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Recent Advances in Investigations of Electronic and Optoelectronic Properties of Group III, IV, and V Selenide Based Binary Layered Compounds

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This review article presents a comprehensive update on recent research trends, advancement and future outlook of selected layered selenide-based binary compounds featuring elements from group III, IV, and V of the periodic table. Due to their highly anisotropic structure as well as their availability in mono, few and multi-layer form, these compounds constitute a perfect playground where a variety of possibility in structural variation as well as functionalities are expected. This potentially gives rise to a library of unique and fascinating 2D selenide-based systems. These systems appear to demonstrate some spectacular variety of fundamental physics as well as indicate that some of these systems can be beneficial for several niche applications directly or indirectly resulting from their electrical and optical properties. As such a description of recent investigations pertaining to some of the key electrical and optical properties of few chosen binary selenide based compounds such as Indium Selenide, Tin Selenide, Gallium Selenide, Germanium Selenide and Bismuth Selenide are described. A final note on immediate research needs and directions in developing these materials systems for future applications are discussed.

1 Introduction

The breathtaking success of graphene science, discovery of families of layered Van der Waals solids, their hetero-structures and hybrids, and realization of rich and exotic band structure of various other two dimensional (2D) layered materials, have opened up several new directions in the understanding of science and technology of 2D layered systems. During the last decade, 2D layered materials have caused a paradigm shift in our understanding of the fundamental properties of nanomaterials and opened up new technological possibilities. The discovery of single-layer graphene\(^1\)–\(^3\) and transition metal dichalcogenides (TMDs)\(^4,5\), initially through mechanical exfoliation have sparked a series of high profile discoveries that impact numerous electronic and optoelectronic areas\(^6\)–\(^8\). Several of these materials were also viewed as potential candidates for future applications as well\(^9\).

The tremendous scientific accomplishments, primarily in the field of graphene science and later in identifying TMD based 2D materials also led to the discovery of or at least gave the impetus to search for a wide variety of compounds, with 2D layered structure, which can possibly be reduced to few atomic layers. One of the key reasons, other than the fact that materials with 2D atomic configurations are extremely interesting from fundamental science\(^1\)–\(^3\), their flat topography is perhaps ideally suited for compatibility with present complementary metal oxide semiconductor (CMOS) technology that drives the electronic industry. As such a major portion of investigations on 2D materials in general focused on their electronics/opto-electronics aspect\(^4\)–\(^6,9,10\). Several key fundamental physical properties were also recognized. For example, unlike graphene, which is a zero band semimetal, a single layer of some TMDs such as Molybdenum disulphide (MoS\(_2\)) has a direct band gap\(^11\) and can be used as a field effect transistor. This was an extremely important finding, which initiated investigations pertaining to optics/optoelectronic properties of 2D materials other than graphene. In that aspect, as described in this article later, some of the layered selenides that we are planning to present here, have a major advantage over other TMD based layered materials.

2 Unique Properties of Layered Selenide Based Materials

One of the main motivation behind investigating layered selenides stems from the fact that these systems can exhibit diverse structural form in the bulk, which leads to multi-functional properties such as thermoelectric\(^12\)–\(^14\), optoelectronics\(^15\)–\(^17\) etc. Out of all selenides, elements of group III, IV and V forms selenide based layered structures, which is mediated through a lone electron pair. The lone electron pair repels the neighboring atoms, thus creating a van der Waals gap between chemically bound layers\(^18\). The fact that many of these, for example, InSe (III-
VI), SnSe (IV-VI), BiSe (V-VI) and their polytypes possess saturated bonds (with no dangling electrons) making them ideal as two-dimensional electron systems. Few/mono layers of these specific selenides, similar to those other 2D materials, show very different but diverse attractive properties compared to their bulk form. For example, selenides in the III-VI (e.g. InSe) and IV-VI (e.g. SnSe) are very good optoelectronic materials, but lately SnSe have also shown to possess other functional properties such as high thermolectric figure-of-merit (ZT). Bi₂Se₃ is another fascinating layered system. While it is known to be a great thermoelectric material, recently it is being investigated as a topological insulator. Layered InSe is predicted to undergo semiconducting to metal transition under electric field application, making it ideal for memory applications. Similarly, theoretical calculations performed on Gallium Selenide (GaSe) nano ribbons also predict that while armchair nano ribbons are all semiconductors with an indirect band gap, most of the zigzag configurations of nano ribbons were found to be metallic with the possibility of showing magnetism.

