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Mass production of two-dimensional materials beyond graphene and their applications

Monolayer MoS₂ epitaxy

Space-confined growth of metal halide perovskite crystal films



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Kai Xiao



Xiangheng Xiao



Yuxi Xu



Woo Jong Yu



Guangyu Zhang



Jun Zhang



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Qing Zhang



Zheng Zhang



Peng Zhou



Shuyun Zhou

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2021

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Editorial

The *Nano Research* Young Innovators (NR45) Awards in two-dimensional materials

Xiangfeng Duan^{1,*} and Qihua Xiong^{2,3,*}

¹ University of California, Los Angeles, USA

² Tsinghua University, China

³ Beijing Academy of Quantum Information Sciences, China

1575–1582

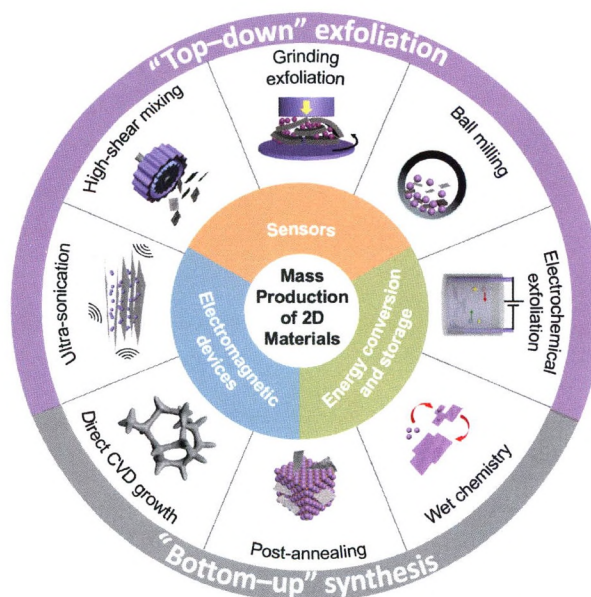
Synthesis

Review Articles

Mass production of two-dimensional materials beyond graphene and their applications

Liusi Yang, Wenjun Chen, Qiangmin Yu, and Bilu Liu*

Tsinghua University, China



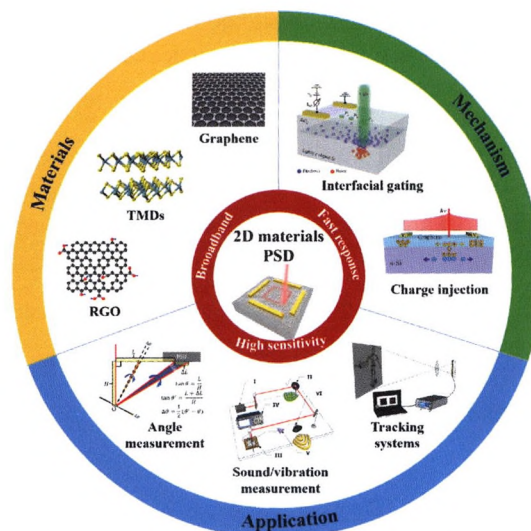
We review recent research progress on mass production of two-dimensional (2D) materials beyond graphene, including “top-down” exfoliation and “bottom-up” synthetic approaches. In addition, the applications that require massively-produced 2D materials are discussed.

1583–1597

Position-sensitive detectors based on two-dimensional materials

Wenhui Wang, Junpeng Lu*, and Zhenhua Ni*

Southeast University, China



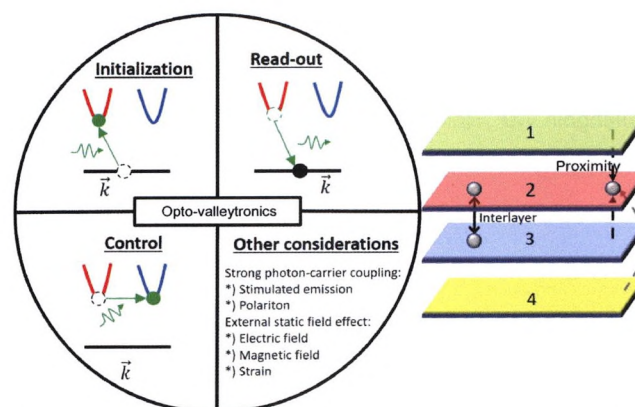
This review summarizes the structures, carrier dynamics, and applications of position-sensitive detector (PSD) based two-dimensional (2D) materials, and highlights the challenges and opportunities in this research area.

1889–1900

Opto-valleytronics in the 2D van der Waals heterostructure

Abdullah Rasmita and Wei-bo Gao*

Nanyang Technological University, Singapore



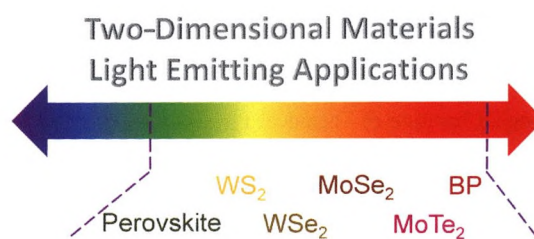
In this article, we review the current understanding of the optical valley physics in the two-dimensional (2D) heterostructure composed of transition metal dichalcogenide and other materials. The challenge of building opto-valleytronics applications using the 2D heterostructure is also discussed.

