Two-dimensional layered $PtSe_2$ for High Speed Near-Infrared Electro-Optic Modulation

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Platinum diselenide can be grown by chemical vapor deposition as a two-dimensional (2D) material and is relatively stable in air. We experimentally demonstrate a 2D $PtSe_2$ electro-optic intensity modulator at 1550nm wavelength. The fabricated $PtSe_2$ modulator has a response speed of 4.8 GHz and a modulation depth of 6 dB.

Keywords: *2D materials, $PtSe_2$, Near-infrared, Modulators*

INTRODUCTION

Two-dimensional (2D) layered platinum diselenide ($PtSe_2$) is of interest for optoelectronic applications because of its attractive properties such as high carrier mobility, good air stability and a layer-tunable bandgap ranging from 0 (bulk) to 1.2 eV (monolayer) [1]. Besides, high quality and scalable 2D layered $PtSe_2$ thin films could be prepared by relatively straightforward synthesis methods which could control the number of monolayers with good repeatability [2]. Hence there has been previous publications reporting the use of 2D $PtSe_2$ for high speed infrared photodetectors [3,4], but its use for optical modulators has been relatively unexplored.

Bound states in the continuum (BIC) PICs have been demonstrated to be an exceptional platform for hybrid integration of 2D materials for providing a naturally flat substrate for integrating 2D materials [5]. Photonic layers are formed by an etch-free E-beam lithography process with low-refractive-index polymer while 2D materials are on the flat high-refractive-index dielectric substrate with negligible influence on the properties of materials during fabrication processes. Here, we propose and experimentally demonstrate a waveguide-integrated $PtSe_2$-based electro-optic (EO) intensity modulator. Double-layered CVD-grown $PtSe_2$ thin films are hybrid integrated with BIC optical waveguide on a crystalline dielectric substrate. In our experiments we used a lithium niobate crystal as the passive substrate. The $PtSe_2$ layer could be modulated with a modulation bandwidth of 4.8 GHz bandwidth and direct intensity modulation, with 6 dB modulation depth, was observed over a broad operation wavelength range from 1500 to 1580 nm, under ambient conditions.

DEVICE FABRICATION AND CHARACTERIZATION

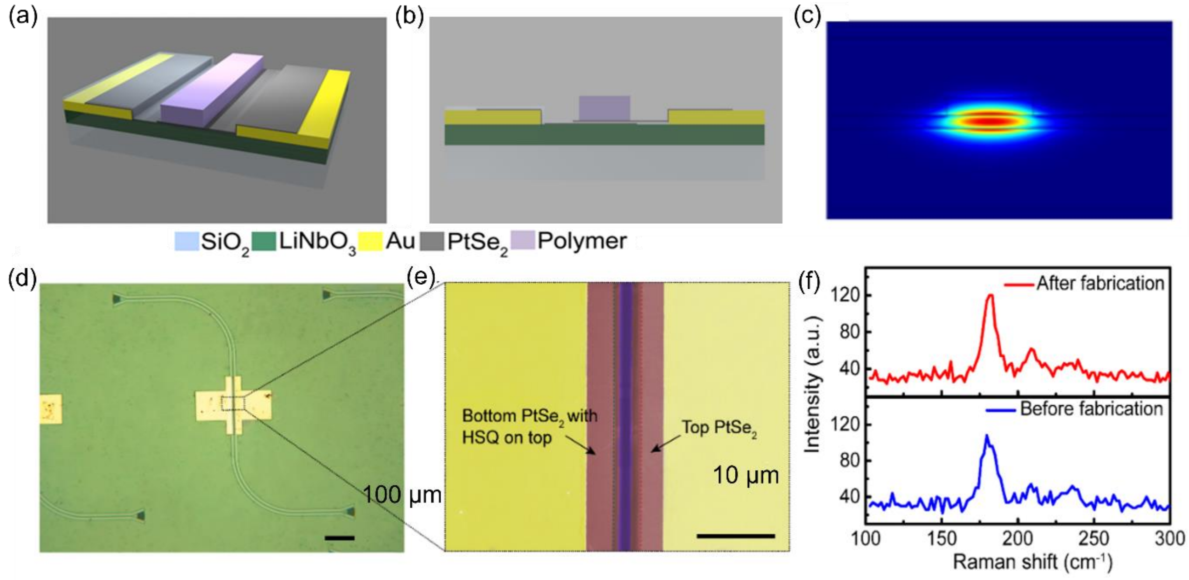

Fig. 1(a) Schematic illustration of the double-layered $PtSe_2$ modulator. (b) Cross section of the device. (c) Mode profile in the cross section of the BIC waveguide. (d) Optical microscope image of the $PtSe_2$ modulator (scale bar: 100 µm). (e) False-color SEM image illustrating the dashed region in Fig.1(d) (scale bar: 10 µm). The waveguide, Ti/Au metallization and $PtSe_2$ thin film *are represented in blue, yellow and red, respectively. The red dashed line represents the boundary of bottom PtSe$_2$ thin film, while the green line represents the boundary of top layer PtSe$_2$. (f) Raman spectroscopy of the PtSe$_2$ thin film before and after the whole fabrication process.*