This article, therefore, is an attempt to capture some of these fascinating discoveries that have laid the foundation for several new directions in materials synthesis as well as advanced application development with Group III, IV, and V Selenide based binary layered Compounds.

2.1 Indium Selenide Based Systems

InSe monolayer is a periodic hexagonal array of 4 atoms, in which Se-In-In-Se are bound by covalent bonds with some ionic character. Each atomic layer can be thought of as (111) plane of Zinc Blende structure. Indium atoms share two of their valence electrons with three neighboring Se atoms. The third electron makes a covalent bond with another In atom, and the In-In bond lies perpendicular to the plane formed by Se atoms. Four out of six valence electrons of Selenium are shared with 3 In atoms (four third electrons per bond), which leaves an unbound electron lone pair on Se atom. In fact, a monolayer InSe is terminated by an electron lone pair on Se atom, which is repelled by the electron lone pair on Se atom. In fact, a monolayer InSe is terminated by an electron lone pair on Se atom, which is repelled by the electron lone pair on Se atom. In fact, a monolayer InSe is terminated by an electron lone pair on Se atom, which is repelled by the electron lone pair on Se atom.

Fig. 1 Panels (a)-(d) and (e) show the electron band structure of N-layer InSe (N=1,2,5,6) and for bulk. Panel (f) shows the stacking of γ-InSe and (g) the electronic band gap Vs layer number is shown.

As evident from these aforementioned studies, one of the key difference in InSe based system is that unlike some TMD such as MoS₂, which goes to direct to indirect band transition upon increasing layer thickness, InSe shows a completely opposite behavior, i.e it goes from indirect to direct band upon increase in layer thickness. The idea of having few layer semiconductor with direct band gap in InSe systems and their polytypes such as In₂Se₃ etc. immediately opened up both theoretical as well as experimental investigations in understanding controlled growth,
Initial investigations on InSe systems focused on mechanically exfoliated layers of samples grown using chemical vapor transport method. Based on the results from DFT and high-field magneto-optics, Mudd et al., reported a significantly smaller electron and exciton effective mass, which is weakly dependent on the layer thickness in few layer InSe. With initial evidence of few layer InSe flakes showing existence of direct band gap, apart from understanding fundamental optical properties, a vast majority of investigations focused on field effect transistors (FET) and/or photocurrent generation with two-dimensional van der Waals semiconductors. Investigations performed so far indicate that typical room temperature mobilities of 1055 cm²/Vs can be achieved. Such back gate engineering, according to this report, can also lead to InSe based FET with a high current on/off ratios of 10⁸ and strong current saturation over a broad voltage window. Similarly, investigations performed on few-layer InSe encapsulated in hexagonal boron nitride under an inert atmosphere showed that carrier mobilities > 10⁴ cm²/Vs at room temperature. This article also reported the observation of fully developed quantum Hall effect.

A large number of investigations also focused on photoconductive studies of InSe based materials. For a detail discussion of several key parameters such as responsivity (R), photoconductive gain, external quantum efficiency (EQE), response time, detectivity (D) etc., of photoconductors/photo-detector and or photo FETs the authors would refer to the article by Buscema et al., which provides an excellent and in-depth study of different aspects of photocurrent generation with two-dimensional van der Waals semiconductors. Investigations performed so far indicate that above mentioned parameters of photo-detectors depend on a variety of factors such as layer thickness, growth method, device characterization parameters, wavelength and intensity of light used etc. As such reports of InSe photoconductors showing very high reponsivities of ~ 56800 A/W, and response times few ms to a variety of factors such as layer thickness, growth method, device characterization parameters, wavelength and intensity of light used etc. As such reports of InSe photoconductors showing very high reponsivities of ~ 56800 A/W, and response times few ms to high reponsivities of ~ 56800 A/W, and response times few ms can be found in the literature. Similar reports of photoresponsivity of ~ 340 A/W, and response times few ms are also reported for monolayered α - InSe synthesized using physical vapor deposition. On the other hand photoresponsivity of up to ~ 1.7 x 10⁵ A/W at λ = 633 nm, with rise and decay
This study also reported an EQE of several percent also of the order of the thickness L. b) L-dependence of the peak intensity of the PL emission from flakes of different thickness L. The inset sketches the PL emission from flakes of different thickness L = 633 nm). The line describes the decrease in PL intensity that would be expected from a reduction in the amount of luminescent material with increasing L. 