1901–1911

Two-dimensional materials for light emitting applications: Achievement, challenge and future perspectives

Yi Zhu, Xueqian Sun, Yilin Tang, Lan Fu, and Yuerui Lu*

Australian National University, Australia



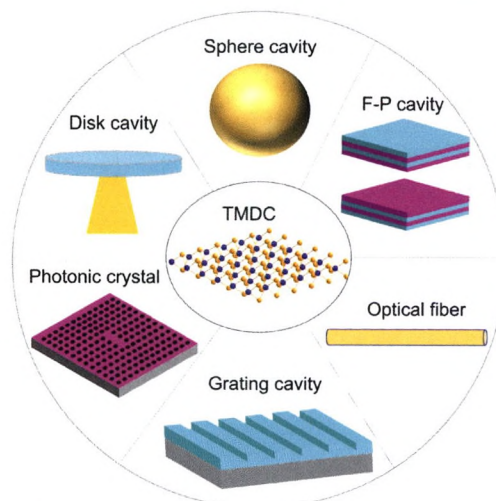
Two-dimensional materials provide tremendous opportunities for future on chip light sources.

1912–1936

Strong exciton–photon interaction and lasing of two-dimensional transition metal dichalcogenide semiconductors

Liyun Zhao, Qiuyu Shang, Meili Li, Yin Liang, Chun Li, and Qing Zhang*

Peking University, China



Recent advances in the strong exciton–photon interaction and lasing of two dimensional transition metal dichalcogenide semiconductors have been developed in the fields of ultra-small and low-energy consumption coherent light sources.

1937–1954

Research Articles

Van der Waals epitaxy of ultrathin crystalline PbTe nanosheets with high near-infrared photoelectric response

Xinxin Zhao^{1,2}, Qing Yin¹, Hao Huang³, Qiang Yu², Bo Liu⁴, Jie Yang^{1,2}, Zhuo Dong^{1,2}, Zhenjiang Shen⁵, Benpeng Zhu⁶, Lei Liao³, and Kai Zhang^{2,*}

¹ University of Science and Technology of China, China

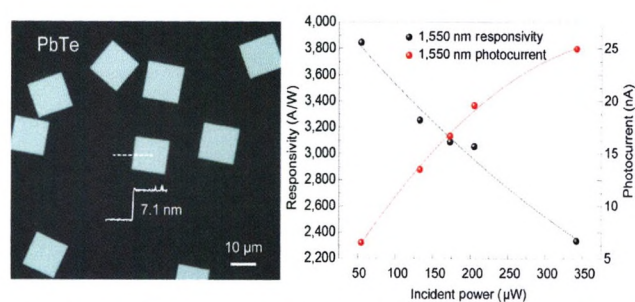
² Suzhou Institute of Nano-Tech and Nano-Bionics (SINANO), Chinese Academy of Sciences, China

³ Wuhan University, China

⁴ Osaka University, Japan

⁵ Hainan Normal University, China

⁶ Huazhong University of Science and Technology, China



Ultrathin crystalline PbTe nanosheets in lateral size of tens of microns with thickness down to ~ 7 nm are synthesized by van der Waals epitaxy. Photodetectors based on the as-grown 2D PbTe nanosheets exhibit an ultrahigh responsivity of 3,847 A/W at the wavelength of 1,550 nm under room temperature.

1955–1960

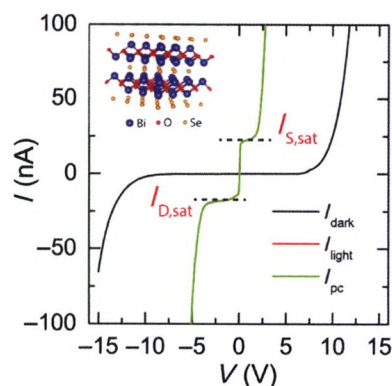
Intrinsic carrier multiplication in layered $\text{Bi}_2\text{O}_2\text{Se}$ avalanche photodiodes with gain bandwidth product exceeding 1 GHz

Vinod K. Sangwan¹, Joohoon Kang^{1,†}, David Lam¹, J. Tyler Gish¹, Spencer A. Wells¹, Jan Luxa², James P. Male¹, G. Jeffrey Snyder¹, Zdeněk Sofer², and Mark C. Hersam^{1,*}

¹ Northwestern University, USA

² University of Chemistry and Technology Prague, Czech Republic

[†] Present address: Sungkyunkwan University (SKKU), Republic of Korea



Metal-semiconductor-metal avalanche photodiodes are fabricated from layered $\text{Bi}_2\text{O}_2\text{Se}$ crystals, yielding intrinsic carrier multiplication factors up to 400, gain bandwidth products exceeding 1 GHz, and detectivities up to 4.6×10^{14} Jones.

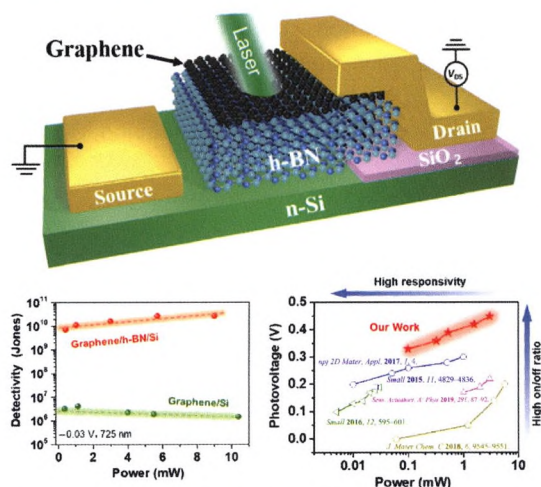
1961–1966

Efficient photovoltaic effect in graphene/h-BN/silicon heterostructure self-powered photodetector

Ui Yeon Won¹, Boo Heung Lee¹, Young Rae Kim^{1,2}, Won Tae Kang^{1,2}, Iimin Lee¹, Ji Eun Kim¹, Young Hee Lee², and Woo Jong Yu^{1,*}

¹ Sungkyunkwan University, Republic of Korea

² Institute for Basic Science (IBS), Republic of Korea



We present a vertically stacked graphene/hexagonal boron nitride/silicon (Gr/h-BN/Si) van der Waals heterostructure to enhance detectivity near-zero external bias of photodetector by inserting thin layer of h-BN to suppress dark current. We propose the mechanisms of carrier flowing in an illuminated environment for reverse and forward current regions.