Figure 1(a) displays the schematic illustration of the PtSe$_2$ modulator and Fig. 1(b) depicts the cross section of device design. Two layers of PtSe$_2$ thin film (in grey colour) separated by a thin insulator formed by a layer of 150 nm thick HSQ (blue) was placed on the LiNbO$_3$ substrate (green). The polymer waveguide (purple) has a thickness of 500 nm sits on top of the PtSe$_2$ capacitor. Here we use a commercially available E-beam resist ZEP 520A (with a refractive index of 1.54) to form the waveguide. Two gold electrodes (yellow) are placed on each side of waveguide. The left electrode is contacted with the lower layer of PtSe$_2$, while the right electrode is contacted with the top layer. The mode profile of the BIC waveguide at 1550 nm is shown in Fig. 1(c). Light is mainly confined in the LiNbO$_3$ substrate below the polymer waveguide while keeping strong interaction with the PtSe$_2$ thin film. The PtSe$_2$ modulator was fabricated by the following process sequence: First, the metal electrodes were lithographically patterned, and 5 nm Ti/100 nm Au were deposited by e-beam evaporation. Then the bottom layer of CVD-grown PtSe$_2$ thin film was wet transferred onto the substrate, followed by EBL patterning and Ar plasma etching. The dielectric layer was started from spin coating of ~150 nm HSQ E-beam resist. After EBL exposure, the HSQ thin film was patterned and turned into SiO$_2$. The top layer of PtSe$_2$ thin film was wet transferred and patterned in the following steps. Finally, the polymer waveguides were fabricated by spin coating followed by EBL patterning. The optical and scanning electron microscope (SEM) images of the device are shown in Fig. 1(d) and Fig. 1(e). The waveguide width is designed to be 2 µm in order to support low-loss BIC mode. The distance between two metal electrodes is 10 µm. The length and width of double layer of PtSe$_2$ capacitor are designed to be 200 µm and 4 µm, respectively. The thickness of the PtSe$_2$ sample is about 4 nm, and was measured by an atom force microscopy (AFM). The quality of the material is confirmed by Raman spectroscopy as illustrated in Fig. 1(f), which shows the measured spectrum before (blue) and after (red) fabrication. No obvious defect peaks or peak position shift were introduced by the whole fabrication process, indicating that there is no structural damage to the PtSe$_2$ thin film.

