Composite photonic platform based on 2D semiconductor monolayers

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Abstract: We demonstrate phase modulation in the near IR by electrostatically doping 2D semiconductor monolayers integrated on SiN waveguides. We show a V_sL of 1.4 Vcm and 0.8 Vcm for MoS2 and WS2, respectively. © 2019 The Author(s)

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Two dimensional (2D) materials including graphene and transition metal dichalcogenides (TMDs) are promising for modulation, detection, and light emission since the doping of these materials can be tuned electrically, on demand. Recently, TMDs such as tungsten disulphide (WS2) or molybdenum disulphide (MoS2) have been shown to exhibit strong changes in their optical properties with doping [1], however so far, these measurements have been done near the band edge, where the material is highly absorptive [2], limiting the applicability of these materials.

Here, we demonstrate that monolayer WS2 and MoS2 experience large changes in their optical properties with induced carrier doping when probed in the near infrared wavelength range (NIR), i.e. in the transparency range. We measure the phase change in monolayer WS2 by integrating the monolayer on a silicon nitride (SiN) waveguide (Fig. 1(a)) side clad with SiO2 in a Mach Zehnder interferometer (MZI) configuration (top inset of Fig. 1(a)). We dope the monolayer by applying a bias voltage across the two electrodes shown in Fig. 1 (a), after dispersing about 3-4 μL of ionic liquid (1-butyl-1-methyl pyrrolidinium tris(pentafluoroethyl)trifluorophosphate ([P14]+ [FAP]-)) to top clad the devices. The applied voltage results in the accumulation of ions on the monolayer, which capacitively dopes the WS2 with average carrier densities of about 1.5 × 10^{13} cm^{-2}[3].

![Fig. 1: Schematic of the ionic liquid gated SiN-WS2 platform. (a) Illustration of the composite SiN-monolayer WS2 waveguide with ionic liquid ([P14]+ [FAP]-) cladding. The monolayer WS2 is doped by applying a bias across the two electrodes, through the ionic liquid, resulting in the accumulation of charged carriers at the interface of WS2. Top inset is the optical micrograph of the fabricated phase modulator with the SiN-WS2 waveguides, before ionic liquid is dispersed on the devices. (b) Change in the effective index (Δn_eff) of the TE and TM mode for a bias voltage of 2 V applied across the electrodes. Figure Inset shows the mode profile for the TE and TM mode at 1550 nm. The Δn_eff extracted from the normalized MZI transmission spectrum (top right inset) measured at different bias voltages. One can see that the there is a pronounced change in the effective index for the TE mode (ie, when the optical E field is in plane with the monolayer) as compared to the TM mode.

We measure an effective index change (Δn_eff) of 1.1 × 10^{-4} RIU (refractive index units) for the TE mode and a minimal index change of 2.5 × 10^{-4} RIU for the TM mode, with a voltage swing of 2V (see Fig. 1(b)), in the NIR wavelength range (1450 – 1650 nm). The change in effective index (Fig. 1(b)) is extracted from the MZI transmission spectra measured at different gate voltages shown in the top inset of Fig. 1(b). One can see from Fig. 1 (b) that the
effective index tuning starts at $|V| > 1$ Volts, when the doping level is sufficiently high to tune the fermi energy into the conduction/valence band, consistent with the electrical measurements performed on monolayer WS$_2$ using [P14$^+$] [FAP] by D. Braga et. al [3]. One can also observe that, as expected, there is a pronounced change in the effective index for the TE mode (i.e. when the optical E field is in plane with the monolayer) as compared to the TM mode. We estimate from COMSOL Multiphysics simulation that the mode overlap with the WS$_2$ layer is 0.08 % and 0.04 % for the TE and TM mode, respectively.

Fig. 2: Phase tuning efficiency of capacitively gated SiN-TMD platform. (a) Illustration of the composite SiN-WS$_2$ platform. The top inset details the WS$_2$-HfO$_2$-ITO capacitor configuration, which gates the monolayer by applying a bias voltage across the dielectric HfO$_2$. The lower inset shows the optical mode overlap profile of 0.016 % between monolayer WS$_2$ and SiN waveguide. (b) $\Delta n_{\text{eff}}$ for the SiN-WS$_2$ device with a mode overlap of 0.016 %. (c) Frequency response of the SiN-WS$_2$ device with a 3 dB frequency response of 0.3 GHz. (d) Schematic of the SiN-MoS$_2$ platform, with an optical mode overlap of 0.08 % between MoS$_2$ and SiN waveguide. (e) $\Delta n_{\text{eff}}$ with voltage for the SiN-MoS$_2$ composite waveguide.

We further demonstrate and characterize the phase modulation efficiency $V_sL$ of gated monolayer TMDs by replacing the ionic liquid with a stack of Hafnia (HfO$_2$) and transparent conductive oxide, indium tin oxide (ITO) to form the TMD-HfO$_2$-ITO capacitor on the SiN waveguide (Fig. 2(a)). We fabricate MZI structures composed of the SiN-TMD waveguides with the TMD-HfO$_2$-ITO capacitor on both the arms of a 100 $\mu$m length unbalanced MZI. We dope the monolayers to about $5 \times 10^{-12}$ cm$^{-2}$ using the TMD-HfO$_2$-ITO capacitor.

We extract a $\Delta n_{\text{eff}}$ in SiN-WS$_2$ waveguides to be $7 \times 10^{-4}$ (RIU) for a 8 V swing, which corresponds to a $V_sL$ of 1.33 V · cm, with a maximum absorption modulation of 0.005 dB/cm (Fig. 2(b)). From the COMSOL Multiphysics simulation, we estimate the optical mode overlap in the SiN-WS$_2$ configuration to be about 0.016 %. We observe that when the mode overlap is increased to 0.03 %, by cladding these SiN-WS$_2$ waveguide with a high index SU-8 photoresist (n = 1.57), the change in effective index also increases. The measured $\Delta n_{\text{eff}}$ for the SU-8 clad SiN-WS$_2$ waveguide is $1.35 \times 10^{-3}$ (RIU), which corresponds to a $V_sL$ of 0.8 V · cm. In Fig. 2(c) we show that these MZI devices exhibit a 3dB bandwidth of 0.3 GHz, limited by the sheet and contact resistance of the monolayer WS$_2$.

We further confirm that this large effect on the optical response due to electrostatic gating extends to other monolayer TMDs. We design the SiN-MoS$_2$ waveguide geometry with a mode interaction to 0.08 % (Fig. 2(d)), and measure a maximum index change of $7.8 \times 10^{-4}$, which corresponds to a $V_sL$ of 1.4 V · cm, with a maximum absorption modulation of 0.003 dB/cm (Fig. 2(e)). The demonstrated strong light matter interaction in the semiconductor monolayer TMDs at transparency wavelengths could open up the door for a range of novel applications using these 2D materials and enable highly reconfigurable circuits with low optical loss and low electrical power consumption.

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