Integration of 2D materials on a silicon photonics platform for optoelectronics applications

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Abstract: Owing to enormous growth in both data storage and the demand for high-performance computing, there has been a major effort to integrate telecom networks on-chip. Silicon photonics is an ideal candidate, thanks to the maturity and economics of current CMOS processes in addition to the desirable optical properties of silicon in the near IR. The basics of optical communication require the ability to generate, modulate, and detect light, which is not currently possible with silicon alone. Growing germanium or III/V materials on silicon is technically challenging due to the mismatch between lattice constants and thermal properties. One proposed solution is to use two-dimensional materials, which have covalent bonds in-plane, but are held together by van der Waals forces out of plane. These materials have many unique electrical and optical properties and can be transferred to an arbitrary substrate without lattice matching requirements. This article reviews recent progress toward the integration of 2D materials on a silicon photonics platform for optoelectronic applications.

Keywords: silicon photonics; two-dimensional materials; graphene; black phosphorus; transition metal dichalcogenides.

1 Introduction

In the past decade, we have observed an unprecedented growth in both the consumption and creation of data. Digital information created in the last 2 years alone now accounts for 90% of the total data currently in existence [1].

Relatedly, the demand for data storage and high-performance computing continues to grow at an exponential rate [2], keeping in step with Moore’s law. This requires much higher bandwidth density for inter-chip communication than ever before (expected to surpass 40 Gbps per interconnect by 2020 [1]). Traditional electrical interconnects are not up to the challenge largely due to limited bandwidth, electrical cross-talk, and low input/output pin density. Silicon photonics, on the other hand, is a promising solution to route information on- and off-chip. It is possible to exploit the benefits of optical networks (such as high bandwidth, low propagation loss, and low cross-talk) while using a platform compatible with current electronics.

While silicon photonics is highly promising for optical routing, a complete optical network also requires the generation, modulation, and detection of light – something difficult to achieve in an entirely monolithic platform. The growth of germanium for photodetection and III–V materials for light generation is technologically challenging on a silicon substrate due to mismatched lattice constants and thermal expansion coefficients [3]. Defects arising from imperfections during crystal growth also tend to limit the optical and electrical performance of such devices [4].

One solution to this problem is to grow materials on a compatible substrate and then transfer them onto silicon. In this way, it is not necessary to match lattice constants or thermal expansion coefficients as required in direct growth processes. Two-dimensional (2D) materials are a class of crystals that naturally lend themselves to this type of transfer process. Because these materials are covalently bonded in-plane and held together out-of-plane by van der Waals forces, individual atomic planes can be mechanically separated from the bulk crystal and placed onto arbitrary substrates. Additionally, an entire family of 2D materials has been discovered with properties that span from metallic to semiconductors and insulators, providing the same building blocks as 3D materials.

Owing to strong quantum confinement out-of-plane, 2D materials have many unique properties that are uncommon in their 3D counterparts, which make them particularly attractive for optoelectronic applications.
For example, graphene exhibits very high mobility \[5\] and uniform optical conductivity \[6, 7\] due to its linear energy-momentum dispersion. Quantum confinement also plays a role in black phosphorus, whose bandgap is highly tunable with the number of layers – from 0.3 eV in bulk to around 2 eV in an isolated monolayer \[8–10\]. Other highly unique properties are also present in transition metal dichalcogenides (TMDCs), which possess a valley degree of freedom that can be accessed optically \[11–13\] and has been used to create an LED that emits circularly polarized light \[14\]. Additionally, as the “bulk” and the surface are one and the same for 2D materials, strong control of the chemical potential can be achieved by simply applying an electric field out of plane \[7, 15\].

