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Manipulating flow of light in 2D materials

Two-dimensional (2D) materials have emerged as promising candidates for miniaturized optoelectronic devices, due to their strong inelastic interactions with light. On the other hand, a miniaturized optical system also requires strong elastic light-matter interactions to control the flow of light. We observed giant optical path length (OPL) from a monolayer molybdenum disulfide (MoS_2), around one order of magnitude larger than that from a monolayer graphene. Using such giant OPL to engineer the phase front of optical beams, we demonstrated, to the best of our knowledge, the world's thinnest optical lens consisting of a few layers of MoS_2 less than 6.3 nm thick.

Refractive optical components rely on the optical path length (OPL) to modify the phase front of an optical beam. The OPL is directly related to the geometrical length of light path. As a result, it is normally expected that the OPL of an ultra-thin 2D material would be too small to have a significant impact on the phase front because of their ultra-thin thicknesses. But we have been able to observe a giant OPL of 38 nm from a monolayer MoS_2, which is more than 50 times larger than its physical thickness of 0.67 nm and around one order of magnitude larger than the measured OPL of a monolayer graphene that was found to be only 4.4 nm (Figure 1).

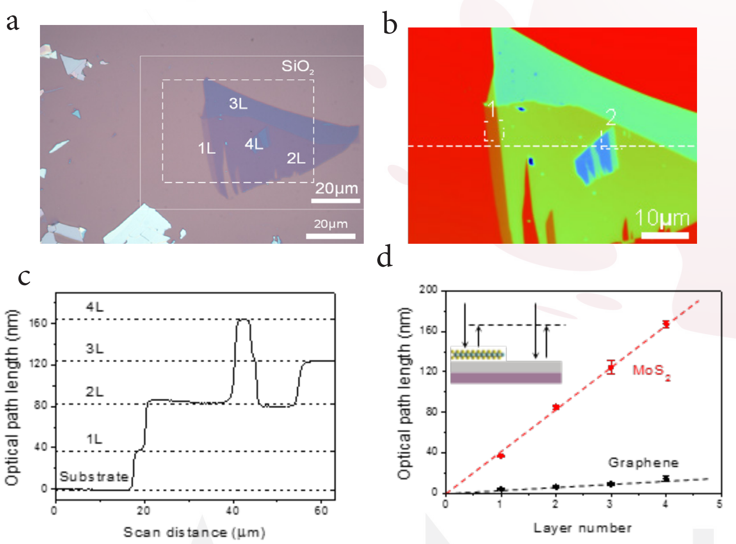

Figure 1 Giant optical path lengths (OPLs) from single- and few-layer MoS_2. a, Optical microscope image of a mechanically exfoliated MoS_2 sample on a SiO_2/Si substrate (275 nm thermal SiO_2). b, Phase shifting interferometry (PSI) image of the region inside the box indicated by the dashed line in (a). c, PSI measured OPL values versus position for 1L, 2L, 3L and 4L MoS_2 along the dashed line in (b). d, Statistical data of the OPL values from PSI for 1L, 2L, 3L and 4L MoS_2 and graphene samples. Inset is the schematic plot showing the PSI measured phase shifts of the reflected light from the MoS_2 flake ($\phi\_(_{MoS2})$) and the SiO_2 substrate ($\phi\_(_{SiO2})$).

This giant OPL is created by relatively strong multiple reflections at the air-MoS_2 and MoS_2-SiO_2 interfaces. The OPL of high-index 2D materials, such as MoS_2, is remarkably larger than that of SiO_2, graphene, Au or Si. And by making use of its giant OPL, we demonstrated phase-front engineering by fabricating the world's thinnest lens based on a few atomic layers of MoS_2 (Figure 2). We started with a flake of uniform 9L MoS_2 and then used focused ion beam (FIB) to mill a pre-designed bowl-shape structure (20 μm in diameter) into the flake (Figure 2a&b). The gradual change of MoS_2 thickness, from the centre to the edge, led to a continuous and curved OPL profile for an incident beam, and this served as an atomically thin (reflective) concave micro-lens (Figure 2c). Based on the measured OPL profile, the focal length f of this MoS_2 micro-lens was calculated to be -248μm.

