Optical Anisotropy of Semiconductor Nanowires

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Abstract- **A novel class of optically anisotropic materials is presented. Layers of semiconductor nanowires fabricated in a bottom-up process exhibit a large in-plane birefringence and show quarter-wavelength retardation for a wavelength of 690 nm. These nanowire metamaterials are promising materials for optical gas- and biosensing.**

I. Introduction

Artificial materials consisting of subwavelength structures are of special interest for applications like optical sensors [1], broadband antireflection coatings [2], and nano-photovoltaic devices [3]. The advantage of artificial materials is the ability to tune their properties depending on the dimensions of the structures. Form birefringence, occurring due to a high density of anisotropic scatterers is one of these properties. Birefringence means different refractive indices for different polarizations of light. Form birefringence occurs in various systems like porous silicon [4] or ensembles of vertically aligned nanowires [5]. Here, we will present measurements of the in-plane birefringence of bottom-up fabricated semiconductor nanowires.

II. Experiments

A. Nanowire Growth

GaP nanowires were grown on top of a [100] GaP substrate in a vapor-liquid-solid (VLS) growth mode by metal-organic vapor phase epitaxy. Before growth, the GaP substrates were cleaned using HNO_3:HCl:H_2O (2:3:3) at 80 °C. To catalyze the growth of the wires, 0.3 nm of gold were evaporated onto the substrate. The length of the nanowires was set by the growth time during VLS growth at 420 °C. The diameter and therewith the filling fraction of GaP was varied by changing to a lateral growth mode at 630 °C. Using this technique, four different samples with different filling fractions of GaP (see Table 1) are fabricated. In Fig. 1, a cross-sectional scanning electron microscopy (SEM) image of sample I is displayed. Most of the nanowires are grown under an angle of around 35 ° with respect to the surface of the sample. Other wires are grown perpendicular to the surface.

B. Optical Measurements

Semiconcuctor nanowire layers are uniaxial materials with two different refractive indices, named ordinary and extraordinary refractive index. The birefringence parameter Δn is defined as the difference of these two indices. This parameter of the nanowire samples shown in Table 1 is determined by measuring the transmission at normal incidence using a diode laser emitting at 690 nm. The nanowire samples were then rotated azimuthally, i.e. around the normal of the sample surface. The transmitted beam was measured for crossed $I_\perp$ and parallel $I_\parallel$ polarization. The ratio of the transmitted intensities $I_\perp/I_\parallel$ is the so called transmission contrast and is displayed for all samples in Fig. 2 as a function of the azimuthal angle. For azimuthal angles from 0 ° to 180° a two-fold symmetry is visible indicating an in-plane birefringence of all samples. At 45 and -45 ° the nanowires are aligned perpendicular or parallel to the incident polarization, so no retardation takes place, which leads to a low contrast. At 0 °, 90 °, and 180 °, the nanowires are aligned to 45 ° with respect to the polarization direction, which allows for retardation and leads to a maximum contrast. For the thinner wires, retardation is weak, which

TABLE I

LIST OF THE SAMPLES INCLUDING AVERAGE DIAMETER; LENGTH OF THE WIRES; VOLUME FRACTION AND BIREFINGENCE PARAMETER δN

Sample	Average diameter [nm]	Length [µm]	Volume fraction [%]	Birefringence Δn
I	22 ± 4	1.2 ± 0.1	7 ± 4	0.003
II	31 ± 3	1.3 ± 0.1	15 ± 5	0.011
III	43 ± 10	1.4 ± 0.2	25 ± 5	0.099
IV	72 ± 19	1.5 ± 0.2	35 ± 5	0.209

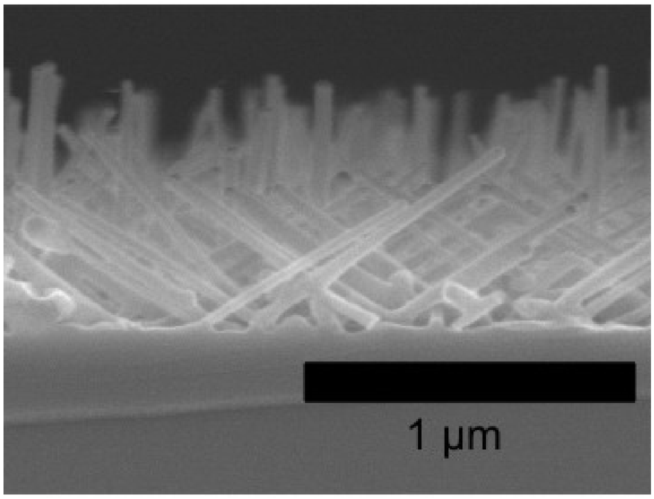

Fig. 1. Cross-sectional SEM image of GaP nanowires grown on a GaP substrate.

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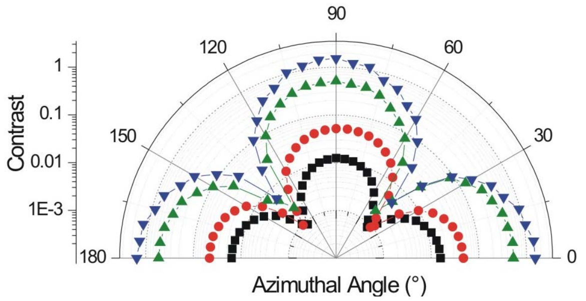

Fig. 2. Ratio of the transmitted intensity I/I as a function of the azimuthal orientation of the nanowires measured at a wavelength of 690 nm, for the sample with a filling fraction of 7 % (black squares), 15 % (red circles), 25 % (green triangles), and 35 % (blue triangles).

corresponds to a small maximum value of the contrast. With increasing nanowire diameter and GaP filling fraction, the maximum value of the contrast is raising and for the sample with the highest GaP filling fraction larger than unity, indicating quarter-wavelength retardation. From the measured retardation, the in-plane birefringence of the nanowire samples can be determined using

$$\left(\frac{I_{\perp}}{I_{II}}\right)_{\max} = \tan\left(\frac{\pi \Delta n L}{\lambda}\right),$$

where Δn, L, and λ correspond to the birefringence parameter, the nanowire length, and the wavelength in vacuum, respectively [6]. The determined birefringence parameters are displayed in Table 1 with an accuracy of 10 %. For the highest filling fraction sample, from the maximum contrast of 1.5, a retardation $\delta = \Delta n L$ of $\lambda/4$ is calculated. This demonstrates the quarter-wavelength retardation for a wavelength of 690 nm.

III. Conclusions

From the measurements described here, we can conclude that we fabricated layers of semiconductor nanowires which exhibit large in-plane birefringence. The highest birefringence nanowire layer reported here shows quarter-wavelength retardation.

The nanowires presented here are GaP nanowires grown on GaP substrates, however, it is important to notice that nanowires can be fabricated using any group IV, III/V, or II/VI semiconductor and can be grown on any semiconductor substrate, offering the possibility of visible, near- and mid-infrared birefringence.

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