RESULTS

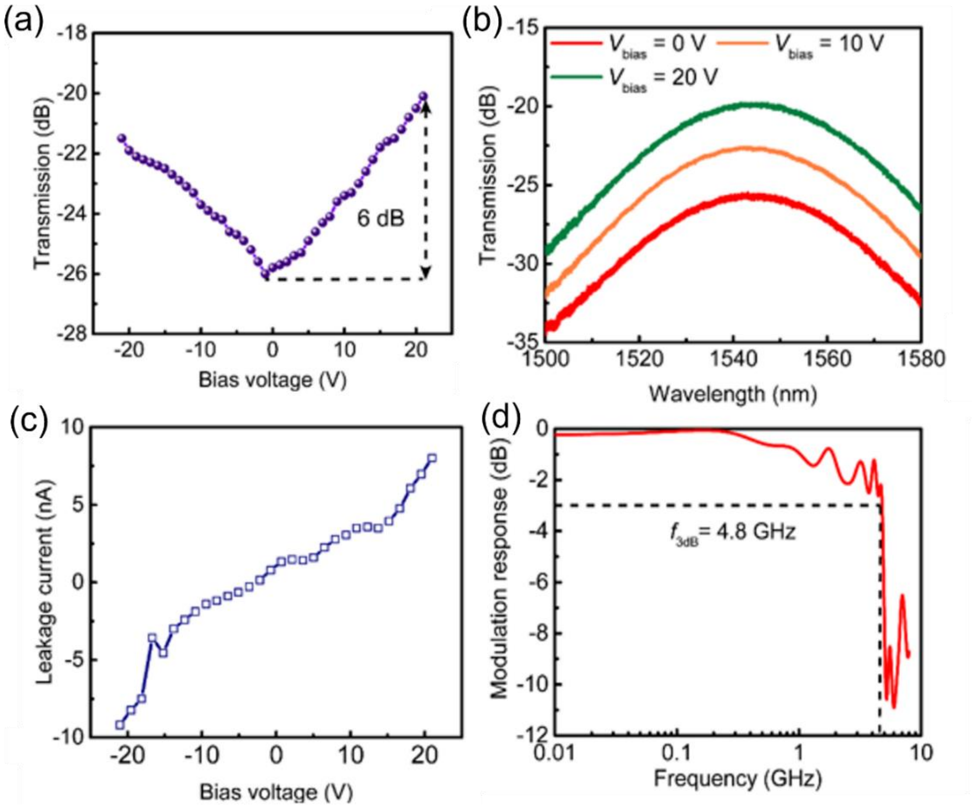

Fig. 2(a) Transmission of light at 1550 nm under different bias voltage V_{bias} from -21 V to 21 V. (b) Broadband optical transmission of the PtSe$_2$ modulator. (c) I-V measurement for the leakage current. (d) Frequency response of the PtSe$_2$ modulator.

The static optical transmission of the PtSe$_2$ modulator was measured with a tunable semiconductor laser, which was coupled to the input waveguide by an optical fiber and a waveguide grating coupler. A mechanical fiber polarization controller was adjusted at the input to couple the TM mode into the waveguide. Fig. 2(a) illustrates the transmission of the device which had 200 µm length of evanescently coupled $PtSe_2$ thin films. The applied bias voltage was varied from -21 V to 21 V. At 1550 nm, the transmission of light through the single straight waveguide was clearly dependent on the voltage applied across the $PtSe_2$ capacitor. The total optical loss of the input and output grating couplers were about 18 dB in the device and we observed an additional voltage dependent loss of about 6 dB while there was about 2dB excess insertion loss from the $PtSe_2$ thin films. The operation principle of the $PtSe_2$ modulator is based on the change in free carrier density under different applied voltages, similar to previously reported double layer graphene modulators [6]. We observed an asymmetry in the modulation response at negative bias and positive biases, that is possibly caused by the different carrier mobility of electrons and holes. Fig. 2(b) shows the wavelength spectral response of our device measured under different bias voltages. From 1500 nm to 1580 nm, the device had a similar modulation depth of about 6dB, indicting a broad optical bandwidth of operation for the $PtSe_2$ modulator. The *I-V* curve of the device is shown in Fig. 2(c). The leakage current was under 10 nA at 20 V bias. The breakdown voltage of the dielectric layer (150 nm HSQ) was measured to be around 30 V. It should be noted that the switching voltage of the device is determined by the dielectric constant and thickness of the dielectric. The switching voltage of the $PtSe_2$ modulator could be reduced by thinning the thickness of the dielectric layer, but the switching speed will be reduced by the larger capacitance and increase in the resistance-capacitance (RC) time constant.

The response speed of the $PtSe_2$ modulator was characterized by the small signal response. A radio frequency (RF) signal generated from a network analyzer combined with a D.C. voltage through bias tee, was applied to the $PtSe_2$ modulator. Light at a wavelength of 1550 nm was directly coupled into the device from the grating coupler and the out-coupled light was received by a 10 GHz high-speed photodetector. Fig. 2(d) plots the measured frequency response S_{21} (S_{21}: ratio between the optical amplitude modulation and the RF signal) of the modulator. The 3dB cutoff frequency of our device is measured to be 4.8 GHz. As CVD-grown $PtSe_2$ has relatively high carrier mobility under ambient conditions [4], the response speed of the modulator is mainly limited by the RC time constant. By simplifying the $PtSe_2$ modulator as an electric circuit, the RC time limited 3 dB bandwidth f_{3dB} can be calculated by $f_{3dB} = 1/(2\pi RC)$, where R is a sum of the output impedance of network analyzer R_o = 50 Ω and the contact resistance at the gold/$PtSe_2$ interface, which is about 150 Ω. Considering the structure of $PtSe_2$ capacitor, with a length of 200 µm, a width of 4 µm and 150 nm SiO_2 dielectric, a capacitance of 174 fF could be estimated. We estimated an RC limited bandwidth of about 4.6 GHz which is in reasonable agreement with the experimentally measured bandwidth. The speed of the $PtSe_2$ modulator could be further improved by optimizing the device structure. For example, the capacitance can be reduced by increasing the thickness of dielectric layer or integrating the $PtSe_2$ capacitor with an optical cavity to minimize the area of planar capacitor while keeping the modulation efficiency in the meantime.

CONCLUSION

In conclusion, we proposed and experimentally verified that $PtSe_2$ may be used for optical intensity modulators. The proof-of-concept device operated at 1550 nm wavelength with a modulation depth of 6 dB and about 4.8GHz modulation bandwidth. The performance of the device could be further improved for higher speed modulation by optimizing the device structure such as integrating with an optical cavity. This work paves the way of $PtSe_2$ based photonic devices, showing that $PtSe_2$ could be potentially utilized for high-speed optoelectronic devices.

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