While 2D materials have many desirable properties, their innate thinness greatly limits light-matter interaction in free space. Graphene, for instance, is able to absorb 2.3% of normal incident light per monolayer \[6, 16\]. This is a considerable amount in terms of a material that is only one atom thick, but very little in terms of total absorption as shown in Figure 1A. One approach has been to insert 2D materials into optical cavities, such as a Fabry-Pérot cavity \[17, 18\], to enhance the optical interaction with the material (see Figure 1B), but this limits the optical bandwidth to the linewidth of the cavity resonance. A solution to circumvent such a limitation is to place the 2D material onto a planar waveguide and couple to the optical mode via the evanescent field \[19\]. In this manner, one is able to decouple the interaction length from the material thickness since the material lies in the same plane as light propagation (Figure 1C).

In this article, we will review recent progress toward integrating 2D materials with silicon photonics for optoelectronic applications. We began by motivating silicon photonics and the benefits of planar integration of 2D materials. In the next two sections, we will discuss progress in photodetection (Section 2) and modulation (Section 3) using 2D materials on silicon photonics. Section 4 presents recent advances in light generation with transition metal dichalcogenides. Finally, Section 5 discusses the potential for novel optoelectronic devices enabled by 2D materials.

2 Photodetection

2.1 Graphene photodetectors

In terms of optical bandwidth, graphene’s gapless nature enables absorption from the ultraviolet to the terahertz regime \[20\]. This extremely broad optical sensitivity is unrivaled by any other known material and is especially attractive for on-chip optical communication where

![Figure 1: Various configurations for light-matter interaction in 2D materials. (A) Normal incident light has the advantage of broadband absorption, but very small total absorption. (B) Absorption can be enhanced by placing a 2D material inside an optical resonator to enhance light-mater interaction. This enhances absorption but limits the optical bandwidth of the device. (C) Waveguide integration of 2D materials overcomes both limitations by providing a platform that increases the interaction length while maintaining broad optical bandwidth.](image)
information can be multiplexed over a wide range of wavelengths. In 2009, Xia et al. demonstrated one of the first graphene photodetectors for normal incident light, which showed near-IR photoresponsivity of 0.5 mA/W at up to 40 GHz without signal degradation (Figure 2A) [21]. However, the responsivity was low (a corresponding quantum efficiency of only $4 \times 10^{-4}$), which was limited partially by the symmetry of the electric field, which was later improved in a subsequent device [25], but mainly by graphene’s fixed 2.3% absorption. A few years later, three groups independently demonstrated the first waveguide-integrated graphene photodetectors with significantly improved responsivities [22, 26, 27]. Through evanescent coupling, over 60% absorption was achieved in a 53-μm-long device [22]. Careful asymmetric placement of the electrical contacts with respect to the waveguide (shown in Figure 2B) also aided to improve responsivity by exploiting the difference in work function between the graphene and the metal [22, 27]. Additionally, these devices show flat responsivity over a wide selection of wavelengths in the telecommunications band [24, 27]. Based on graphene’s measured optical response [6, 7], this trend is expected to extend to the visible and mid-IR.

The flexibility of using a planar waveguide geometry opens the possibility for novel device designs. By stacking two graphene monolayers separated by a thin dielectric, Youngblood et al. demonstrated a dual-function graphene photodetector and modulator in a single device geometry (Figure 2C) [23]. The top graphene sheet served as a transparent gate electrode, which tuned the Fermi level and, therefore, the optical absorption in the bottom graphene layer. To measure the optical absorption in the bottom layer with high precision, the device was placed onto one arm of an unbalanced Mach-Zehnder interferometer. Other designs have used photonic crystal waveguides to guide light [28] and enhance optical absorption through cavity resonance [29]. While this can improve optical absorption and allow for devices with smaller footprints, incorporating resonant enhancement will of course limit the usable optical bandwidth of the device.

