Research article

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Phosphorene-assisted silicon photonic modulator with fast response time

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Abstract: All-optical modulators avoid the conversion from external electronic signals to optical signals and thus have the potential to achieve an energy-efficient high-speed photonic system. Phosphorene recently debuted as an attractive material that exhibits outstanding high electron mobility, strong light-matter interaction and modifiable bandgap, making it ideal for all-optical modulators. In this paper, by incorporating a phosphorene and silicon-based micro-ring resonator (MRR), we first propose and experimentally demonstrate a unique phosphorene-integrated all-optical modulator in telecommunications. By utilizing a phosphorene thin film with an average thickness of 22 nm as the absorption material, the rise time of only 479 ns

and decay time of 113 ns are achieved, which is the fastest reported response time in the family of phosphorene modulators. The corresponding 3 dB bandwidth is larger than 2.5 MHz, and it exhibits a low-loss performance benefited from its finite bandgap. The proposed phosphorene/MRR hybrid modulator may have potential in the applications of all-optical interconnections.

Keywords: phosphorene; modulators; all-optical devices; integrated optics devices.

1 Introduction

All-optical signal processing is more energy efficient in telecommunications since the conversion from external electronic signals to optical ones is removed [1, 2], which significantly meets the demands for growing data capacity and processing speed. All-optical modulators can control the input light by another light to achieve signal modulation. Thus, the two lights interact with each other in an optical medium, typically in an optical fiber or an integrated photonic chip. Assisted by two-dimensional (2D) materials, all-optical modulators have been widely applied in telecommunications based on the principle of saturable absorption [3, 4], the optical nonlinear Kerr effect [5, 6] and the thermo-optic effect [7, 8]. However, these all-optical modulators exhibit a relatively slow response time in the hybrid structure of silicon waveguides and 2D materials. It is essential to achieve an all-optical modulator with small footprint, low power consumption and fast response time.

In the past few decades, 2D materials, such as graphene [7, 9, 10], MXene [11–13], phosphorene [14, 15], antimonene [16, 17], bismuthene [18] and transition metal dichalcogenides (TMDs) [19, 20], have attracted tremendous interests due to their outstanding properties in optical modulator applications [21]. Assisted by these nanomaterials, a lot of efforts have been exerted in all-optical modulators. A graphene-clad microfiber shows good performances in an all-optical modulator with a modulation depth (MD) of

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38% and a response time of 2.2 ps, which has an ultra-fast response time but cannot achieve a large MD due to Pauli blocking in the graphene [3]. An all-optical modulator with a phosphorene-deposited microfiber had a conversion efficiency of $0.029 \pi/\text{mW}$, while the response time was only of microseconds [14]. In integrated devices, a graphene-on- Si_3N_4 chip achieved a response time of 253 ns but with a low energy efficiency and a high power consumption limited by the thermal conductivity of Si_3N_4 [7]. A feasible solution is to combine the merits of 2D materials and silicon waveguides with excellent thermal conductivity efficiency to enhance the light-matter interaction.

2D black phosphorus (BP), also named as phosphorene, recently debuted as a novel 2D material that might compete with graphene thanks to its high electron mobility, strong light-matter interaction and modifiable bandgap [22–24]. BP is stacked from monolayer phosphorenes by van der Waals force, which are formed by phosphorus atoms in a puckered honeycomb structure. We can exfoliate BP from a bulk material and transfer the BP pieces directly onto a silicon waveguide without an additional etching process. The bandgap of BP is in the range from 0.3 (bulk) to 1.5 eV (monolayer) [25, 26], which remains a direct bandgap for all thicknesses, bridging the gap between graphene and TMDs. Thus, BP can absorb the light ranging from visible light to near-infrared light [27]. These unique properties make it extremely suitable for optical communication devices such as optical Kerr switchers [28–30], wavelength converters [13], photodetectors [31, 32], modulators [14] and saturable absorbers [33]. Integrating 2D materials to silicon-based devices has the advantages of easy fabrication, improved light-matter interaction and compatibility with complementary metal oxide semiconductor (CMOS) fabrications [34]. To further enhance the light-matter interaction in silicon devices, we can integrate BP to a silicon micro-ring resonator (MRR). MRR has a high-Q resonance peak which increases the MD, and the resonant light in the MRR significantly increases the time of light-matter interaction. MRRs are ideal for telecommunication and data processing applications [35, 36]. The hybrid of BP and silicon MRR results in high efficiency and fast response time on a silicon integrated platform based on the thermo-optic effect.

