Integrated nanophotonics based on nanowire plasmons and atomically-thin material: supplementary material

KENNETH M. GOODFELLOW¹, RYAN BEAMS¹, CHITRALEEMA CHAKRABORTY²,
LUKAS NOVOTNY³, AND A. NICK VAMIVAKAS^{1,*}

¹Institute of Optics, University of Rochester, Rochester, New York 14627, USA

²Materials Science, University of Rochester, Rochester, New York 14627, USA

³College of Physics, Jilin University, Changchun 130012, China

*Corresponding author: nick.vamivakas@rochester.edu

Published 4 September 2014

This document provides supplementary information to “Integrated nanophotonics based on nanowire plasmons and atomically-thin material,” <http://dx.doi.org/10.1364/optica.1.000149>. We detail the methods used to fabricate the sample in the main text. We detail our methodology for calculating photon re-emission efficiency from wires. We demonstrate devices that displayed large enhancement and high polarization contrast. We also display results of a simulation of an MoS₂ flake on a silver nanowire.

<http://dx.doi.org/10.1364/optica.1.000149.s001>

SAMPLE FABRICATION

A solution of silver nanowires (Nanostructured and Amorphous Materials, Inc.) with 386 nm average diameter and 8.6 μm average length is diluted at a 2000:1 ratio of ethanol to solution, and a small amount ($\sim 150\ \mu\text{L}$) is stamped onto a clean silica coverslip using a polycarbonate membrane filter (5 μm pore diameter, SPI Supplies, Inc.). The coverslip was placed in a petri dish with a hole bored in it and held in place with rubber cement for the transfer. On a separate silicon substrate with 270 nm of oxide (Si/SiO₂), we exfoliated MoS₂ from the bulk (SPI Supplies, Inc.) by micromechanical cleavage using adhesive tape (Semicorp). The optical interference due to the thickness of the oxide allows for identification of single-layers [1], which is also confirmed by Raman spectroscopy (Fig. 1b top panel). The flakes were lifted off using a poly(methyl methacrylate) (PMMA)-based technique. After a candidate MoS₂ flake is found on the Si/SiO₂, two coats of 495K PMMA and one coat of 950K PMMA were spun onto the Si/SiO₂; the sample was baked for 5 minutes at 105° C then immersed in 1 M NaOH at 80° C until release begins (about 10 minutes). It was transferred to deionized (DI) water, where the PMMA film was detached with assistance from tweezers. The petri dish with the wire sample was then filled with DI water, and a suitable wire was found using an inverted microscope with a long working distance

objective. The PMMA film was transferred to the petri dish, and a post with a teflon-coated end attached to a micropositioner was brought into contact with the PMMA. Using a Harvard PhD 2000, the water was pumped from the petri dish; the objective focus could be adjusted to position the flake over the wire. The sample dried before immersion in an acetone bath to dissolve the PMMA.

ESTIMATION OF PHOTON RE-EMISSION EFFICIENCY FROM WIRES

Figure S1a displays a bare wire of length 5 μm (wire in text was about 7 μm long). Figure S1b shows a scanning electron microscope (SEM) image of a different wire to show the tapered end geometry. We show plasmon propagation resulting in photon reemission for the wire in Fig. S1a in Fig. S1c with the laser polarized parallel to the wire, and Fig. S1d displays the image resulting from displacing the collection and excitation focal volumes by a transverse length equal to the wire length. These images are contrasted to Fig. S1e and S1f, in which the excitation is perpendicular to the wire. The filters in front of the APD are an optical density filter to cut three orders of magnitude of light (OD3) and a 633/10 bandpass. From this, we can estimate the photon-to-photon conversion efficiency. For this wavelength and power, the input photon flux is approximately 6.4×10^{13} photons/s. At the

APD, the photon flux is approximately 2.5×10^6 photons/s for the parallel excitation. Accounting for the OD3 filter (1000x reduction) and a factor of 4-6x for losses in the system (including a beamsplitter and a pinhole apparatus), we arrive at an efficiency of about 0.015% to 0.023% for this wire. The ratio of photon flux out to photon flux in takes the form of $R = Ae^{\frac{-L}{L_o}}$, where A represents a factor encompassing the photon-to-plasmon and plasmon-to-photon coupling efficiencies, and L_o is the propagation length. Using simulation data, we estimate L_o to be about $3.1 \mu\text{m}$ for our wires. Using this value and the calculated efficiency for the wire in Fig. S1a, we calculate A to be between 7.37×10^{-4} and 1.13×10^{-3} . Applying these values to the wire in the main text, we can estimate the efficiency to be about 0.008% to 0.012%.