Another attractive feature of using graphene is the potential for very high-speed photodetection. This is enabled by its extremely high carrier mobility, and speeds greater than 500 GHz have been predicted [21]. Ultrafast autocorrelation measurements have experimentally measured the intrinsic frequency response of graphene photodetectors [30, 31]. This revealed that after initial excitation and rapid carrier-carrier scattering (on the order of tens of femtoseconds), the photo-excited carriers undergo a fast cooling process (i.e. the recombination time) mediated by phonon scattering and are collected at the contacts on a time scale (i.e. the transit time) that depends on the mobility, transit length, and field potential in the channel. While a fast recombination time can improve the overall speed of the photodetector, a faster transit time is always more desirable as a faster carrier collection is required to achieve high quantum efficiency. It was shown that both these processes occur on the order of a few picoseconds in graphene, which corresponded to an intrinsic frequency response of 262 GHz and an internal quantum efficiency of 16–37% in relatively low mobility devices [30].

Improved high-frequency design of electrical contacts [32] and the use of van der Waals heterostructures to improve mobility [24] have resulted in graphene waveguide-integrated detectors able to detect data rates up to 50 Gbps. In the latter case, Shiue et al. encapsulated single-layer graphene between two sheets of boron nitride (BN) and fabricated 1-D contacts (see Figure 2D) [24]. The BN encapsulation has been shown to dramatically improve mobility by reducing Coulomb scattering found in SiO$_2$-supported graphene in addition to providing an atomically smooth substrate [33]. Reduced contact resistance has also been demonstrated in BN/graphene/BN heterostructures by exposing the graphene edge through a dry etch process before depositing a metal layer [5]. These improvements increased the 3-dB bandwidth to 42 GHz, and a maximum responsivity of 0.36 A/W was observed. It was also demonstrated that in the nonlinear regime, the photodetector operated as an on-chip autocorrelator with a timing resolution of 3 ps.

### 2.2 Black phosphorus photodetectors

While graphene is very attractive from the perspective of speed and broad optical sensitivity, it is fundamentally limited by its zero bandgap. In photodetectors, this manifests itself as a dark current, which can be much larger than the measured photocurrent when the photodetector is operated in the photoconductive mode (i.e. a bias voltage is applied to improve the responsivity) [25]. The inability to turn off the conductance of graphene devices leads to continuous energy consumption and high shot noise associated with the dark current, which significantly limit their use in real-world applications. One solution is to operate graphene photodetectors in the photovoltaic mode at zero bias and rely on a built-in asymmetric field profile to sweep photo-excited carriers to the metal contacts [22–32]. However, this approach is limited by the relatively weak responsivity at zero bias.

In contrast to graphene, TMDCs have bandgaps in the range of 1–2 eV, which allow for very large field-effect on-off...
Figure 2: Graphene photodetectors. (A) The first graphene photodetector was illuminated with normal incidence light and gated with the substrate. Inset: SEM and optical microscope images of device (scale bars 2 μm and 80 μm, respectively). (B) Waveguide integrated graphene photodetector demonstrated by Gan et al. An asymmetric placement of electrodes enabled photodetection at zero-bias. (C) Multifunctional graphene photodetector and modulator using two different metal contacts to create a built-in potential. An integrated Mach-Zehnder is used to measure the graphene absorption with high precision. (D) High-speed graphene photodetector with van der Waals passivation and 1D edge contacts. Autocorrelation measurements with a resolution of 3 ps were demonstrated with this device. Reproduced with permission from Refs. [21] (A), [22] (B), [23] (C), and [24] (D).

ratios, but their frequency response is typically limited to several kHz due to mid-level trap states and low mobility [34, 35]. Picosecond response times in few-layer WSe₂ have been observed with autocorrelation measurements where the photo-excited carriers were extracted vertically using a van der Waals heterostructure [36]. In this design,
the channel length is limited by the thickness of the WSe₂ rather than the spacing between two lateral electrodes. As the response time scales as the channel length squared for transit-limited devices, these vertical heterostructures can significantly improve the frequency response of 2D materials with low mobility. However, the bandgap of TMDCs corresponds to the visible spectral range and, thus, is unsuitable for applications in the near- and mid-IR range.