We used a far-field scanning optical microscopy (SOM) to characterize the fabricated MoS_2 micro-lens. The micro-lens was moved along the z-axis in steps of 10 μm by a piezo-electrically driven stage. The camera recorded a series of the intensity distributions with the MoS_2 micro-lens positioned at different z values. A three-dimensional dataset was generated and a cross section profile was obtained along the x- and z-axes to illustrate the average distribution of the light intensity in these directions (Figure 2d). When the MoS_2 micro-lens was placed at a distance $2|f|$ above the focal plane, the focused incident light would be exactly reimaged which is equivalent to the light coming from a point source. Therefore, the camera recorded a well-focused light spot. The focal length f of the MoS_2 micro-lens was measured to be -240 μm ($2f$ = -480 μm), which matches very well with the simulated value (-248 μm).

In conclusion, we have shown that high-index 2D materials have extraordinary elastic interactions with light. As a result, wavefront shaping can be accomplished with atomically thin 2D materials, enabling a new class of optical components entirely based on high-index 2D materials. Moreover, compared to conventional diffractive optical com-

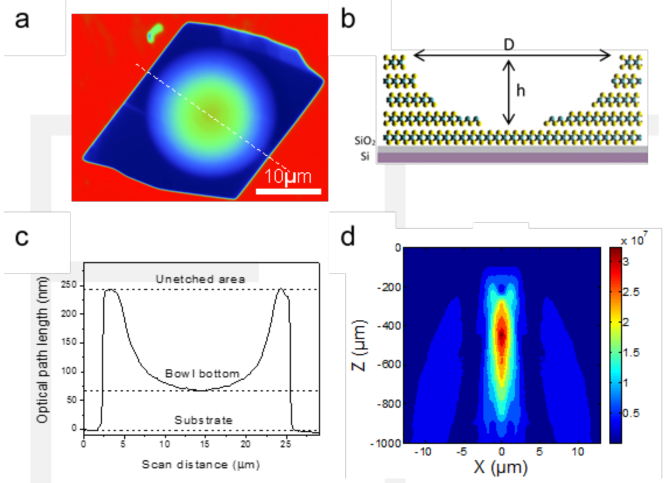

Figure 2 Atomically thin micro-lens fabricated from a few-layers of MoS_2. a, PSI image of an atomically thin micro-lens fabricated on a 9L MoS_2 flake. b, Schematic plot of the micro-lens structure. c, Measured OPL values versus position for the direction indicated by the dashed line in (a). d, Intensity distribution pattern of the MoS_2 micro-lens measured by scanning optical microscopy (SOM).

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ponents, the spatial resolution of phase-front shaping is much smaller than the wavelength, and is only limited by the nano-fabrication resolution, making it possible to eliminate undesired diffractive orders. 2D materials also offer many unique advantages:

1. the extremely uniform thickness and the prefect surfaces with atomic roughness in layered high-index 2D materials provide us fantastic ways to precisely control the phase front of a wave.
2. the unique and large tunability of the refractive index by electric field in layered MoS_2 will enable various applications in electrically tuneable atomically thin optical components, such as micro-lenses with electrically tuneable focal lengths, electrical tuneable phase shifters with ultra-high accuracy, which cannot be realized by conventional bulk solids.
3. 2D optical components represent a significant advantage in manufacturing compared to conventional 3D optical components, because different functionalities can all be achieved in a 2D platform sharing the same fabrication processes and this will greatly facilitate the large-scale manufacturing and integration.

We would like to acknowledge support from the ACT node of the Australian National Fabrication Facility (ANFF) and, particularly, the technical support on the FIB provided by Dr. Li (Lily) Li. We acknowledge the financial support from an ANU PhD scholarship; the Office of Naval Research (USA) under grant number N00014-14-1-0300; the Australian Research Council (grant number DE140100805); and the ANU Major Equipment Committee.

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Spring has sprung in Canberra and what does that mean, both Floride and hayfever season has started.