DEVICE WITH LARGE ENHANCEMENT

Figure S2 displays data for the MoS_2 /wire device that had the highest enhancement. Figure S2a presents a wide-field image of the region of interest, and the corresponding fluorescence image is shown in Fig. S2b. Spectra taken at the MoS_2 /wire interface as well as on the MoS_2 on substrate $\sim 2 \mu\text{m}$ from the wire are shown in Fig. S2c. In addition to the spectral shift described in the main text, we also notice an increase of $\sim 40\times$ between the height of the two peaks.

HIGH-CONTRAST SINGLE-LAYER MoS_2 /WIRE DEVICE

Figure S3a shows a wide-field image for another single-layer MoS_2 /wire device, and the corresponding fluorescence image is shown in Fig. S3b. Figure S3c shows the fluorescence image resulting when the collection and excitation focal volumes are displaced by a distance corresponding to the wire length. The image is overlaid on a CCD image of the device. The prominent feature is a result of exciting at the wire end opposite the MoS_2 . The normalized polarization response as a function of angle rotated on the half-wave plate is shown in Fig. S3d. We see that this sample has a much higher contrast between the two orthogonal polarizations of about 80%.

FDTD SIMULATION OF THE MoS_2 /NANOWIRE STRUCTURE

Figure S4 displays results of a simulation of the MoS_2 /wire device. Figure S4a shows the simulation interface. A 380 nm silver nanowire is on a silica substrate with MoS_2 on one end of the wire. For the MoS_2 , we assume a refractive index of 6 [5]. Figure S4b shows the electric field profile at the beginning of the simulation with excitation at the uncovered end of the wire. The flake is outlined with a dotted line. The field profile after the simulation is shown in Fig. S4c for the excitation end (labeled 1 in Fig. S4a) and in Fig. S4d for the MoS_2 end (labeled 2 in Fig. S4a). We notice that the field in Fig. S4d has non-zero components in the MoS_2 located directly at the wire as well as a short distance away. This is similar to what was observed in the experiments.

REFERENCES

1. M. M. Benameur, B. Radisavljevic, J. S. Héron, S. Sahoo, H. Berger, and A. Kis, Nanotechnology **22**, 125706 (2011).
2. C. Lee, H. Yan, L. E. Brus, T. F. Heinz, J. Hone, and S. Ryu, ACS Nano **4**, 2695 (2010).
3. A. Reina, H. Son, L. Jiao, B. Fan, M. S. Dresselhaus, Z. Liu, and J. Kong, J. Phys. Chem. C **112**, 17741 (2008).
4. R. S. Sundaram, M. Engel, A. Lombardo, R. Krupke, A. C. Ferrari, P. Avouris, and M. Steiner, Nano Lett. **13**, 1416 (2013).

Fig. S1. (a) CCD image of a bare wire. (b) SEM image of a bare wire. For (a) and (b), scale bars are 1 μm . (c) Demonstration of plasmon propagation along the nanowire in (a) and photon reemission at the opposite end. (d) Image resulting from displacing the collection and excitation focal volumes by a transverse length equal to the wire length. (e) and (f) The corresponding images to (c) and (d) for the polarization parallel to the wire. For (c) through (f), $\lambda = 635 \text{ nm}$, Power = 20 μW .

Fig. S2. (a) Wide-field image of the single-layer MoS₂/wire device. (b). Fluorescence image of the device shown in (a). Scale bars for (a) and (b) are 1 μm . The two white circles correspond to the locations of the spectra in (c). For (b) and (c), $\lambda = 532 \text{ nm}$, power = 5 μW . For (c), spectral integration time = 40 s.

Fig. S3. (a) Wide field image for another single-layer MoS₂/wire device. Scale bar is 4 μm . (b). Fluorescence image of the device in (a). Scale bar is 4 μm . (c) Fluorescence image resulting from displacing the collection and excitation focal volumes by a transverse length equal to the wire length. A CCD image of the device is overlaid with the fluorescence image. Scale bar is 4 μm . Left (right) inset: Feature when light is polarized parallel (perpendicular) to the wire. Scale bar in each is 1 μm . For (b) and (c), $\lambda = 633 \text{ nm}$, Power = 5 μW . (d) Normalized polarization contrast of the MoS₂ fluorescence as a function of excitation polarization angle. 0° corresponds to polarization perpendicular to the wire.

Fig. S4. (a) Interface for the FDTD simulation (Lumerical Solutions, Inc.), representing a 380 nm diameter, 8 μm long silver nanowire with MoS₂ on one end. The substrate is silica ($n=1.5$). (b) Top view of the electric field profile showing excitation at the uncovered end. (c) Cross-section view of electric field profile at the position marked "1" in (a). (d) Cross-section view of electric field profile at the position marked "2" in (a).