Plasmonic Enhancement in Anisotropic Thin Films of Rhenium Disulphide (ReS_2)

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***Abstract*—Anisotropic optical constants of N-layer ReS_2 are determined by angle resolved reflection measurements. Optimum parameters for a metal nanoparticle array leading to maximum light-matter interaction are determined using numerical simulations. Plasmonic enhancement in absorptance of the ReS_2 layer and photocurrent are demonstrated experimentally.**

I. INTRODUCTION

Unlike molybdenum and tungsten based transition metal dichalcogenides (TMDs), rhenium disulphide (ReS_2) remains a direct band-gap material from bulk to monolayer due to weak interlayer coupling [1]. Another difference is that its optical and electrical properties are highly anisotropic in the layer plane [2], [3], mainly due to Peierls distortion that dimerizes Re atoms to form zigzag chains running along one crystallographic axis (also known as b-axis) in the layer plane [4]. This also means that the resistivity perpendicular to the b-axis is much larger than that along the b-axis [5]. With these properties, ReS_2 is considered as a promising material for future various optical and opto-electronic applications such as optical switches [6], field-effect transistors [7], and photo-detectors [7]–[9].

Working with multilayers of ReS_2 has some advantages such as higher absorptance and photo-luminescence compared to monolayers of ReS_2 simply due to increased quantity of the material. Further increase in the absorptance and photo-luminescence can be obtained via plasmonics as has been demonstrated with other TMDs [10]–[13]. In order to maximize light-matter interaction at a particular wavelength, one needs to determine multiple parameters of a plasmonic structure, such as material type, shape, dimensions, and periodicity of a metal nano-particle array. This can be done with either analytical techniques [15], [16] or numerical methods. However, both approaches require refractive index of each material used in the design. To the best of our knowledge, anisotropic optical constants of ReS_2 have not been reported yet. In this work, we first conducted experimental and numerical studies to determine the anisotropic optical constants of ReS_2. Next, a gold (Au) nanoparticle array was designed to maximize the absorptance around 630 nm. The designed array was fabricated on top of a thin ReS_2 film. The absorptance of this structure was measured and experimental results were compared with numerical ones. Finally, a similar structure was used in a photo-diode setup. It is observed that plasmonic structure indeed increases the photo-current.

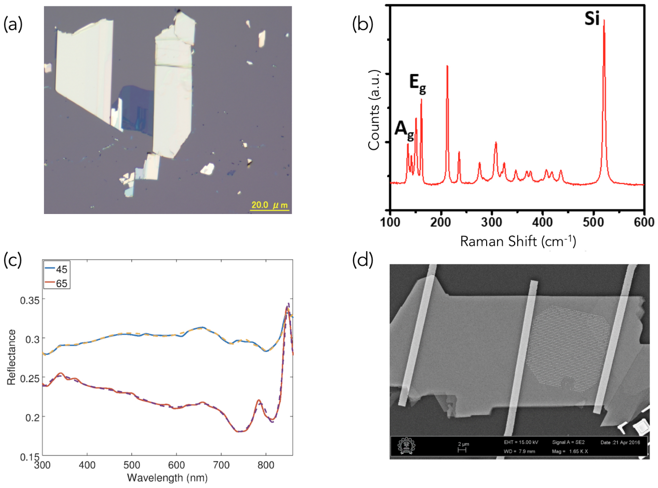

Fig. 1. (a) Optical microscope image of a thin ReS_2 film. (b) Raman spectrum of ReS_2. (c) Experimental and numerical reflectance data, where the latter is obtained with the extracted optical constants. Blue and red solid lines represent the measured data, where the incidence angle was 45 and 65 degrees, respectively. (d) A scanning electron microscope scan of a gold nanoparticle array fabricated on a thin ReS_2 film with a bottom gate.

A. Determination of Anisotropic Optical Constants

A 150×200 μm^2 thin film of ReS_2 was transferred onto thermally grown SiO_2/Si substrate by standard exfoliation technique as shown in Fig. 1 (a). The thickness of the SiO_2 and ReS_2 films are 280 nm and 250 nm, respectively, where the thickness of ReS_2 was determined by an Asylum AFM system. The quality of ReS_2 was checked via its Raman spectrum, see Fig. 1 (b). Reflectance from the substrate with and without the ReS_2 film was measured with an ellipsometer at various incident angles along two directions perpendicular to each other. Since the main application is plasmonic enhancement, we used only p-polarized light covering the wavelength range of 300 - 1000 nm.

ReS_2 was assumed to have a refractive index tensor with only non-zero diagonal terms. Similar to [14], a search algorithm was created to find six unknowns: n_x, k_x, n_y, k_y,n_z, and k_z, where n_η and k_η are the real and imaginary parts of the complex refractive indices along the

η-direction, where $\eta = x,\ y$, or z. The input parameters of the search algorithm includes refractive indices of Au, SiO_2, and Si [17], thicknesses of the SiO_2 and ReS_2 layers, and initial ranges for n_η and k_η. Then the algorithm calculates the reflectance at every wavelength value measured using a set of refractive index values chosen from the finite range defined initially and compares numerical results with experimental data. The set of values giving minimum error on six different measurements, i.e. three different incident angles along two perpendicular directions, was recorded. This procedure was iterated several times using the estimates from the previous iteration as the center point of the new range. The iteration was stopped when the difference between two consecutive estimates was less than machine epsilon. The determined refractive index tensors show that ReS_2 is indeed a highly dispersive and highly anisotropic material. Fig. 1 (c) shows very good agreement between experimental and numerical reflectance spectra for the incidence angles of 45 and 65 degrees. Note that the numerical results were obtained using the developed anisotropic optical constant model. The average absolute error was less than 0.5%.

B. Plasmonic Array Design, Fabrication, and Characterization

Optimum parameters of a metal nano-particle array yielding maximum absorptance at 630 nm were determined using a commercially available electromagnetic solver, Lumerical. The plasmonic array was assumed to consist of Au cylinders. Radius of 140 nm, height of 70 nm, and edge-to-edge particle spacing of 180 nm were determined to be optimal for the Au plasmonic array.

The designed structure was fabricated on top of a 75 nm thick ReS_2 film following typical electron beam lithography and lift-off processes as shown in Fig. 1 (d). The measured spectrum exhibits very good agreement with the one obtained numerically and the plasmonic structure increases the absorptance by 40%.

C. Plasmonically Enhanced ReS_2-based Photo-Detectors

Lastly, a thin ReS_2 film decorated with a Au nanoparticle array was tested in a typical photo-detector setup. Photo-current flowing through the structure was measured while changing the drain-to-source voltage from -1 V to 1 V with and without external illumination. Again, a significant increase in the photo-current was observed. Detailed analysis of the experimental results including transient characteristics, which are not provided here for the sake of brevity, will be discussed at the conference.

II. CONCLUSION

Anisotropic optical constants of ReS_2 have been determined by angle resolved reflection measurements. Optimum parameters for a metal nanoparticle array leading to maximum light-matter interaction are determined with numerical simulations. Plasmonic enhancement in the absorptance of the ReS_2 layer has been demonstrated experimentally. Photodetectors deploying ReS_2 with and without a Au plasmonic structure also exhibit significant enhancement in the photocurrent in the visible region.

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