Black phosphorus (BP) was rediscovered as a van der Waals material a few years ago [8] and is already showing great promise for the near- and mid-IR [37–41]. With a direct bandgap that scales with the number of layers from the visible to mid-IR [9, 10, 42], BP is an exciting new addition to the family of 2D materials. Recent work has shown that when alloyed with arsenic, the bandgap can be pushed even further to 150 meV [43]. Unlike TMDCs, the mobility of BP is measured to be as large as 1,350 cm²/V-s at room temperature in thin samples [44] and greater than 10,000 cm²/V-s in bulk samples at low temperatures [45]. Additionally, the buckled structure of BP causes it to have unique anisotropy in optical absorption [42, 46], carrier mobility [46], and thermal conductivity [47–49]. Owing to this anisotropy, polarization-sensitive photodetectors have been demonstrated with BP as shown in Figure 3B [51].

Shortly after the first demonstration of BP field effect transistors [8], several groups demonstrated normal incidence photodetectors using BP [38–40, 50]. Like normal incident graphene photodetectors, however, these devices were limited to responsivities of tens of mA/W due to small absorption. Additionally, the frequency response of these initial BP photodetectors was poor, and it was unclear if they could be operated at speeds higher than a few kHz. Figure 3A shows one such photodetector, which has a rise and fall time on the order of a few milliseconds [50]. In 2015, Youngblood et al. demonstrated

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**Figure 3:** Black phosphorus photodetectors. (A) Normal incidence black phosphorus photodetector. Slow detection speeds were observed in this device with a rise and fall time on the order of a few milliseconds. (B) Polarization-dependent photocurrent in BP. Anisotropic optical absorption along the x- vs. y-direction accounts for the difference in measured photocurrent. (C) BP waveguide-integrated photodetector. A top gate is used to dope the channel intrinsic for high-speed detection. The device shows an open eye diagram for data rates as high as 3 Gbps. (Scale bar for optical image is 100 μm.) (D) Methods for passivating BP using van der Waals heterostructures. Both graphene and BN provide high-quality passivation as can be seen in AFM profiles of partially covered BP allowed to oxidize (scale bars are 4 μm). Reproduced with permission from Refs. [50] (A), [51] (B), [41] (C), and [52] (D).
the first waveguide-integrated BP photodetector (Figure 3C), which showed an intrinsic responsivity of 135 mA/W and 657 mA/W in 11.5-nm- and 100-nm-thick devices, respectively [41]. By adding a transparent graphene gate to the thinner device and measuring the photoresponse at various gate voltages, they were able to observe two unique photocurrent mechanisms at play. At large doping levels, the slower bolometric effect dominated, which has thermal origins \(f_{\text{mid}} = \frac{3GHz}{300kHz}\). Low doping levels, on the other hand, revealed an RC-limited photovoltaic effect \(f_{\text{mid}} = 3 GHz\) where the photocurrent had the same sign as the applied bias. Additionally, the dark current was greatly reduced for low doping levels giving results comparable to waveguide-integrated germanium photodetectors with a similar configuration [53]. Again, by using an integrated Mach-Zehnder interferometer, the absorption in the BP layer was accurately determined, and the internal quantum efficiency was found to be as high as 50% for large bias voltages.

Recent work by Guo et al. revealed that trap states arising from impurities and surface states in the BP can provide a gain mechanism through the photogating effect [37]. This effect was most pronounced at the maximum of the trans-conductance \(\Delta I_D/\Delta V_G\) where the hole transit time was shortest, but the number of available trap states for the electrons was large. According to Guo et al., the ability to trap photo-excited electrons leads to a large photovoltaic gain, which is the ratio of the electron trap lifetime to the hole transit time \((G = \tau_e/\tau_h)\). For a mid-IR wavelength of 3.39 μm, responsivity as high as 82 A/W was achieved at 500 mV bias and 1.6 nW incident power. However, this gain drastically reduces with increasing optical power as the available trap states are saturated and operate at low frequencies \((f_{\text{mid}} = 1.1 kHz = 1/2\pi\tau_e)\). As the power increases, the effect of these trap states reduces, and the dominant photocurrent mechanism at low doping levels is the high-speed photovoltaic effect [41].