Here, we propose and experimentally demonstrate a phosphorene-assisted silicon MRR modulator in all-optical telecommunications. The rise time and decay time are only 475 and 134 ns, respectively, where the 3 dB bandwidth of 2.5 MHz is measured in our experiment. To our knowledge, these results are the fastest response time of BP in silicon-based modulators. Besides, integrating BP to silicon devices has the advantages of easy fabrication

and CMOS compatibility. The hybrid of BP and silicon photonics has potential in future integrated all-optical interconnections.

2 Device fabrication and principle

The schematic structure of a phosphorene-assisted silicon photonic modulator is displayed in Figure 1A. In this design, we first used a silicon-on-insulator (SOI) platform to fabricate the MRR by choosing the etching depth of 220 and 80 nm for the strip waveguides and grating couplers, respectively. The gap distance between the 100- μm -diameter MRR and the straight waveguide was set to 80 nm, and the waveguide width was 500 nm. To avoid the loss caused by BP, it was exfoliated as thin as possible, and then transferred on the top of the micro-ring waveguide by using the imprint-transfer process. At last, we spin-coated a 500-nm-thick polymethyl methacrylate (PMMA) layer on the chip to prevent the BP from interacting with water in air. Figure 1B shows the microscope image of the device before spin-coated. Figure 1C shows the scanning electron microscopy (SEM) image of the BP-MRR hybrid structure. The Raman spectrum of BP exhibits typical A_g^1 , B_{2g} and A_g^2 phonon vibration mode, as shown in Figure 1D. The Raman spectrum is consistent with the previous research works [37]. The linear absorption spectrum of BP is illustrated in Section A of Supplementary Material. The thickness of the BP was measured to be 22 nm with an atomic force microscope (AFM), as shown in Figure 1E, and the BP size was tailored within $10 \mu\text{m} \times 20 \mu\text{m}$ to make sure that the MRR loss is not affected by the BP.

The principle of the modulator is based on the thermo-optic tuning of the resonance wavelength of the MRR, given by

$$\lambda_m = \frac{2\pi n_{\text{eff}} r}{m} \quad (1)$$

where r is the radius of the MRR, n_{eff} is the effective refractive index of the BP/silicon hybrid waveguide and m is a positive integer called the resonance order. Thus, the resonant wavelength changes with n_{eff} , which is typically affected by the temperature. When a pump light emits on the BP, the temperature of the BP increases due to its absorption, and then the heat is transferred to the silicon waveguide under the BP, which performs a red shift in the output spectrum. We put the probe light in the resonator, and it will exhibit an intensity modulation as long as the pump light with high power heats the BP. The probe light will be modulated if the pump light is emitted in the

Figure 1: Structure and characterization of the BP modulator.

(A) Three-dimensional schematic illustration of the BP/MRR hybrid all-optical modulator. The probe light (red) and pump light (blue) are both coupled into the MRR waveguide. (B) Top-view microscope image of the device. (C) SEM snapshot of the BP-MRR hybrid structure. The red dashed curve indicates the boundary of the BP thin layer. (D) Raman spectrum of the BP material of the device. (E) The thickness measurement results using an AFM. The average thickness of the BP is 22 nm.

waveguide or from the free space. Since the BP absorbs light in a wide range, we used 980 and 1550 nm light to illuminate the BP in our experiment.