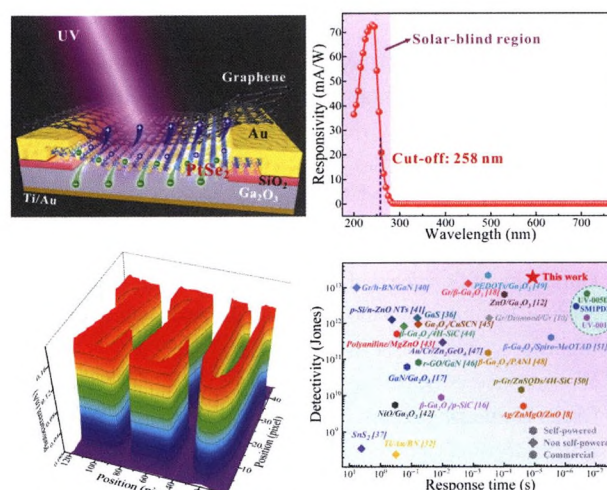
1967–1972

Highly sensitive solar-blind deep ultraviolet photodetector based on graphene/PtSe₂/β-Ga₂O₃ 2D/3D Schottky junction with ultrafast speed

Di Wu¹, Zhihui Zhao¹, Wei Lu², Lukas Rogée², Longhui Zeng^{2,*}, Pei Lin¹, Zhifeng Shi¹, Yongtao Tian¹, Xinjian Li¹, and Yuen Hong Tsang^{2,*}

¹ Zhengzhou University, China

² The Hong Kong Polytechnic University, Hong Kong, China



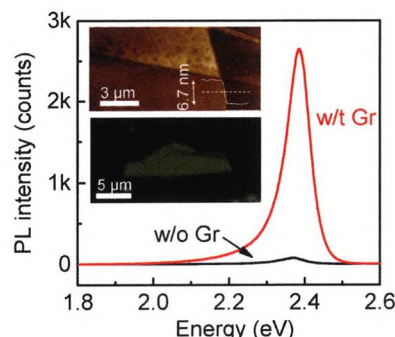
A highly sensitive solar-blind deep ultraviolet photodetector based on graphene/PtSe₂/β-Ga₂O₃ Schottky junction is demonstrated, which shows a large detectivity and an ultrafast response speed.

1973–1979

Giant enhancement of photoluminescence quantum yield in 2D perovskite thin microplates by graphene encapsulation

Wancai Li, Jiaqi Ma, Xue Cheng, and Dehui Li*

Huazhong University of Science and Technology, China



We observed the photoluminescence quantum yield of two-dimensional (2D) perovskite thin microplates has been enhanced 28 times by graphene encapsulation. The enhancement mechanism is the reduced quantum confined Stark effect due to the reduced surface depletion field, which leads to the enhanced radiative recombination efficiency.

1980–1984

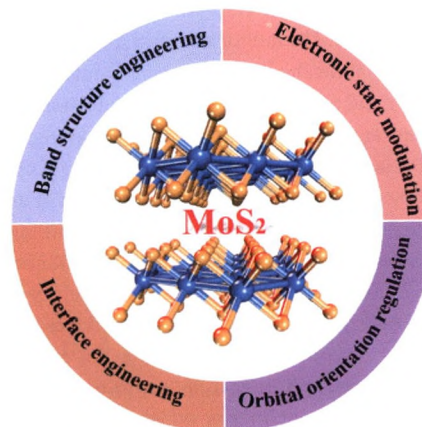
Catalysis/Energy

Review Articles

Two-dimensional MoS₂ for hydrogen evolution reaction catalysis: The electronic structure regulation

Shuwen Niu, Jinyan Cai, and Gongming Wang*

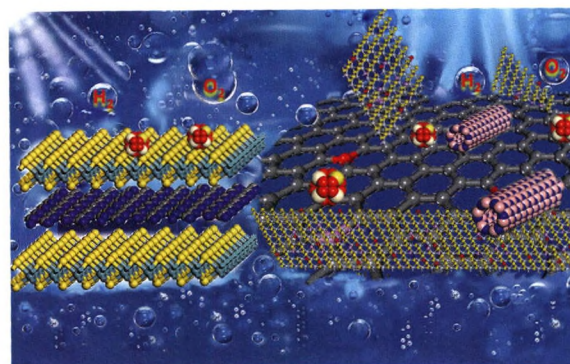
University of Science and Technology of China, China



In this review, we summarize the recent process of the electronic structural modulation of MoS₂ for hydrogen evolution catalysis.

1985–2002

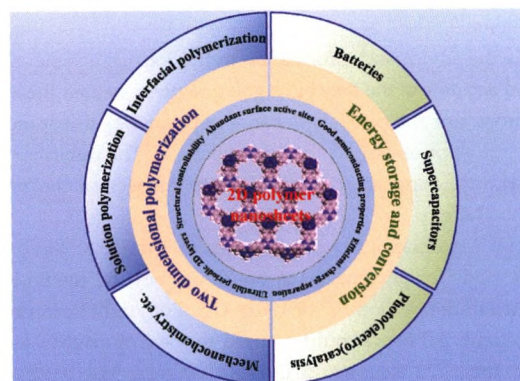
Transition metal dichalcogenide-based mixed-dimensional heterostructures for visible-light-driven photocatalysis: Dimensionality and interface engineering

Xiaorong Gan¹, Danyuan Lei^{2,*}, Ruquan Ye², Huimin Zhao³, and Kwok-Yin Wong⁴¹ Hohai University, China² City University of Hong Kong, Hong Kong, China³ Dalian University of Technology, China⁴ The Hong Kong Polytechnic University, Hong Kong, China

The photoactivity of two-dimensional transition metal dichalcogenide heterostructures for visible-light-driven photocatalytic water splitting can be regulated through dimensionality and interface engineering.