While BP photodetectors have superior dark current performance compared to graphene detectors, there are also a few drawbacks. First of all, the best room temperature mobility in few-layer BP is two orders of magnitude less than that achievable in graphene [44]. This limits the ultimate speed of BP photodetectors, but using a vertical van der Waals heterostructure might be one way to overcome this. Second, the absorption per layer of BP is less than graphene (about one-eighth) at near- and mid-IR wavelengths [42]. This is not a significant issue when using multi-layer BP, but it could lead to longer integrated devices as the thickness of BP is reduced. Finally, BP suffers from oxidation and degradation when exposed to humidity and light [54]. This has been solved by either passivating the surface with an ALD-grown dielectric [55] or sandwiching BP between other 2D materials such as graphene or BN [52] as shown in Figure 3D. As there are approaches to overcome these drawbacks, BP photodetectors remain very promising for IR applications.

### 3 Modulators

#### 3.1 Graphene modulators

While the lack of a bandgap limits graphene’s practical applications for photodetectors, strong, broadband optical absorption, combined with a low density of states, makes graphene very promising for optical modulation. The principle behind optical modulation in graphene relies on the ability to tune the magnitude of its Fermi level to greater than (or less than) half the incident photon energy. At this point, graphene is no longer able to absorb incoming photons by inter-band transition as there are either no available carriers or excited states [15]. Although it is true that this approach should work from infrared to visible wavelengths due to graphene’s linear dispersion relation (intra-band absorption begins to play a significant role in the far infrared and terahertz region), it becomes increasingly difficult to achieve chemical potentials much larger than 0.4 eV. This is because the Fermi level scales as the square root of the gate voltage, which is, in turn, limited by the breakdown field of the gate dielectric. Polymer electrolytes, on the other hand, have much higher gate capacitance than traditional gate dielectrics [56], but operate at slow speeds as the doping mechanism requires physical movement of ions through the electrolyte. Therefore, most optical modulator studies have focused on near-IR wavelengths.

The first functional graphene modulator was demonstrated by Liu et al. in 2011 [57]. In this device, a sheet of CVD graphene was draped over a doped silicon waveguide, separated by a 7-nm-thick Al₂O₃ cladding as illustrated in Figure 4A. The doped silicon waveguide was used as a back gate and controlled the Fermi level in the graphene. A modulation depth of around 4 dB and an RC time-limited bandwidth of 1 GHz were observed. This design suffers from a trade-off between free carrier absorption if the silicon waveguide is heavily doped and a large RC time constant if it is lightly doped. A solution that was both suggested [62] and demonstrated [58] a year later was the use of two graphene monolayers separated by a thin dielectric (Figure 4B). In this design, the bottom graphene layer is gated by the top, which can act either as a
transparent gate electrode or additional absorber depending on the chemical potential [62]. This improved design showed a modulation depth of 6.5-dB and 3-dB bandwidth of 3 GHz [58]. Later groups reported improved results on a waveguide geometry including a dual-function photodetector and modulator [23], a modulator with 3.3-dB insertion loss and 16-dB modulation depth [63], and a device capable of 10-Gbps modulation speeds [64].
Although integrating graphene onto a waveguide has the benefit of being very broadband optically, there is a fundamental trade-off between modulation depth and energy consumption. A longer device will provide greater modulation depth, but will result in a higher capacitance and, therefore, consume more energy per bit flip [65]. One solution to this problem is to integrate a smaller graphene absorber into an optical resonator. This will reduce power consumption at the expense of optical bandwidth. Two groups independently demonstrated using graphene on a photonic crystal cavity (PCC) to modulate the resonance conditions [66, 67]. While both groups used ion gel (which cannot be used for high-speed applications) to control the Fermi level in graphene, the device area was greatly reduced, which could lead to significant energy savings. A graphene/BN/graphene van der Waals heterostructure combined with a PCC was later demonstrated, which was not limited by the use of ion gel (Figure 4E) [59]. This device suffered from excess capacitance, however, which reduced the $3$-dB bandwidth to $1.2$ GHz.

