeder laser integrated into the laser head, which reduces the nominal linewidth to 0.005 cm^{-1}. The temporal full width at half maximum (FWHM) of the laser pulse used is 7 nanoseconds. Available wavelengths are the fundamental wavelength of 1064 nm, second harmonics of 532 nm, third 355 nm and the fourth 266 nm with their maximum intensities of 440, 230, 120, 55 mJ respectively. The pulse energy before splitting was measured using a PE50 detector, Ophir-Spiricon. The diameters of the split beams and the incident beam were identical at 7 mm. No noticeable changes in beam profiles were observed after split by using a pyroelectric array camera, Pyrocam III, Ophir-Spiricon but the beam diameter decreases with the decrease of laser intensity. Dichroic mirrors directed the split beams onto the sample surface with their incident angles. The laser intensity modulation on the surface is a sinusoidal function of two laser pulses overlapping on the surface,[11]

$$I(x) = I_0 + 2\, I_0 \cos(2\pi x/p)\ [r(1-r)]^{1/2} \quad (1)$$

where I_0 is the intensity of the laser pulse before splitting, r the splitting ratio between the two pulses, and p the period of the interference, p, can be calculated using the equation,

$$p = \lambda/[2\sin(\alpha)] \quad (2)$$

where λ is the wavelength of the laser pulse and α the incident angle measured from the surface normal as shown in Figure 1.

The laser system is equipped with a manual button switch. This enable us to produce a single laser pulse of fundamental and harmonic wavelengths from the system. A single application of IILP on the surface is carried out by using the manual switch. After the laser exposure, the sample surfaces were examined by atomic force microscope (AFM), Bruker Multimode 8. Contact and Scanayst modes were used to image the surfaces.

DISCUSSION

Generally GaAs(001) surfaces show dots and nanowires when the surface is exposed to IILP. The control of nanostructure shapes, either dots or wires, will be discussed elsewhere. **Figure 2** shows nanowires observed from GaAs(001) surfaces that are exposed to IILP of 266 nm with the interference angle, α, of 41°.

These nanowires have the average width of 20 ± 2.2 nm while its height is 3.2 ± 0.5 nm. The cross-sectional area of these nanowires has a trapezoid shape with flat top. The separation between nanowires is 202.2 ± 1.4 nm. The calculated interference angle is 41.1° using equation (2). This values is consistent with the intended angle of 40 from the designed layout of Figure 1. The nanowire width is about 10 times smaller than the period between nanowires. This kind of narrow nanowires have never been reported by the laser interference patterning technique.

Comparison with other AFM images suggests that the wider and taller nanowires are observed when the area is exposed to a stronger laser intensity. **Figure 3** shows AFM images from the GaAs(001) surface that is exposed to a single IILP with laser wavelength of 355 nm and interference angle of 9.3°, resulting a period of 1.1 μm.. It is noted that the period is more than five times larger width of nanowires in Figure 2 due to the smaller interference angle used. The numbers in FIG 3-(a) indicate the approximate positions of an AFM probe (for example, see #28, dark triangle with a red laser illumination) and the corresponding AFM images of 3 μm are shown below picture (a). The measured interference period is 1,100 nm, consistent with the interference parameters used. The dark feature on the left upper corner in Figure 4-(a) is due to an irregular surface morphology. The overall shape of damage is similar to the laser intensity

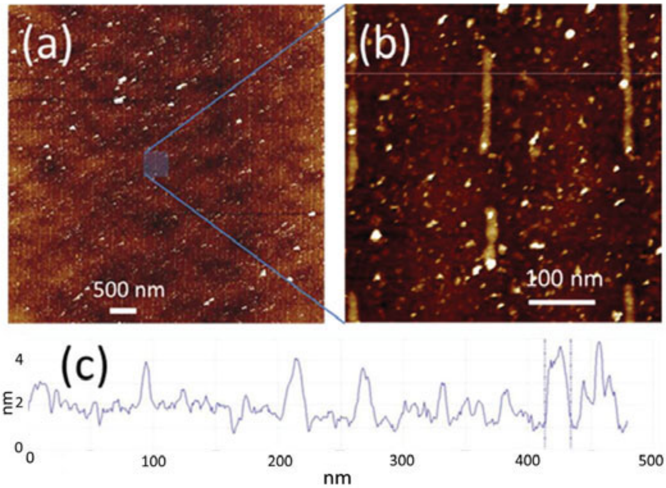

Figure 2. AFM images obtained from GaAs(001) surfaces that are irradiated by two separate exposures of IILP. The pulse wavelength is 266 nm with the measured pulse energy of 50 mJ per pulse. The interference angle, α, was 41°. Image size is 6 μm for (a) while 480 nm for (b). The line profile, (c), is obtained from the white line in (b). The double dotted lines in (c) is to measure the base width of nanowires in (b).

profile that is obtained by a pyroelectric camera. Therefore we can assume that laser intensity is weaker as the position is farther away from the "boundary". Large melted features are seen at the boundary line, #16. It seems that the holes in image #16 are formed due to the joining of heated material from the interference maxima lines as the material is pushed into the cold interference minima lines. A lower laser intensity yielded strips starting from image #14. It seems that the trenches are due to the removal of materials as the area absorbs more photons at the interference maxima area. The trench depth increases with intensity as measured from the images, 30 nm in #14 and 5 nm in #28. This observation suggests that wider and taller nanowires are resulted from the exposure to a stronger laser intensity. Further study on the mechanism of nanowire formation is necessary.

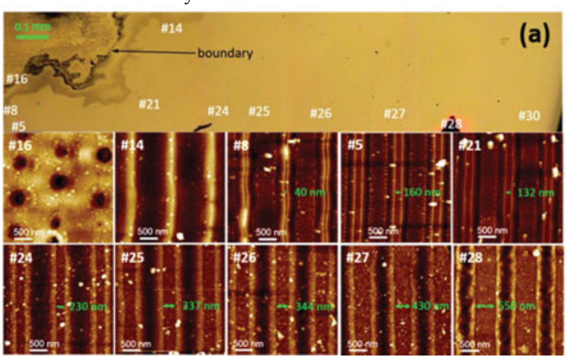

Figure 3. (a)-stitched image from the GaAs(001) surface, which is obtained using the camera attached on top of AFM imaging station. The surface was exposed to a single IILP with laser wavelength of 355 nm and interference angle of 9.3°. The numbers in (a) designate the AFM probe positions for the AFM images below. #28 in (a) is the actual image of the triangular end of the AFM probe used to take images.

CONCLUSIONS

Applications of laser interference on the semiconductor surfaces have resulted in formation of narrow nanowires. AFM observations from the GaAs(001) surfaces indicate that the width of nanowire can be as small as 20 nm. The measured base width is more than 10 times smaller than the interference period for nanowires observed from the GaAs surface. The analysis of AFM images suggests that the width and height of nanowires can be controlled by the intensity of interferential laser pulses. The observations suggest a novel route of fabricating nanowires directly on semiconductor surfaces.

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