3 Experiment and results

3.1 Pumping in free space

Figure 2A shows the schematic illustration for free-space pumping. The probe light is coupled into the waveguide by the grating coupler, and the pump light vertically illuminates the BP in free space. The probe light is generated by an amplified spontaneous emission (ASE) light source in

the C-band, and the pump light is generated by a 980-nm continuous-wave laser. By changing the power of the pump light, the spectra of the probe light are measured and recorded, as shown in Figure 2B. The pump light is incident upon the top of the BP material, and the diameter of the pump light spot is similar to the size of the fiber core since we move the fiber as close to the chip surface as possible. From Figure 2B, one can see that the pump light can be absorbed by the BP and further heat the waveguide, leading to a phase shift in the MRR.

The spectra in Figure 2B indicate that the resonance wavelength has a significant red shift by 1.07 nm while the amplitude is not changed, which means that there is a pure phase shift and the optical loss is not induced in the MRR when the pump power is gradually increased

Figure 2: The schematic diagram and results for free-space pumping.

(A) Sketch of the modulator when 980-nm pump light is applied from outside space. (B) Transmission spectra of the MRR for different pumping powers.

from 0 to 250 mW. So, the BP is heated by 980-nm laser light, leading to a change in the effective refractive index of the MRR. The power of the pump light is relatively large because lots of energy cannot be injected to the BP material. However, in the integrated all-optical communications, it is more valuable to pump the probe light inside the waveguide using a telecom band pump light, because the all-optical interconnections are connected by waveguides. We need to couple the pump light in the waveguide by grating couplers. Thus, we made another setup to couple the pump light in the waveguide.

3.2 Pumping in waveguides

Figure 3A illustrates that the probe light and the pump light are both coupled in the MRR waveguide. We choose the wavelengths of 1551.4 nm for the pump light and 1545.5 nm for the probe light. The difference in the wavelengths between the pump light and probe light is up to three times the free spectral range (FSR), which can make sure that the two lights are separated by optical filters before the photodetector. The detailed setup of the experiment is illustrated in Section 6.2.

To obtain the wavelength shift of the modulator, the spectrum of the C-band was measured when an ASE probe light was injected in the waveguide. Meanwhile, we coupled the 1551.4-nm laser for the pump light to the waveguide. By gradually increasing the power of the

pump light from 0 to 12.9 mW, the resonance wavelength had a red shift of 0.31 nm without any amplitude change in the spectrum, which indicated a pure phase modulation in the MRR, as shown in Figure 3B. The shifted spectrum will go back to its original place as soon as we remove the pump light.

To measure the dynamic response of the modulator, the pump light was modulated with a 500 kHz square waveform signal (shown as the blue curve in Figure 3C). Then we measured the waveform of the output probe light (shown as the red curve in Figure 3C). The rise time (from 10% to 90%) was 479 ns and the decay time (from 90% to 10%) was 113 ns. The rise time was decided by the heating speed powered by the pump light, whereas the decay time by the cooling speed. To measure the bandwidth of the modulator, we loaded different sine signals on the pump light and recorded the waveform of the probe light in the output port. By measuring the amplitude of each output wave, the radio frequency response was measured, as illustrated in Figure 3D, which shows that the 3 dB bandwidth is more than 2.5 MHz.

4 Discussion

In Section 3, we measured the wavelength shift of the modulator when pumping in free space and inside the waveguide. The phase shift of the device is due the temperature change in the BP/MRR hybrid waveguide, which

Figure 3: The schematic diagram and results for pumping in waveguides.

(A) Sketch of the modulator when applied pump light and probe light both coupled in the waveguide. (B) Transmission spectra of the output when coupled in different powers of the pump light. (C) Measured waveform of the probe light (red) when the pump light (blue) is modulated with a 500 kHz square waveform signal. (D) Frequency response of the modulator, where the blue line is the fitting curve of measured data.

is illustrated theoretically in Section B of Supplementary Material. The phase change can be calculated by

$$\Delta\varphi = \frac{\Delta\lambda}{\text{FSR}} 2\pi \quad (2)$$

where FSR is 1.8 nm, as measured from the spectrum of the MRR.

Figure 4A illustrates the phase change of the MRR when pumping the 980-nm laser from the air. The tuning efficiency is $0.008 \pi/\text{mW}$ according to the slope of the fitting curve. However, as the spot of the light is significantly larger than the material size, the actual power in the BP is less than the power we recorded. We can obtain a larger tuning efficiency as soon as we focus the light to a smaller spot.