Ring resonators have also been used to increase the efficiency of graphene modulators and have been much more successful in experimental demonstrations. While PCCs have the advantage of a much smaller mode volume, ring resonators are easier to fabricate and usually have a higher Q, which compensates for the larger size. The first graphene modulators integrated on a ring resonator were optimized for low-voltage applications and overall efficiency rather than speed [68, 69]. The highest $3$-dB bandwidth demonstrated in a graphene modulator is $30$ GHz with a modulation depth of $15$ dB [60]. This was achieved by Phare et al. who designed a ring resonator (see Figure 4D) that was undercoupled for high loss and critically coupled for low loss. By changing the loss due to graphene in the resonator, the coupling between the ring and bus waveguide was modulated with an efficiency of $1.5$ dB/V.

In applications not requiring high-speed modulation, graphene’s excellent thermal conductivity [70] could be useful for thermal tuning of silicon photonics. Yu et al. demonstrated thermal tuning in both a Mach-Zehnder interferometer and a micro-disk resonator using graphene to conduct heat from a non-local metal heater (Figure 4E) [61]. Graphene, itself, can also be used in place of a traditional metal heater as demonstrated by Gan et al. [71]. This has the advantage of a higher modulation speed compared with traditional silicon thermo-optic modulators, and sub-microsecond rise and fall times have been observed.

### 3.2 Black phosphorus modulator

While an integrated optical modulator has yet to be demonstrated using BP, a few theory papers have suggested that an out-of-plane electric field could be used to change the optical absorption of multilayer BP [42, 72]. For several nm-thick BP, two competing mechanisms affect the optical absorption. The first is the Pauli-blocked Burstein-Moss shift (BMS), similar to graphene, which prevents optical absorption for photons with energies less than twice the Fermi level. This tends to increase the optical bandgap. On the other hand, the quantum-confined Franz-Keldysh (QCFK) effect causes the wavefunctions of a quantum well to extend into the bandgap in the presence of an electric field. This decreases the optical bandgap and fights the BMS effect at high doping levels. Lin et al. calculated these combined effects for the case of a BP quantum well integrated on a silicon waveguide and demonstrated that a $62\%$ reduction in the required voltage swing could be obtained in a $20$-nm-thick BP quantum well compared with graphene for an equivalent change in absorption [72]. The improvement comes from the QCFK effect, which is not limited by temperature-induced smearing of the optical transition edge, which is present in graphene at room temperatures. However, this improvement in efficiency only occurs for wavelengths near the band edge of the BP quantum well where the QCFK effect is strongest. Very recently, modulation due to both the BMS and QCFK effects have been experimentally observed at low temperatures for BP flakes on a SiO$_2$/Si substrate [73], but an integrated BP modulator has yet to be realized.

### 4 Optical sources

In the previous sections, we described devices that are able to modulate and detect light provided there is already optical power in the waveguide. In all these experimental demonstrations, the optical power was generated off-chip and coupled to the waveguide via butt coupling or a grating structure. Off-chip optical sources are technologically easier to manufacture and replace in a system, but suffer from increased cost of integration, coupling losses, and power consumption regardless of circuit activity. On-chip optical sources, on the other hand, can be distributed in multiple locations and selectively powered off when part of the CPU or circuit is inactive. In some optimized architectures, this can improve energy efficiencies by $10–20$ dB [74]. Given the benefits of on-chip optical
sources and the compatibility of 2D materials, optical sources based on van der Waals materials have been a growing topic of interest in the last few years [75]. In this section, we will discuss recent progress toward generating light using 2D materials and their potential for integrated photonics.