It has been busy past three months, and looks like the next three months will be even busier, with the Annual ANFF Showcase, 'Mind the Gap', on 16-17 November 2016, as well as COMMAD in Sydney on 12-14 December 2016. For futher details see our web site for the links.

The ANFF ACT Node users annual survery is now completed and the information is being compiled. To those who made comments they will be responded to in the next month. The winner of the survey competition was Jun Peng of CECS. He won a tablet, eight hours of free machine time, and an ANFF Polo shirt. Jun was very surprised and happy that he took the time to complete the survey.

We would like to say thank you to all users who took the time to complete the survey. Is it a very helpful tool to make sure we are providing our users great service, communication & accessability.

Sue

Electron Beam Lithography

Electron beam lithography (EBL) is most suited for prototyping due to its combination of flexibility and patterning accuracy. Our RAITH 150 EBL is a versatile 30kV system that allows the control of the electron beam to expose dedicated resists to create lithographic patterns well into the sub-µm range. Feature sizes of 20 nm are frequently exposed and hardware and software automation allows us easy and repeatable multilayer exposures. Our system is equipped with FBMS (Fixed beam moving stage) exposure technology with "zero-stitching-error" approach for patterns that can be several millimeters to centimeters long, while maintaining lateral dimensions below 100 nm up to micrometers.

One of the characteristic figures of the e-beam lithography process is the critical dose. It is defined as the charge deposited by the electron-beam in order for the exposed regions to be removed completely by the developer. When electrons accelerated with a certain voltage penetrate into a material, they are subjected to back and forward scattering. Some of the incident electrons are scattered with a very large angle and are responsible for the exposure of the resist in areas away from the actual beam position. The additional dose resulting from back-scattered electrons give rise to the proximity effect (PE) which is the main limiting factor for e-beam lithography accuracy. The magnitude of this effect is dependent on the accelerating voltage. High accelerating voltages (100 kV) reduces PE due to a larger penetration depth of the electrons in the substrate material. In this case, the large angle scattering occurs further away from the resist with the probability of them becoming absorbed in the material before reaching the resist is much higher. However, this is not the case for lower accelerating voltages; thereby our 30 KV Raith 150 causes a more pronounced PE. Consequently carefully apply PE corrections next time you use the system.

Over the span of one decade, Raith 150 has been vibrant in serving ground breaking research for applications in, though not restricted to, photonics/opto-electronics. Top-down and bottom-up approaches have been perfected to exhibit novel device concepts in III-V semiconductors. To manifest a few examples a nanopillar ensemble is shown in fig. 1(a), distributed feedback grating is shown in fig. 1(b) and 50 nm vertical nanosheets are represented in fig. 1(c). Researchers at ANU and beyond are pursuing a growing desire for smaller devices (nano dimensions) driven by the moore's law. Evolutionary high-end electron beam lithography is vital in bringing compactness and improved efficiency for device and circuit technology of photonics/opto-electronics components and systems. ***Dr Naeem Shahid***

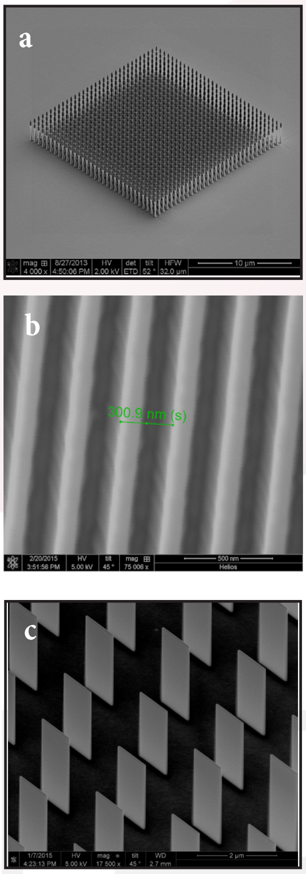

Figure 1: SEM images of the nanoengineered assembly (courtesy Shagufta Naureen and Philippe Caroff). (a) Noanopillar ensemble (b) Distrbuted feedback gratings (c) Standing nanosheet membranes.

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