Fig. 2 (a) Typical microPL spectra of InSe layers at T = 300 K with peak intensity strongly dependent on the layer thickness L (P = 0.1 mW and λ = 633 nm). The inset sketches the PL emission from flakes of different thickness L. b) L-dependence of the peak intensity of the µPL emission. The line describes the decrease in PL intensity that would be expected from a reduction in the amount of luminescent material with decreasing L. Reprinted from ref. 38, with the permission of John Wiley and Sons.

The performance of GaSe based FETs, phototransistors and photodetectors can be influenced by the synthesis techniques. As example, pulsed laser deposited (PLD) GaSe nanosheet network shows photoresponsivity and EQE ranging from 0.4 A/W and 100 % at 700 nm, to 1.4 A/W and 600 % at 240 nm, respectively. In this article, it was claimed that the high photoresponsivity is related to the mid-gap states of the grain boundaries in the nanosheet network. Another group of researchers recently demonstrated that the p-type GaSe nanoribbons synthesized through a one-step thermal deposition process (thickness 15 nm) shows excellent spectral responsivity of 31.1 A/W and EQE of 11046 %.

In another recent study, layered GaSe phototransistors and photodetectors demonstrated that performance can be altered by changing the number of layers. They speculated that the increasing the carrier concentration with increasing thickness governs the resistivity of the devices and which results in the increase in photoresponsivity. Yufei Cao et al. systematically investigated and showed that electrode configurations can have drastic influence on the performance of these GaSe devices. In particular they showed that shrinking the spacing of the electrodes as well as using bottom contacts over top contacts can enhance the photosensitivity of layer GaSe devices. They have shown that the photo responsivity increases from 40 to 900 A/W with electrode spacing shrinking from 10 µm to 90 nm for the top contacted devices while it increases further from 200 to 5000 A/W when bottom contacts spacing reduces from 8 µm to 290 nm.

Exposure to different environmental conditions can modulate the performance of these devices.
Fig. 3 (a) Crystal structure of In$_2$Se$_3$. (b) Atomic Force Microscopy scan of In$_2$Se$_3$ FET device. (c) Transfer curve for the device in b measured between contacts 3 and 4. (d) I-V curves at back-gate voltages measured between contacts 3 and 4. (e) Transfer curves with different laser illumination power ($\lambda = 640$ nm). The laser powers increase in series increments of 1, 3, 5 from 1 nW to 5 mW. Inset shows the shift of the threshold voltage for increasing powers. (f) Photocurrent versus laser power for different back-gate voltages. (g) Responsivity calculated from the measured photocurrent in panel f. (h) Exponent ($\alpha$) extracted from panel f for each gate voltage. Reprinted with permission from ref. 62. Copyright (2015) American Chemical Society.

the behavior of the thin GaSe devices. Shengxue Yang et al. demonstrated that mechanically exfoliated 5 nm thick GaSe can be sensitive to gas molecules. They have shown that the few-layer GaSe phototransistors exhibits improved performance under O$_2$ environment than air. Further, they have enhanced the photoresponse and EQE by thermal annealing the devices. Where, they claim that, chalcogen vacancies produced by thermal annealing act as active sites for the foreign molecules that increase the sensitivity to the surroundings.

2.3 Tin Selenide Based Systems

Group IV monochalcogenides, such as SnSe show exotic properties characterized by their structural features, layer orientation, stacking etc. which offers possible tunability to their physical properties by various structural and chemical modifications.

Typically, SnSe crystallizes in layered orthorhombic structure, which is a distortion form of rock salt structure. There are eight atoms per unit cell forming bilayer layers along the longest axis. These layers connect through weak van der Waals interactions. Each Sn atom has seven Se neighbors. Three of them covalently bound to Sn atoms within the layers and others bound through the longer bonds. Two of the second nearest neighbors lie within the layer while the other two are in the adjacent layer as shown in Fig. 4(b).

Recent studies reported that the physical properties of SnSe are extremely sensitive to the atomistic details of its structure. There is a possibility to determine the critical features of the electronic properties by modifying the atomistic structure. Based on the DFT calculation, our recent work found that the directivity of interlayer plays a major role in the details of the electronic structure. The bulk and monolayer SnSe shows the indirect band gap (Fig 4(a)). Possible strain-induced indirect-direct transition has been theoretically predicted.

Fig. 4 (a) Electronic band structure of SnSe. The Brillouin zone for Orthorhombic structure is shown as inset (b) Atomic configuration of SnSe.