4.1 Transition metal dichalcogenide light-emitting diodes

TMDCs suffer from low mobility, which hinders electrical performance, but have other properties that are highly desirable for optical applications. When thinned to a single atomic layer, TMDCs transition from an indirect to a direct bandgap semiconductor. Additionally, the exciton lifetime is on the order of a several nanoseconds, which is several orders of magnitude longer than graphene [76, 77] and black phosphorus [78]. It was also recently shown that treating MoS2 and WS2 with a superacid can dramatically improve the photoluminescent quantum yield to near unity by repairing sulfur defects in the crystal, which reduces non-radiative recombination [79, 80]. These properties make TMDCs ideal for applications requiring light emission.

Many studies have investigated photoluminescence in TMDCs, but electrical pumping is a major requirement for on-chip optical sources. The first demonstration of electroluminescence in a TMDC used a split-gate MoS2 FET. In this device, Sundaram et al. used two top gates to electrostatically dope the channel n- and p-type and demonstrated diode-like electrical characteristics [81]. The device was fabricated on a transparent glass substrate, which allowed optical probing of the channel under the top gates. By comparing the absorption, photoluminescence, and electroluminescence spectra of the MoS2 monolayer, it was found that the lower-energy B exciton was the main contributor to electroluminescence. Ross et al. demonstrated a similar device (Figure 5A) using a monolayer WSe2 channel and exfoliated BN as the gate dielectric [82]. This device boasted three orders of magnitude improvement in efficiency over the MoS2 LED, and the emitted photon energy was shown to be gate tunable.

These early demonstrations of TMDC LEDs relied on electrostatic gating to create a lateral p-n junction, but subsequent devices used van der Waals heterostructures. Cheng et al. used a naturally p-type WSe2 monolayer and few-layer n-type MoS2 to create a vertical p-n junction capable of emitting light [83] as illustrated in Figure 5B. Another approach used BN as a tunnel barrier and graphene as transparent electrodes. This type of vertical van der Waals LED was demonstrated by Withers et al. where monolayers of MoS2, WS2, and WSe2 were stacked between a top and bottom graphene/BN tunneling contact to create single and multiple quantum well structures [84]. These devices showed extrinsic quantum efficiencies of nearly 10% and remained stable after months of periodic measurement. Low-temperature electroluminescence from a typical device is shown in Figure 5C. Additional devices were also demonstrated on a flexible substrate with no noticeable changes in performance under a uniaxial strain of up to 1%.

4.2 Transition metal dichalcogenide lasers

Placing a TMDC monolayer on top of a PCC or disk resonator provides the optical feedback necessary for lasing [85–87]. This is possible due to a strong overlap between the optical mode of the cavity through the evanescent field near the cavity-monolayer interface. Additionally, the use of a nanoscale optical cavity can greatly enhance spontaneous emission through the Purcell effect [88, 89] and reduce the lasing threshold of the gain material. Wu et al. used a GaP PCC to achieve lasing in a WSe2 monolayer (Figure 5D) [85]. Through a 30-fold enhancement of the PCC quality factor over previous studies [88, 89], the Purcell effect was strongly enhanced, which enabled lasing at temperatures below 160 K. The β factor (a figure of merit that is defined as the fraction of spontaneous emission into the cavity mode) was measured to be 0.19 – indicating 19% of the total emission was coupled into the cavity mode. This value is comparable to quantum-dot PCC lasers [90]. However, unlike quantum-dots which are randomly distributed and challenging to contact electrically, TMDCs can be controllably transferred or grown on a target substrate giving them potential for scaling.

