Chalcogenide glass waveguide-integrated black phosphorus mid-infrared photodetectors

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Received 15 September 2017, revised 8 January 2018
Accepted for publication 8 February 2018
Published 27 February 2018

Abstract
Black phosphorus (BP) is a promising 2D material that has unique in-plane anisotropy and a 0.3 eV direct bandgap, making it an attractive material for mid-IR photodetectors. So far, waveguide-integrated BP photodetectors have been limited to the near-IR on top of Si waveguides that are unable to account for BP’s crystalline orientation. In this work, we employ mid-IR transparent chalcogenide glass (ChG) both as a broadband mid-IR transparent waveguiding material to enable waveguide-integration of BP detectors, and as a passivation layer to prevent BP degradation during device processing as well as in ambient atmosphere post-fabrication. Our ChG-on-BP approach not only leads to the first demonstration of mid-IR waveguide-integrated BP photodetectors, but also allows us to fabricate devices along different crystalline axes of BP to investigate, for the first time, the impact of in-plane anisotropy on photoresponse of waveguide-integrated devices. The best device exhibits responsivity up to 40 mA W⁻¹ and noise equivalent power as low as 30 pW Hz⁻¹/² at 2185 nm wavelength. We also found that photodetector responsivities changed by an order of magnitude with different BP orientations. This work validates BP as an effective photodetector material in the mid-IR, and demonstrates the power of the glass-on-2D-material platform for prototyping of 2D material photonic devices.

Keywords: chalcogenide glass, black phosphorus, mid-infrared, waveguide-integrated photodetector

(Some figures may appear in colour only in the online journal)

Introduction

Chalcogenide glasses (ChGs) have proven themselves a valuable material for integrated photonics applications, due to their high refractive index, broadband transparency, and versatile fabrication conditions [1]. The family of glasses receives its name from its composition of chalcogen atoms—S, Se, and Te—which are covalently bonded in a network with metalloids—such as Ge, Sb, and Ga. Relative compositions can be tuned to control the band edge, mechanical properties, and refractive index (n from 2 to 3.5) [2, 3]. ChGs’ high refractive index enables high-index-contrast waveguides with strong mode confinement, allowing extremely low-loss, small-footprint photonic circuits [4–6]. Furthermore, their broad transparency window extends from visible to the far-IR, making them ideal optical media for mid-IR (2–20 μm) photonics [7, 8].
Previously we have demonstrated high-Q mid-IR ChG resonators, paving the way for ChG based sensors, filters, and active devices [9, 10]. ChGs have also demonstrated photosensitivity and exceptional third-order nonlinearities [11–14], making them a promising candidate for all optical processing and light written optical components [15–19]. In addition to novel optical properties, ChGs can be deposited at low temperatures (<150°C) on numerous substrates through vapor or solution-based methods, which is in contrast with most crystalline material based waveguides that require epitaxial growth [20, 21]. This has allowed us to integrate ChGs with unique substrate platforms such as flexible polymers and fluoride optical crystals [22–26].

Recently, we have shown that the ChG platform can also be utilized to enable direct photonic integration on 2D van der Waals solids [27]. 2D van der Waals materials display a myriad of remarkable optical properties, such as tunable bandgaps in transition metal dichalcogenides, exceptional nonlinearities in III–VI compounds, and plasmonics in graphene [28–31]. While the growing family of 2D materials possess exceptional optical properties, their thickness prevents considerable light–matter interaction in the traditional surface-normal-incidence configurations. By placing the 2D materials on top planar waveguides or cavities, the light propagates parallel to the plane of the crystal and is no longer limited by its thickness [32, 33]. However, previous devices position 2D crystals on top of existing photonic structures, only utilizing the relatively weak evanescent fields and often necessitating additional planarization steps [34–37]. ChGs, like 2D materials, bond to their substrate through van der Waals interactions, allowing them to be easily deposited at room-temperature onto 2D crystals, serving both as a passivation layer and waveguide material. This glass-on-2D-material technology offers a promising route for rapid prototyping integrated photonics involving 2D materials. Most pristine 2D materials are still prepared by mechanical exfoliation, resulting in small micron-scale flakes. Through the glass-on-2D-material platform, the waveguides can be lithographically fabricated on top of the 2D sample, allowing for consideration of the flake’s crystalline orientation and geometry. With an already large array of 2D materials, and an even larger number of potential stacked heterostructures, ChGs offer a convenient method to rapidly prototype 2D material based photonic devices from micron-scale crystals—in analogous to metal electrode patterning in 2D material electronic device prototyping.