Recent investigations also indicate that apart from being classified as traditional thermoelectric materials, few layers of SnSe systems also possess electrical/optical properties suitable for various opto-electronic applications. For example; Su et al. showed the possibility of SnSe$_2$ FET devices with high drive current capacity. This study reported that the FET mobility increases from 8.6 cm$^2$/Vs at 300K to 28 cm$^2$/Vs at 77 K. Similarly Guo et al. reported high mobility FETs using few-Layer SnSe. They found that it is possible to fabricate thin layer n-type SnSe$_2$ FETs with room temperature mobility 85 cm$^2$/Vs at 300K which
increases to $\sim 225$ cm$^2$/Vs at 78 K. High on-off ratio up to $10^5$ at 78 K were also seen in these devices. In another study, investigators evaluated a variety of combination of gating conditions on few-layer n-type SnSe$_2$ Transistors$^{109}$ and showed that it is possible to obtain SnSe$_2$ FETs with ON/OFF ratios $\sim 10^4$ using Hafnium Dioxide (HfO$_2$) back-gate as dielectric in combination with a layer of polymer electrolyte. Modulation of electrical properties of SnSe$_2$ layers using site selective doping is also reported$^{108}$. In this article, the authors showed the possibility of achieving carrier concentration of $\sim 10^{16}$cm$^{-2}$ by doing the SnSe$_2$ lattice using shallow electron donor such as chlorine$^{108}$. Theoretical calculations performed by L.C Zhang et al., also predicts that it is possible to have extremely high monolayers of SnSe with very low lattice thermal conductivity and very high hole mobility$^{87}$.

Strong Visible-Light Absorbance in Few-Layer SnSe was reported by Shi et al.$^{95}$ Solar cell applications using thin films of SnSe has been investigated as well$^{101}$. Optoelectronic properties of single crystal SnSe nanoplates were evaluated by Zhao et al.$^{104}$. They reported on controlled growth of these nanoplates on mica substrates using vapor transport deposition method. SnSe nanoplate FET devices show a p-type conduction with mobility $\sim 1.5$ cm$^2$/Vs. On white light illumination, these devices operating under 0.1 V bias between the source and drain show a current increase $\sim 0.06$. Typical photoresponsivity value of $\sim 330$ A/W was obtained. Thin layers of SnSe$_2$, grown directly on SiO$_2$ substrate using CVD show a photoresponsivity of 1.9 A/W, under 1 V bias between the source and drain, when illuminated with light of $\lambda = 800$ nm$^{15}$. The possibility of utilizing SnSe$_2$ systems for high performance photo detectors are also reported by Zhou et al.$^{103}$. In this study it was reported that few layer SnSe$_2$ can show high spectral gain $\sim 1.1 \times 10^3$ A/W, EQE $\sim 2.6 \times 10^5$ % and detectivity $\sim 10^{10}$ Jones.

Chemical modification using alloying or doping to enhance the electronic properties was also observed for SnSe. Chen S et al. reported that Te doped SnSe shows the indirect band with 0.608 eV, which is smaller than the pure SnSe$^{91,92}$. T. Wei et al. reported that the bandgap of Te doped SnSe keeps decreasing until the Te concentration saturates in the doped sample SnSe(1-x)Tex. This saturation value is reported as $x=0.16^{93}$. Na doped SnSe
also decrease the band gap value gradually and it depends on the concentration of the doped Na\textsuperscript{93–95}.

### 2.4 Germanium Selenide Based Systems

Similar to tin selenide, GeSe, another member of group IV-monochalcogenides crystalizes in the distorted rocksalt structure. Several theoretical investigations are performed on this system as well\textsuperscript{30,31,35,125–127}. Electronic band gap of GeSe is also reported to be indirect 1.14 eV (which is higher than that reported for bulk SnSe 0.86 eV\textsuperscript{35,125,126}. Potential applications of mono-and few layer GeSe are very similar to that of tin selenide from the same group\textsuperscript{30,33}.