2003–2022

Two-dimensional polymer nanosheets for efficient energy storage and conversion

Yumei Ren^{1,2,3}, Chengbing Yu^{1,*}, Zhonghui Chen^{3,4,*}, and Yuxi Xu^{3,*}¹ Shanghai University, China² Zhengzhou University of Aeronautics, China³ Westlake University, China⁴ Henan University, China

The recent research progress in the preparation methods of two-dimensional (2D) polymer nanosheets, mainly including interfacial polymerization and solution polymerization has been summarized. The structure–property relationships of various 2D polymers are thoroughly discussed. Their applications in the fields of energy storage and conversion, and the future perspectives have also been presented.

2023–2036

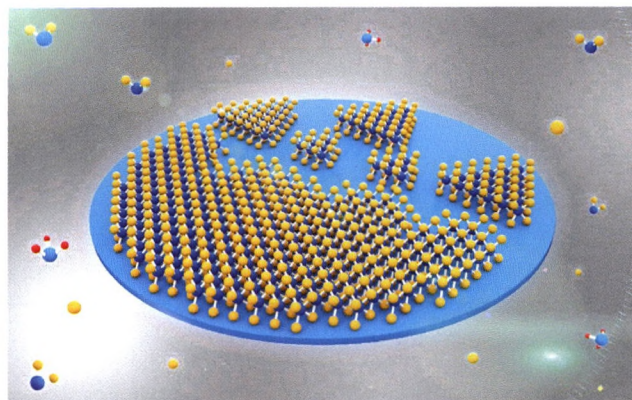
Monolayer MoS₂ epitaxy

Zheng Wei^{1,2}, Qinqin Wang^{1,2}, Lu Li^{1,2}, Rong Yang^{1,2,3}, and Guangyu Zhang^{1,2,3,*}

¹ Beijing National Laboratory for Condensed Matter Physics and Institute of Physics, Chinese Academy of Sciences, China

² University of Chinese Academy of Sciences, China

³ Songshan Lake Materials Laboratory, China



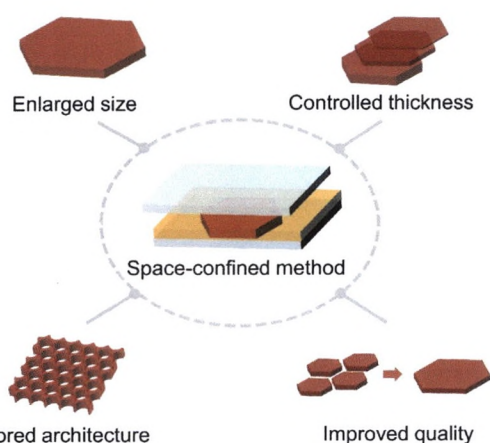
This article reviews the epitaxial growth of monolayer MoS₂ with a particular focus on large-scale and high-quality films.

1598–1608

Space-confined growth of metal halide perovskite crystal films

Linyi Li, Jinxin Liu, Mengqi Zeng, and Lei Fu*

Wuhan University, China



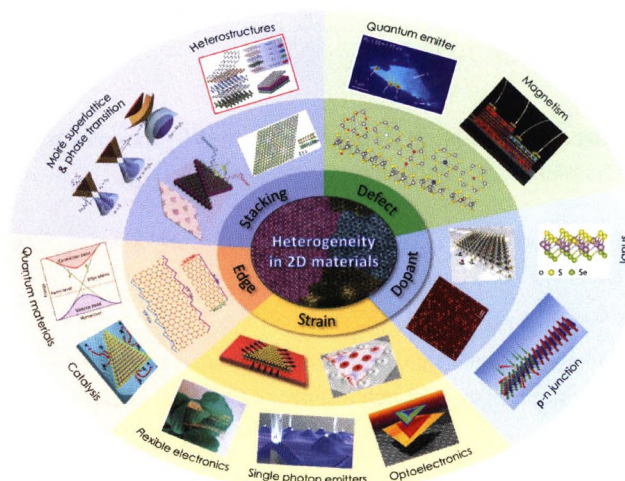
The size, thickness, quality and structure of the perovskite crystal film could be optimized through the space-confined method with various modified strategies.

1609–1624

Heterogeneities at multiple length scales in 2D layered materials: From localized defects and dopants to mesoscopic heterostructures

Hui Cai, Yiling Yu, Yu-Chuan Lin, Alexander A. Puretzky, David B. Geohegan, and Kai Xiao*

Oak Ridge National Laboratory, USA



This paper provides a comprehensive review of controlled synthesis and processing of heterogeneities at multiple length scales and their impact on the macroscale properties and functionalities of two-dimensional (2D) materials.

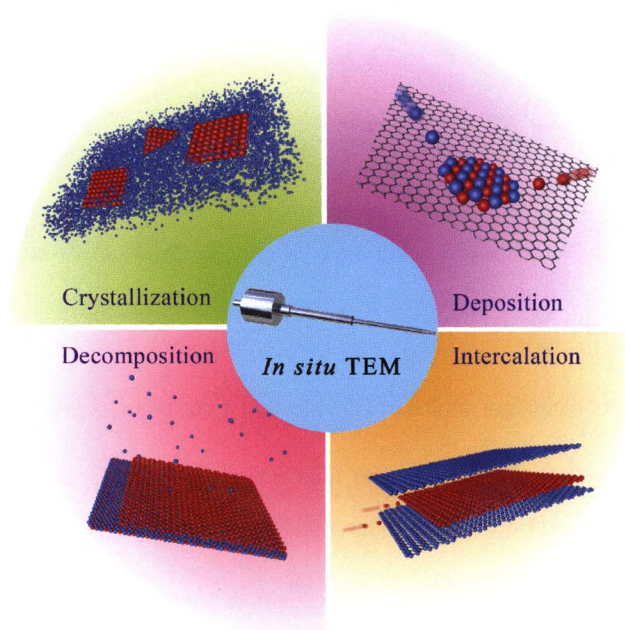
1625–1649

Atomic-scale insights into the formation of 2D crystals from *in situ* transmission electron microscopy

Yatong Zhu¹, Dundong Yuan¹, Hao Zhang¹, Tao Xu^{1,*}, and Litao Sun^{1,2,*}

¹ Southeast University, China

² Southeast University-Monash University Joint Research Institute, China



Here we review the recent *in situ* transmission electron microscopy (TEM) works on the formation of two-dimensional (2D) crystals under electron irradiation, thermal excitation as well as voltage bias. The underlying mechanisms are also elucidated in detail, providing key insights into the nucleation and formation of 2D crystals.