Black phosphorus (BP) is one such 2D material that has uniquely advantageous optical properties, but has not been fully utilized due to its difficult integration into photonic devices. In the last two years, 2D BP, or phosphorene as a monolayer, has garnered massive interest due to its direct bandgap and high mobility (up to 1000 cm²/V·s) [38, 39]. Like graphene, BP atoms are oriented in a hexagonal lattice, however the atoms are also bent in a corrugated pattern, resulting in strongly anisotropic in-plane electrical and optical properties [40]. Furthermore, BP’s direct bandgap evolves drastically from 2 eV as a monolayer into the mid-IR (0.3 eV) as a bulk material. These combined properties make BP an extremely attractive material for mid-IR photodetectors, as its finite bandgap prevents significant dark current, unlike graphene. To date, several BP and black arsenic phosphorus based free-space photodetectors have been demonstrated, showing impressive gain mechanisms, yet these detectors are still constrained by the thickness of the BP flakes [41–47]. There have also been successful waveguide integrated photodetectors, however their operation is limited to the near-IR [48, 49].

In this work, we demonstrate the first waveguide integrated BP photodetectors that operate in the mid-IR. By applying the glass-on-2D-material platform, we are not only able to extend photodetection to the mid-IR in BP, but also design photodetectors that account for BP’s flake geometry and in-plane anisotropy to maximize its photoresponse. This approach also enables rapid prototyping of photodetectors on BP flakes of different thicknesses and orientations to probe the optoelectronic behavior of individual BP flakes.

Methods

BP flakes were mechanically exfoliated and transferred onto 3 µm oxide silicon wafers using the all-dry stamping method [50]. Flake thickness was determined by atomic force microscopy and polarization resolved Raman spectroscopy was performed to determine the crystalline orientation of the BP flakes as illustrated in figure 1(a). As the laser polarization changes relative to the BP crystal axis, the intensity of the \( A_2^1 \) Raman mode reaches a maximum when the polarization is along the armchair direction of the BP [51]. Figure 1(d) shows an exemplary Raman spectra for different excitation polarizations, while figure 1(e) shows the angle dependent intensity of the \( A_2^1 \) mode that was used to determine the flake’s orientation. The detector device layout was designed accounting for the specific flake geometry and crystalline orientation. The detectors’ electrodes (50/10 nm Au/Ti) were first patterned on the flakes, as in figure 1(b). 30 nm of Ge\(_{22}\)Sb\(_{12}\)Se\(_{60}\) ChG was then evaporated onto the BP to passivate it for the remainder of the fabrication and device characterization. Throughout the deposition, the substrate was held near room temperature (<40°C) without any active cooling measures. BP oxidizes in ambient conditions, thereby ruining its electronic and optical properties; however our previous work has demonstrated ChG as an effective passivation layer for BP, as well as being generally compatible with other exfoliated 2D materials due to the extremely low thermal budget during ChG deposition and processing [27]. Single-mode waveguides with a thickness of 470 nm and a width of 1100 nm were subsequently fabricated on the flake by double layer resist lift-off [52]. Figure 2(f) shows an optical microscope image of a fully fabricated device.

The devices were tested using a 2.0–2.55 µm tunable CW laser (IPG Photonics). 3%–4% of the beam was split to a reference detector to monitor the signal power in real time, while the rest was edge coupled into the devices by focusing through a ChG asphere lens. The beam was chopped at 1 kHz and the reference signal and electrical signal from the BP photodetectors were measured by lock-in amplifiers.

current preamplifier was used to apply bias and amplify the signal from the BP photodetectors. The devices’ electrical contacts were wire bonded, which allowed for signal maximization without using contact probes. For power dependent measurements, input power was controlled using two variable optical attenuators.

Results and discussion

We first characterized the device responsivity as a function of applied bias at different incident powers. Devices with differing flake thickness and orientation showed markedly different responses. Figure 2(a) plots our highest measured responsivity for Device A—a 32.4 nm thick flake with the waveguide oriented parallel to the armchair direction (photocurrent along zigzag) pictured in figure 2(c). A linear response with negligible zero-bias photocurrent dominates with a responsivity up to 40 mA W⁻¹. We therefore conclude that the device operates predominantly in the photoconductive mode, and our measurement reveals a Johnson-noise-limited NEP of 30 pW Hz⁻¹/₂. It is observed that at lower powers the device responsivity increases, consistent with the observation of Guo et al [43]. Fabricated on an different 8.3 nm thick flake parallel to the armchair direction and pictured in figure 2(d), Device B’s response is presented in figure 2(b). This device demonstrates a partial photovoltaic response, which is likely a result of non-Ohmic contact with the metal electrodes. To avoid breakdown in the thinner flake, bias below 0.1 V was maintained for Device B. Although Device B has a lower responsivity 8 mA W⁻¹, its dark current is orders of magnitude lower as shown in figure 3(e), likely due to its reduced thickness. The decreased dark current results in a lower shot-noise-limited NEP of 23 pW Hz⁻¹/₂. In contrast to graphene based devices, this low dark current is achievable because of BP’s finite bandgap. These results demonstrate that flake thickness strongly affects device performance and can be chosen to improve NEP and responsivity.