GeSe is also one of those materials whose band-gap overlaps with the solar spectrum. In the past simple chemical routes to synthesize single crystal sheets of these materials are reported\textsuperscript{125}. These single crystals of GeSe were found to be of p-type semiconducting layered structure with a narrow band gap of 1.14 eV. Solution phase synthesis of micrometer long thin nanosheets was also reported by Xue et al.\textsuperscript{128}. In this article, anisotropic photoreponsne properties of individual micrometer-sized single-crystal GeSe nanosheets was reported. By fabricating suitable devices which probed the in plane and out of plane photoresponse properties of these nanosheets, the authors showed novel anisotropic photo switching properties. By using a white light source, the authors reported that on/off switching ratio of the device perpendicular to the layers is about 5.5, while that of the device parallel to the layers is only 1.6. Mukherjee et al.\textsuperscript{121} reported the synthesis of high-quality, single-crystalline, micrometer-sized 2D GeSe nanosheets using vapor deposition technique. They reported that upon device fabrication with standard photo lithography process using Gold (Au) as contact electrodes, Au formed uneven Schottky barriers with GeSe nanosheet. They also demonstrated that few layer GeSe nanosheets photodetector can give rise to 3.5 A/W photo responsivity at near Infra-Red wavelength (808 nm) spectrum with EQE % ∼ 537. The authors claim that the formation of the SB, perhaps is one of the main contributor to the photo responsivity behavior. Similar, SB effects in photocurrent generation was also found in single crystalline GeSe\textsubscript{2} nanobelts grown on CVD technique. These devices showed a photo responsivity of 2764 A/W when illuminated with 532 nm light\textsuperscript{120}.

### 2.5 Bismuth Selenide Based Systems

Similar to other selenide-based layered materials, Bi\textsubscript{2}Se\textsubscript{3}, the prototypical topological insulator, shows new properties as it approaches the two-dimensional limit. A particularly intriguing finite-size effect in Bi\textsubscript{2}Se\textsubscript{3} is that it transforms to an insulator at the surface, effectively behaving like conventional (trivial) insulators. Gapped surface states originate from quantum tunneling between the top and bottom surface wavefunctions in ultra-thin Bi\textsubscript{2}Se\textsubscript{3}. The effect was theoretically predicted to exist below 6 quintuple layers (QL)\textsuperscript{129–131} and later also confirmed by first-principles calculations\textsuperscript{132–134}. Experimental verification followed soon after through angle-resolved photo emission spectroscopy (ARPES) measurements\textsuperscript{135,136}. In Fig. 5(a), we show the band structure of 2 QL Bi\textsubscript{2}Se\textsubscript{3} that includes both surface and bulk bands. The well-established gamma-point surface Dirac cone of Bi\textsubscript{2}Se\textsubscript{3} is gapped at the 2 QL level as evident from the 0.15 eV direct band gap. Other mechanisms such as weak localization effects also lead to surface gap opening in few-layer Bi\textsubscript{2}Se\textsubscript{3}, but it is of the order of meV\textsuperscript{137,138}.

Another related property change originating from finite-size is the increase in the bulk band gap of few-layer Bi\textsubscript{2}Se\textsubscript{3}. As shown in Fig. 5(a), the lowest non-surface band lies 0.5 eV above the valence band maximum that is 0.2 eV higher than the bulk band gap of Bi\textsubscript{2}Se\textsubscript{3}. Very recently, optical spectroscopy measurements on our Bi\textsubscript{2}Se\textsubscript{3} films grown using magnetron sputtering have validated this change in band structure\textsuperscript{139}. In Fig. 5(b), we show the direct gap analysis data for the 2 and 6 QL Bi\textsubscript{2}Se\textsubscript{3} film obtained from their optical absorption data (plot of (α E)\textsuperscript{2} vs E). The examination finds that the measured band gap of the 2 (6) QL is 0.8 (0.5) eV. The 0.3 eV blue shift is in excellent agreement with theoretical calculations\textsuperscript{134}. An added band gap increase of nearly 0.2 eV is observed irrespective of thickness that we attribute to the Burstein-Moss effect\textsuperscript{140}. High carrier concentration that is typical of Bi\textsubscript{2}Se\textsubscript{3} leads to an apparent increase in the optical band gap. Confinement in all three directions leads to further increase in the bulk band gap to as high as 2.5 eV as demonstrated in Bi\textsubscript{2}Se\textsubscript{3} nanoparticles\textsuperscript{141}. Taken together, we find that finite-size is very effective in engineering higher band gaps in Bi\textsubscript{2}Se\textsubscript{3}.