1650–1658

Research Articles

Fast growth of large single-crystalline WS₂ monolayers via chemical vapor deposition

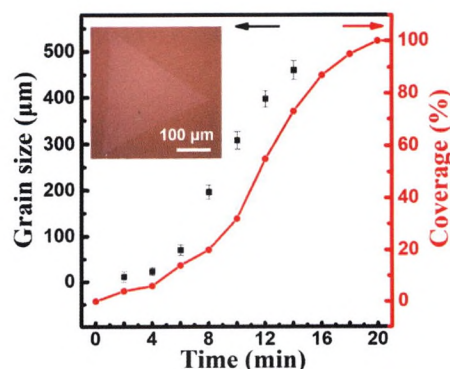
Shengxue Zhou^{1,2}, Lina Liu¹, Shuang Cui³, Xiaofan Ping¹,
Dake Hu¹, and Liying Jiao^{1,*}

¹ Tsinghua University, China

² Ningxia Normal University, China

³ Sinopec Beijing Research Institute of Chemical Industry, China

1659–1662



The fast growth of single crystalline WS₂ monolayered flakes with a side length of up to ~ 500 μm was achieved via chemical vapor deposition using K₂WS₄ as the growth precursor.

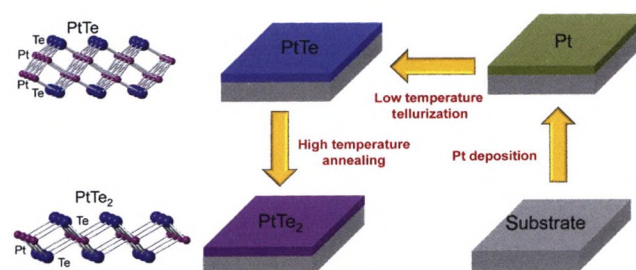
Growth of large scale PtTe, PtTe₂ and PtSe₂ films on a wide range of substrates

Kenan Zhang¹, Meng Wang¹, Xue Zhou¹, Yuan Wang¹,
Shengchun Shen¹, Ke Deng¹, Huining Peng¹, Jiaheng Li¹,
Xubo Lai¹, Liuwan Zhang¹, Yang Wu¹, Wenhui Duan^{1,2},
Pu Yu^{1,2}, and Shuyun Zhou^{1,2,*}

¹ Tsinghua University, China

² Collaborative Innovation Center of Quantum Matter, China

1663–1667



A convenient experimental method for growing centimeter-scale PtSe₂, PtTe₂ films and the hitherto-unreported PtTe film via deposition of Pt film followed by selenization or tellurization is reported. A phase control between the new PtTe phase and PtTe₂ phase is also achieved by annealing under Te flux.

Doping/Electronic Property Modulation

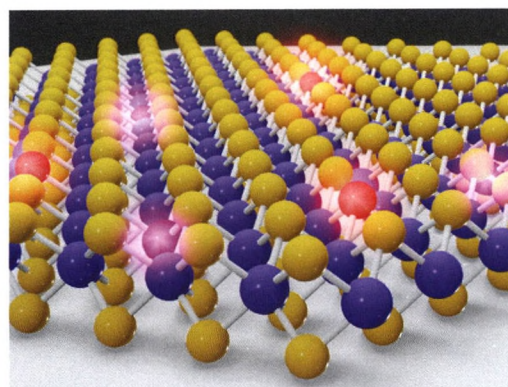
Review Articles

Substitutional doping in 2D transition metal dichalcogenides

Leyi Loh, Zhepeng Zhang, Michel Bosman*, and Goki Eda*

National University of Singapore, Singapore

1668–1681



Substitutional doping in two-dimensional (2D) group 6 transition metal dichalcogenides (MX₂, M = Mo, W; X = S, Se, Te) is key to enabling novel functionalities of these materials. We review the recent progress in the understanding of the physical effects of doping.

Surface charge transfer doping for two-dimensional semiconductor-based electronic and optoelectronic devices

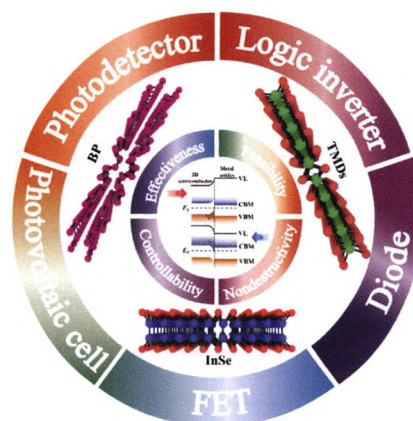
Yanan Wang¹, Yue Zheng^{1,2}, Cheng Han^{2,*}, and Wei Chen^{1,3,4,*}

¹ National University of Singapore, Singapore

² Shenzhen University, China

³ International Campus of Tianjin University, China

⁴ National University of Singapore (Suzhou) Research Institute, China



Surface charge transfer doping (SCTD) is emerging as an effective and non-destructive doping technique to provide reliable doping capability for two-dimensional (2D) materials as well as to tune their electronic and optical properties, which facilitates the rational design and construction of 2D-based functional devices with the optimized performance.