When we pump the 1545-nm laser from the grating coupler, the phase shift is calculated, as shown in Figure 4B. The tuning efficiency is $0.164 \pi/\text{mW}$, as the fitting curve shows. In this case, pump light is coupled into the waveguide by the grating coupler; thus the BP along the waveguide is in the evanescent field causing the heat effect. Moreover, we have made a calibration in our calculations by deducting the coupling loss introduced by the grating coupler, which is about 7.9 dB.

To further investigate the response performance of the modulator, we increased the modulation frequency of the square waveform signal up to 5 MHz, as shown in Figure 4C. As the modulation frequency increased, the signal waveforms gradually deformed from the edge-smoothed square wave to a triangle wave, which are mainly attributed to the hysteresis effect of heat generation and dissipation [8, 38].

Compared with fiber-based optical modulators, our integrated modulator has the potential to be deployed in

large integrated interconnections, and it shows the fastest response time in all-optical silicon modulators based on the thermal-optical effect. Moreover, the results of the BP/MRR hybrid modulator can be improved by a high-Q MRR to reduce the power of the pump light or by a large size of BP to increase the interaction distance of the modulator.

5 Conclusion

In this paper, we proposed and fabricated an all-optical modulator based on a phosphorene-assisted silicon MRR with fast response time. The modulator achieves a fast heat transmission time due to the direct contact between the BP and MRR, which also enhances the light-matter interaction in waveguides. We achieve the rise and decay times of only 475 and 134 ns and tuning efficiency of $0.164 \pi/\text{mW}$ at the C-band due to the thermal-optical effect. This work brings BP to the field of photo-thermal integrated devices. The proposed modulator will have potential to be applied in all-optical communications especially on integrated devices.

6 Methods

6.1 Device fabrication

The fabrication started with commercial SOI wafers with a 220-nm-thick silicon layer on top of a $2\text{-}\mu\text{m}$ SiO_2 -buried layer. E-beam lithography and inductively coupled plasma were used to fabricate the micro-rings, waveguides and gratings. After the waveguide fabrication, a 10-nm

Figure 4: Phase shift and dynamic response of the modulator.

(A) Phase shift results when illuminating different powers of the 980-nm pump light from outside. (B) Phase response of different powers of the 1550-nm band pump light from the waveguide. (C) Measured waveforms of the probe light when the pump light is modulated with a square waveform signal at different frequencies.

aluminum oxide layer was deposited on the chip by atomic layer deposition at 150°C for isolating silicon and BP.

The BP flake was exfoliated from bulk material by using the tapes and transferred onto the top of the ring waveguide by polydimethylsiloxane slice. This process was needed to choose the appropriate BP flake with the help of an optical microscope. At last, we spin-coated a 500-nm-thick PMMA layer on the chip to prevent the BP from interacting with the water from air.

6.2 Experimental setup

The setups of our experiment are illustrated in detail in Section C of Supplementary Material. To measure the dynamic response of the modulator, a pump light at 1551.4 nm was modulated by a commercial intensity modulator (JDSU 21067769-002, Viavi Solutions, San Jose, CA, USA) with a square waveform electrical signal injected into the all-optical modulator. The square wave was generated by the function/arbitrary waveform generator (DG4202, RIGOL, Beijing, China) and had a repetition rate of 500 kHz while the peak-to-peak (V_{pp}) voltage was set to 3 V. The wavelength of probe light was set to 1545.5 nm, which was three times the FSR away from the pump light. Both the pump light and probe light were generated by a tunable laser source (TLG-200, Alnair Labs, Tokyo, Japan) and the pump light was amplified by an erbium-doped fiber amplifier (AEDFA-33-B-FA, Amonics, Hong Kong, China). At the output part, we used an optical filter to filter the pump light to ensure that only the probe light enter the photodetector (KG-APR-200M, Conquer, Beijing, China). The output waveform of the photodetector was recorded by a 200-MHz oscilloscope (DG4202, RIGOL, Beijing, China).

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