The presence of gapped surface states and higher bulk band gap at the few-layer level is of significant interest for electronic applications of Bi\textsubscript{2}Se\textsubscript{3}. One exciting prospect is potentially higher ON/OFF ratios necessary for robust transistor performance\textsuperscript{134}. Materials-related issues need to be addressed to achieve such potential. The presence of selenium vacancies in thin-films and single crystals generate high bulk carrier concentration (n\textsubscript{3D} > 10\textsuperscript{18} cm\textsuperscript{−3}) in Bi\textsubscript{2}Se\textsubscript{3}. As a result, the Fermi level moves to the conduction band generating n-type carriers. Few-layer Bi\textsubscript{2}Se\textsubscript{3} also show high carrier concentration independent of the growth method and substrate. As the data in Table 3 indicates, both exfoliated and Physical vapor deposition grown samples (Molecular Beam Epitaxy and sputtering) show high carrier values. High values can also be induced by mechanical exfoliation\textsuperscript{142}, and exposure to ambient conditions\textsuperscript{143,144}. Studies show that doping with Sb\textsuperscript{145,146}, electrochemical doping\textsuperscript{142} and synthesis in Se-
rich conditions\textsuperscript{122} lower carrier concentrations in Bi\textsubscript{2}Se\textsubscript{3}.

Resistivity, on the hand, is strongly thickness dependent. Temperature-dependent resistivity and field-effect-transistors measurements demonstrate strong insulating behavior in 2 and 3 QL Bi\textsubscript{2}Se\textsubscript{3} films\textsuperscript{123,147,148}. As shown in Table 3, over an order of magnitude change in resistivity is recorded at room temperature on our Bi\textsubscript{2}Se\textsubscript{3} films of different thicknesses grown using magnetron sputtering. A similar trend is also observed in Molecular Beam Epitaxy (MBE) grown films\textsuperscript{124,147,148} implying, again, growth methods and conditions play a secondary role. Noteworthy is the fact that the increased resistivity of few-layer Bi\textsubscript{2}Se\textsubscript{3} strongly correlates with bulk band gap increase as shown in Fig. 5. Mobilities values are low typically between 10-50 cm\textsuperscript{2}/Vs for few-layer Bi\textsubscript{2}Se\textsubscript{3}\textsuperscript{123,124,147}. Our data also indicate that enhanced scattering at the film-substrate also influences resistivity and mobility values.

### Table 3 Transport properties of few-layer Bi\textsubscript{2}Se\textsubscript{3} films

<table>
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<tr>
<th>Growth Method</th>
<th>Thickness (nm)</th>
<th>Bulk concentration ($\times 10^{19}$ cm\textsuperscript{-3})</th>
<th>Resistivity (300K) ($\times 10^{-4}$ Ω cm)</th>
<th>Ref.</th>
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<tr>
<td>MBE on Si(100)</td>
<td>3</td>
<td>0.028</td>
<td>77.4</td>
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<tr>
<td></td>
<td>4</td>
<td>1.1</td>
<td>105</td>
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<tr>
<td>Exfoliated on SiO\textsubscript{2}/Si</td>
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<td>385</td>
<td>1000</td>
<td>123</td>
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<tr>
<td></td>
<td>14</td>
<td>107</td>
<td>370.3</td>
<td></td>
</tr>
<tr>
<td>MBE on Al\textsubscript{2}O\textsubscript{3} (0001)</td>
<td>2</td>
<td>10</td>
<td>12</td>
<td>124</td>
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<td>2</td>
<td>9</td>
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3 Conclusions and Future Outlook

Although the study of atomically thin layered selenide based systems and 2D materials along with their heterostructures, have picked up its pace quite a bit in the last few years, as evident from several recent reviews\textsuperscript{10,149–152} the field is still very new and is wide open. Some of the aspects that might play a very important role in developing these materials for a variety of advance applications are as follows. First and foremost, from the point of view of advancement in materials synthesis, efforts leading to reliable growth techniques, which will provide materials with consistent physical properties are crucial. Similarly, robust processes for large area/wafer scale synthesis of a variety of 2D layered materials systems are also needed. Techniques such as Atomic Layer Deposition (ALD), Pulse Laser Deposition (PLD), Molecular Beam Epitaxy (MBE), Sputter Deposition etc. can be explored further.

Like any other field, a tight synergy between theoretical predictions and experimental understanding of these systems will propel the field of layered selenides further.

For example, predictive modeling suggests the possible application of InSe for sensing small gas molecules\textsuperscript{153}. Various other approaches such as oxidation\textsuperscript{154} have been suggested for modifying the electronic properties of InSe. Similarly, strategic doping, with atomic precision of some of these selenide based compounds can lead to functionality control of these materials. For example, based on DFT calculation, X. Li et al. predicted possible n/p characteristics upon substitutional chemical doping on the anion site\textsuperscript{155}. Similarly, many exciting possibilities exist for selenide-based topological materials, their performance in a heterostructure or hetero crystal configuration\textsuperscript{156} and compatibility with diverse materials will be some of the factors dictating their electronic device applications.

**Conflict of interest**

There are no conflicts of interest to declare.

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