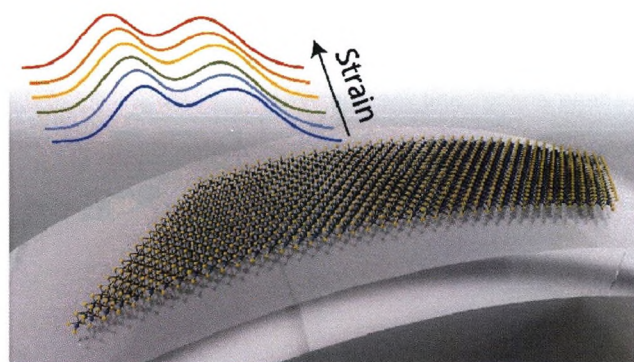
1682–1697

Research Articles

Strain engineering in single-, bi- and tri-layer MoS₂, MoSe₂, WS₂ and WSe₂

Felix Carrascoso, Hao Li, Riccardo Frisenda*, and Andres Castellanos-Gomez*

Consejo Superior de Investigaciones Científicas, Spain



We systematically study how uniaxial strain modifies the optical properties of single-, bi- and tri-layer transition metal dichalcogenides.

1698–1703

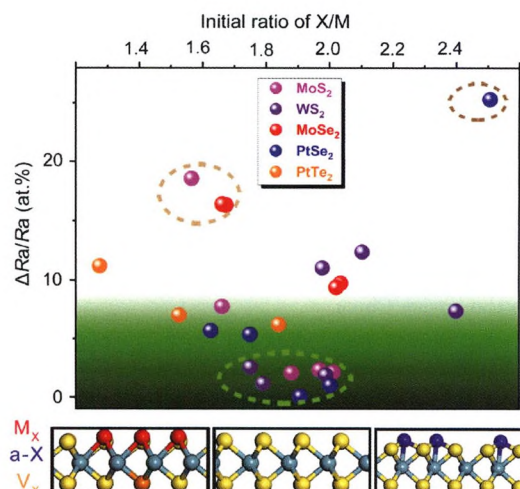
Enhancing stability by tuning element ratio in 2D transition metal chalcogenides

Zhenjia Zhou¹, Tao Xu², Chenxi Zhang¹, Shisheng Li³, Jie Xu¹, Litao Sun^{2,*}, and Libo Gao^{1,*}

¹ Nanjing University, China

² Southeast University, China

³ National Institute for Materials Science (NIMS), Japan



Stable two-dimensional (2D) transition metal chalcogenides rely on their stoichiometric bonded element ratio. Vacancy defects with X atoms, antisite defects with M atoms, and additive X atoms all reduce the environmental stability.

1704–1710

Review Articles

Detection of electron–phonon coupling in two-dimensional materials by light scattering

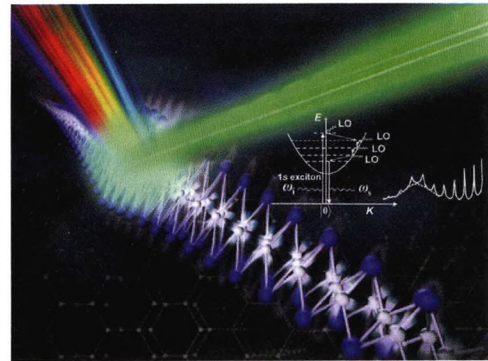
Jia-Min Lai^{1,2}, Ya-Ru Xie^{1,2}, and Jun Zhang^{1,2,3,*}

¹ Institute of Semiconductors, Chinese Academy of Sciences, China

² University of Chinese Academy of Sciences, China

³ Beijing Academy of Quantum Information Science, China

1711–1733



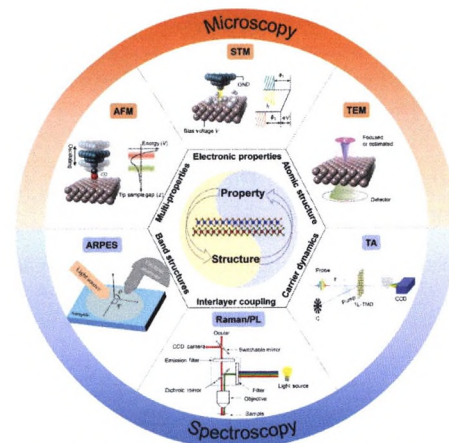
Inelastic light scattering provides a powerful experimental tool to explore electron–phonon interaction in solid materials. This review gives an overview of basic theory and experiment advances of Raman and Brillouin scattering in two-dimensional (2D) materials.

The coupling effect characterization for van der Waals structures based on transition metal dichalcogenides

Baishan Liu, Junli Du, Huihui Yu, Mengyu Hong, Zhuo Kang, Zheng Zhang*, and Yue Zhang*

University of Science and Technology Beijing, China

1734–1751



Developing the coupling effect characterization techniques to unveil the structure–property–performance relationship of van der Waals (vdW) heterostructures is crucial for fundamental science and practical applications.

Electronics

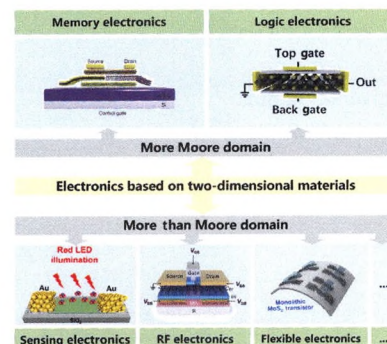
Review Articles

Electronics based on two-dimensional materials: Status and outlook

Senfeng Zeng, Zhaowu Tang, Chunsen Liu, and Peng Zhou*

Fudan University, China

1752–1767



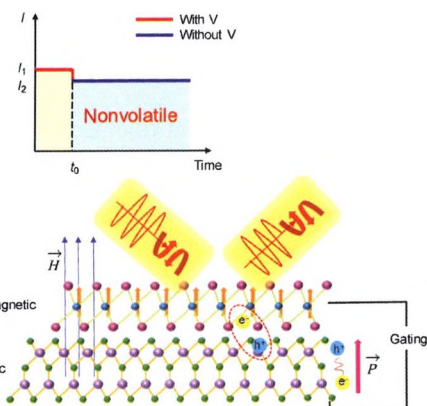
More Moore and More than Moore are proposed as two paths to maintain the development of the semiconductor industry. Two-dimensional materials are proposing to be applied in future electronic devices by the More Moore and More than Moore paths.