To gain more insight into the photodetection mechanism, the power (P) dependent responsivity R of Device A was measured. The responsivity was found to decrease with increasing intensity, in agreement with previous studies of BP photodetectors. The relationship is well modeled by the power law relation $R \propto P^{-\alpha}$ with $\alpha = -0.34$. This sublinear dependence has previously been attributed to the saturation of trap states at higher intensities which aid in detection through the photogating mechanism [37, 40]. The spectral response in figure 3(b) shows a decreasing responsivity with increasing wavelength. This is evidence of Pauli blocking, suggesting...
that our BP flakes have high doping and that the device performance can be significantly improved by gating. This also indicates that although the devices are 40 \( \mu \)m in length, a significant fraction of the light remains unabsorbed at the longer wavelength end.

To determine the role of BP orientation on photodetector performance, we fabricated photodetectors with perpendicular orientations on one single BP flake, shown in figure 1(f). Device C has its waveguide parallel to the armchair direction, while Device D is parallel to the zigzag direction. The waveguides for the two devices are split by a 50/50 MMI to ensure that equal amount of light reaches each device. Since the devices were fabricated on the same flake with a uniform 43 nm thickness (confirmed with AFM), we attribute the observed photoresponse difference between Devices C and D to in-plane anisotropy of BP. The dark currents of the two devices were measured and are shown in figure 4(a). Their mobility differs by nearly a factor of 3, which can be attributed to BP’s anisotropic in-plane mobility and is consistent with previous studies of BP’s anisotropy [40]. It has also been shown that optical absorbance varies dramatically along the zigzag and armchair directions of BP [40, 51]. In terms of responsivity, Device C and D both show considerably lower responsivities to Devices A and B, which might be attributed to differing degrees of degradation during flake preparation. Device C which is oriented along the armchair direction has a responsivity nearly an order of magnitude larger when comparing figures 4(b) to (c). This dramatic difference in responsivity can be attributed to the differences in mobility and absorbance along the zigzag and armchair directions, each contributing to about a factor of 3 difference. This demonstrates that when designing waveguide integrated photodetectors on BP, crystalline orientation must be considered to optimize device performance.

Figure 2. Device A and B performance: (a) and (b) AFM profile and optical microscope images of Device A (a) and B (b). (c) Measured (dots) and linear fit (lines) dark current and resistance of Devices A and B. (d) Responsivity as a function of applied voltage at varying incident 2185 nm laser powers for Device A. (e) Responsivity as a function of applied voltage at varying incident 2185 nm laser powers for Device B.
Conclusion

This work has shown that ChG can be applied as a passivation layer as well as a mid-IR waveguiding material for BP device integration. We have implemented the ChG-on-BP architecture to realize the first waveguide integrated BP photodetector in the mid-IR. Its finite bandgap allows for significantly lower dark currents compared to graphene, making it the preferred option for detection in low light conditions. Furthermore, the power and wavelength dependent measurements suggest that device performance can be greatly improved by tuning the Fermi level either by electric gating or doping of the BP flakes. We also showed that the orientation of the device relative to the armchair and zigzag directions of the BP strongly affects device performance. Ultimately, the glass-on-2D-material platform enabled precise control over device architecture to study the BP photodetectors and can be easily applied to other 2D materials for photonic device prototyping.

Acknowledgments

This material is based upon work supported by the National Science Foundation under award numbers 1453218 and 1506605, Graduate Research Fellowship under Grant No. 1122374, Public technology research program/international cooperation of Zhejiang province, China under Grant No. GJ18F050001, and International Science and Technology Cooperation Project of Ningbo City, China under Grant No. 2017D10008. The authors also acknowledge fabrication facility support by the MIT Microsystems Technology Laboratories and the Harvard University Center for Nanoscale Systems, the latter of which is supported by the National Science Foundation under award 0335765.

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