Ye et al. also demonstrated lasing in a layered SiN/WS2/hydrogen silsesquioxane (HSQ) disk resonator (Figure 5E) [86]. HSQ was used as both a hard mask for etching and as a cladding layer to increase the mode overlap between the SiN resonator and the WS2. The pump power required to reach threshold at 10 K was around 10 MW/cm² and was achieved with an ultrafast laser (190 fs pulse width) to minimize heating. Compared to Wu et al. who showed an ultralow threshold of 1 W/cm² and used a CW pump laser, the lower quality factor and large volume of the disk resonator contributed to the relatively high lasing threshold in this device. Salehzadeh et al. also observed lasing in the four-layer MoS2 on a SiO2 disk resonator/microsphere hybrid cavity at
room temperature [87]. By treating the MoS$_2$ with oxygen plasma, the authors claimed enhanced PL efficiency from direct bandgap transitions due to increased interlayer separation [91].

To date, there have been no demonstrations of TMDC optical sources fully integrated on a photonic circuit. While the TMDC lasers mentioned previously were fabricated on planar PCCs and disk resonators, the isolated cavities required optical pumping and emission to be coupled into and out of the devices through normal incidence. For on-chip optical applications, it is necessary to couple laser emission to waveguides rather than free space. Additionally, it would be imperative that these TMDC lasers could be pumped electrically rather than optically. This will require more sophisticated photonic circuit designs and likely require the use of van der Waals heterostructures.

5 Future directions

There is a bright future for 2D optoelectronics and many novel applications beyond those reviewed above have been proposed. One such application is integrated quantum optics using 2D materials on a silicon photonics platform. Theoretical calculations have suggested that TMDCs integrated on a silicon nitride PCC with a modest quality factor ($Q \sim 10^5$–$10^6$) could allow optical bistability and single-photon blockade devices at low optical powers [92]. This exploits the strong second-order
optical nonlinearity observed in TMDCs [93, 94], which is also electrically tunable [95]. Additionally, this strong second-order susceptibility could potentially be used for parametric down conversion by integrating TMDCs onto a photonics platform for applications requiring on-chip quantum entanglement such as quantum encryption.

Recent experimental results with various 2D materials have shown further promise for the field of quantum optics. Optically pumped single quantum emitters have been observed in both WSe$_2$ [96, 97] and BN [98]. These single quantum emitters are spatially localized by crystal defects and have linewidths much sharper than their delocalized exciton counterparts. Strong photon anti-bunching is observed as well, confirming single-photon emission. Electrically pumped single quantum emitters have also been demonstrated in WSe$_2$ using vertical van der Waals heterostructures [99, 100]. In both devices, a monolayer of WSe$_2$ is sandwiched by two few-layer BN flakes and contacted with graphene top and bottom electrodes. This forms a quantum well band structure where electrons tunnel from the graphene electrodes through the BN barriers and radiatively recombine at localized defects in WSe$_2$, emitting a single photon. While these devices have yet to be integrated on a photonic platform, the path to integration is relatively straightforward and could be used to create on-chip quantum emitters.

A few other potential directions could be the use of van der Waals heterostructures for optical amplification or the generation of mid-IR light using BP. The first case involves transferring a MoSe$_2$/WSe$_2$ heterostructure onto a waveguide and creating gain through electrical or optical pumping. Rivera et al. demonstrated that due to the type II band alignment between MoSe$_2$ and WSe$_2$, long-lived inter-layer excitons could exist with a lifetime of 1.8 ns [101]. This is much longer than the expected intra-layer exciton lifetime in the same materials, and achieving population inversion could be easier in this system than an isolated monolayer. More thorough studies of the radiative and non-radiative recombination dynamics of these inter-layer excitons will reveal whether or not optical gain is possible. The second case involves creating a mid-IR LED with BP if non-radiative recombination rates can be reduced. This is especially attractive as the bandgap is layer dependent, and emission is expected to be linearly polarized [102].

While the field of integrated optoelectronics with 2D materials is still in its infancy, significant progress has been made toward a fully on-chip optical network. Already high-performance photodetectors, modulators, and optical sources have been experimentally demonstrated and further improvements can be expected as more is discovered about this unique family of materials. The next steps involve developing new growth techniques and ways to scale the manufacturing of van der Waals heterostructures. This knowledge will enable further optimization of these devices and the potential for novel applications in the near future.

References