Ferromagnetic and ferroelectric two-dimensional materials for memory application

Zhen Liu, Longjiang Deng, and Bo Peng*

University of Electronic Science and Technology of China, China

1802–1813



The van der Waals heterostructures comprising two-dimensional (2D) ferromagnetic and ferroelectric materials provide plenty of opportunities to achieve integrated on-chip spintronic and non-volatile memory devices in future.

Research Article

Gate-tunable linear magnetoresistance in molybdenum disulfide field-effect transistors with graphene insertion layer

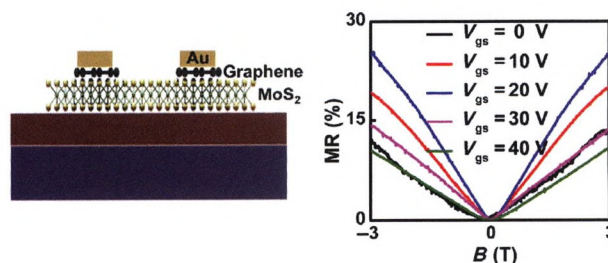
Hao Huang¹, Hongming Guan², Meng Su¹, Xiaoyue Zhang², Yuan Liu³, Chuansheng Liu¹, Zhihong Zhang², Kaihui Liu², Lei Liao^{1,3,*}, and Ning Tang^{2,*}

¹ Wuhan University, China

² Peking University, China

³ Hunan University, China

1814–1818



Molybdenum disulfide field-effect transistors with graphene insertion layer are fabricated using a physical transfer method. Gate-tunable linear magnetoresistances (MRs) are obtained at 2 K, and can be explained by the classical linear MR model caused by spatial fluctuation of carrier mobility.

Optoelectronics

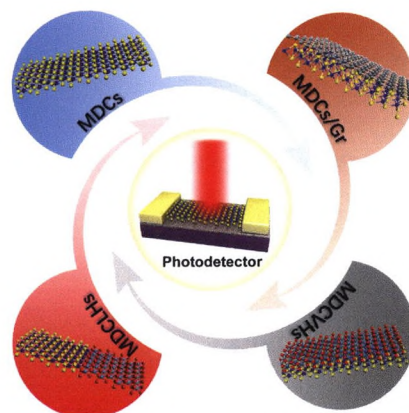
Review Articles

Recent progress about 2D metal dichalcogenides: Synthesis and application in photodetectors

Yongfeng Pei, Rui Chen, Hang Xu, Dong He, Changzhong Jiang, Wenqing Li*, and Xiangheng Xiao*

Wuhan University, China

1819–1839



The vapour phase methods have been widely used in the growth of two-dimensional (2D) metal dichalcogenides and their heterostructures. Recent progress about high-performance photodetectors based on metal dichalcogenides and various heterostructures has been summarized.

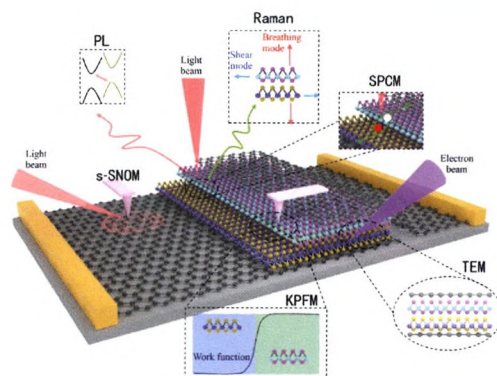
Recent progress and challenges on two-dimensional material photodetectors from the perspective of advanced characterization technologies

Fang Zhong^{1,2,3}, Hao Wang^{1,2}, Zhen Wang^{1,2,*}, Yang Wang¹, Ting He^{1,2}, Peisong Wu^{1,2}, Meng Peng^{1,2}, Hailu Wang¹, Tengfei Xu¹, Fang Wang¹, Peng Wang^{1,2}, Jinshui Miao¹, and Weida Hu^{1,2,*}

¹ Shanghai Institute of Technical Physics, Chinese Academy of Sciences, China

² University of Chinese Academy of Sciences, China

³ ShanghaiTech University, China



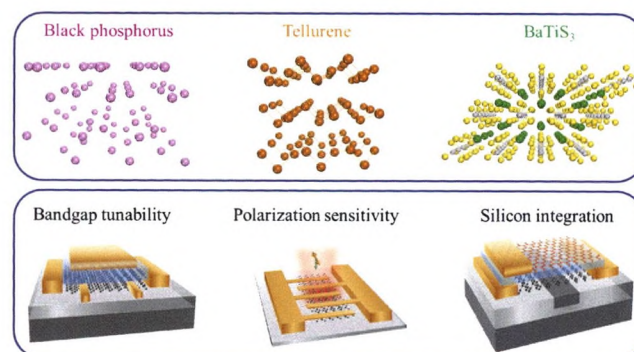
In this review, the progress and challenges on two-dimensional (2D) material photodetectors are systematically discussed from the perspective of advanced characterization technologies, including transmission electron microscopy (TEM), Raman, photoluminescence (PL) spectroscopy and Kelvin probe force microscope (KPFM), scanning photocurrent microscope (SPCM), and scattering scanning near-field optical microscope (s-SNOM). These technologies provide access to deep comprehension of intrinsic mechanisms and further facilitate the development of next-generation photodetectors based on 2D materials.

1840–1862

Emerging low-dimensional materials for mid-infrared detection

Jiangbin Wu*, Nan Wang, Xiaodong Yan, and Han Wang*

University of Southern California, USA



Recent progress in study of mid-infrared (IR) detectors based on the low-dimensional materials, including black phosphorus, black arsenic phosphorus, tellurene and BaTiS₃, from the perspectives of crystal structure, material synthesis, optical properties, and the detector characteristics was reviewed.

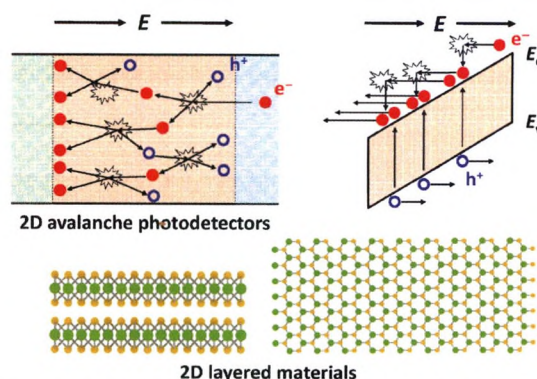
1863–1877

Avalanche photodetectors based on two-dimensional layered materials

Jinshui Miao^{1,*} and Chuan Wang^{2,*}

¹ Shanghai Institute of Technical Physics, Chinese Academy of Sciences, China

² Washington University in St. Louis, USA

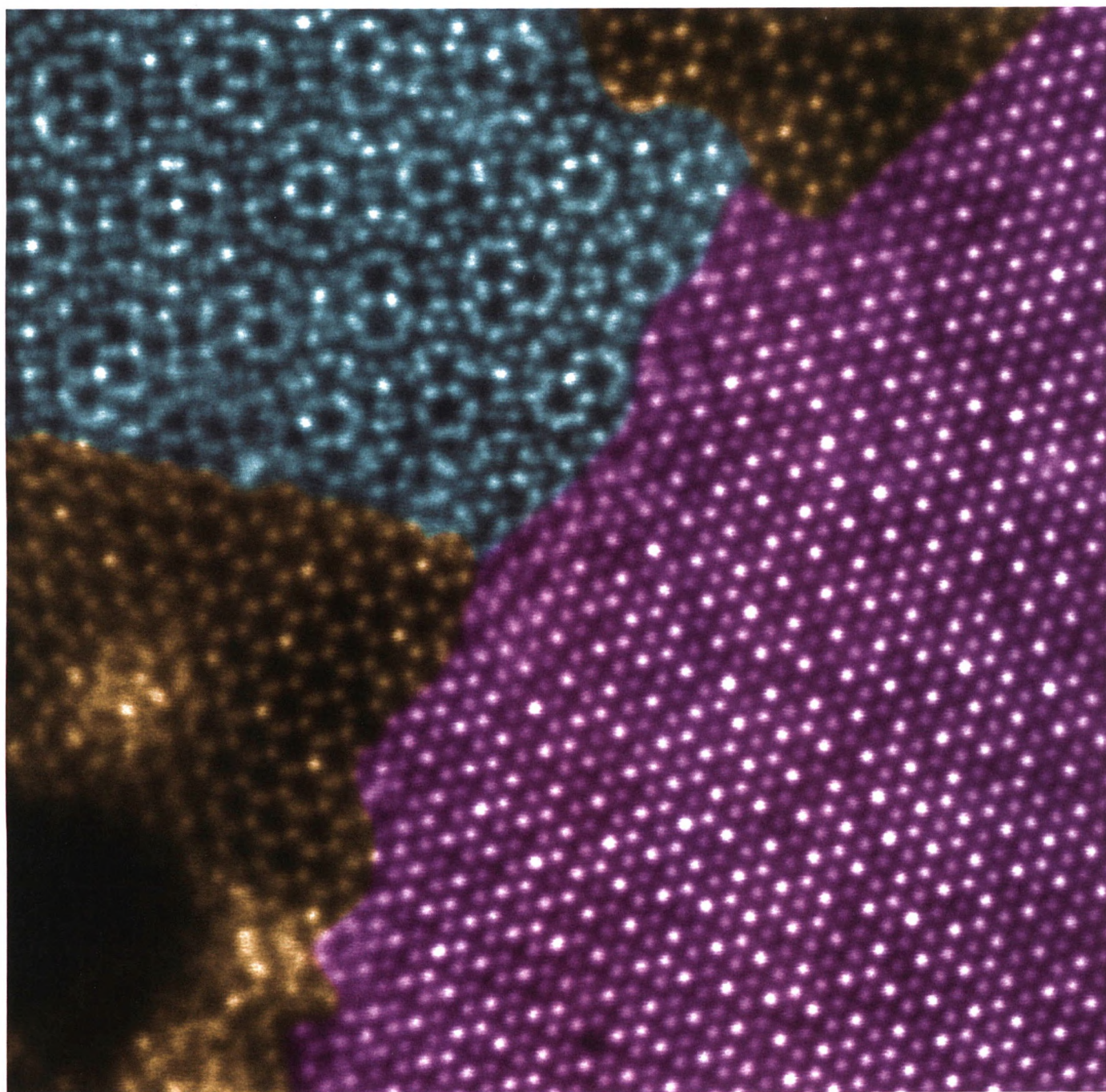


Impact ionization, which can achieve carrier multiplication, is a promising strategy to design two-dimensional (2D) material-based photodetectors with high gain. In this review, a host of emerging avalanche photodetectors based on 2D materials and their van der Waals heterostructures, and their potential applications in the field of photon-counting technologies are detailed.

1878–1888

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