

Applications of MoS₂ as a Two-Dimensional Material Beyond Graphene

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In 2004 the emergence of graphene sparked interest in studying its unique properties as a possible replacement for silicon in modern electronics. However, due to the absence of a band gap graphene is no longer a candidate for applications to field effect transistors (FETs). However, in graphene's place several materials emerged. Among these materials is molybdenum disulfide (MoS₂) and other transition metal dichalcogenides (TMDs). MoS₂ has been the subject of much research in the past few years and it has been studied for several applications, here application to FETs is of focus.

I. INTRODUCTION

By the end of the last century microelectronics had revolutionized the world, the majority of which are silicon-based devices. Today millions of these silicon-based devices are used in many common electronic devices and have become unavoidable throughout everyday life. Though the first field-effect device was patented in 1925, it was not until 1960 that the first metal-oxide semiconductor field effect transistor was demonstrated [26, 34, 46]. A later, devices were being made with several thousand components on a single chip. From there the progress increased at a rapid rate, a process now known as Moore's law, predicting that for each new generation of memory chip and microprocessor unit, the device size would be reduced by 33%, the chip size would be increased by 50%, and the number of components on a chip would quadruple every three years [39, 46]. This has been proven to be true, and up until recently had shown no signs of stopping. Many times the material limitations were overcome by advances in technology that were seemingly insurmountable and effectively had placed a cap on Moore's law, which ultimately led to new techniques and even more pristine silicon-based materials. However, the limit to oxide thickness has finally placed a maximum on the growth of the silicon-based semiconductor device industry [46]. This impending limit caused many to look for solutions that involved the use of SiO₂ devices and also alternatives to silicon. The result of the latter has given way to a breadth of literature and research that was unforeseen a decade ago. The search for alternatives to silicon resulted in research into many new, nontraditional materials. Several notable examples are organic conductors and carbon nanotubes [3, 10]. Arguably one of the most interesting nontraditional materials to come out of such research was graphene.

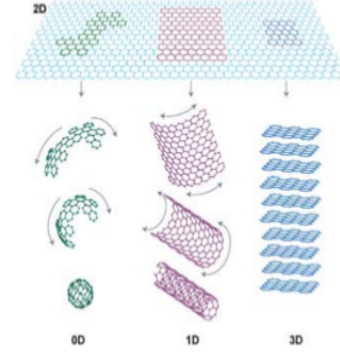


FIG. 1. Graphene can be envisioned in several dimensions. 0-dimensional buckyballs, 1-dimensional nanotubes, or 3-dimensional graphite [43].

II. GRAPHENE AS A NEW TWO-DIMENSIONAL MATERIAL

In 1985, with the discovery of fullerenes, the amount of known carbon allotropes increased [29, 36]. Fullerenes suggested the existence of a one-dimensional form of carbon, known as carbon nanotubes, which were first demonstrated in 1991 [24]. Despite several theoretical studies involving the use of a single layer of graphite, it was not until 2004 that the first monolayer graphene sheet was isolated [40, 41]. In the most basic sense, graphene is simply a single layer of carbon atoms densely packed into a honeycomb lattice. It is used to describe properties of several carbon-based materials (graphite, fullerenes, nanotubes, etc..., see Fig.1) [11, 40, 47]. This was significant because scientists had tried for many years to synthesize monolayers of graphite, though only succeeding in obtaining materials around 10 layers thick [36].

A. Properties of Graphene

To date, graphene's properties have been the focus of much research, both theoretical and experimental. Graphene has many unique properties that have paved the way for new subfields in condensed matter physics (i.e. 'relativistic' condensed matter physics). These

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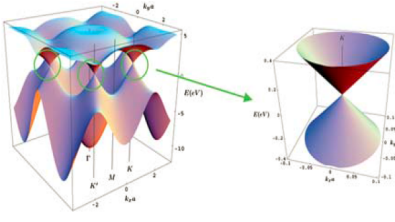


FIG. 2. 3-D representation of the electronic band structure of graphene. The right side shows an enlarged view near the Fermi level in one k point [36].

properties are primarily a result of its low dimensionality and its band structure that allows electrons to mimic relativistic particles [21]. This newly discovered phenomenon has allowed for the study of relativistic effects in condensed matter experiments. This includes the appearance of the atypical quantum Hall effect and the confirmation of other relativistic phenomena [42, 54, 60]. However, it is worth noting that this peculiar band structure can be modified by stacking three or more layers of graphene [36].

For applications to electronics, a material's band gap is of interest. In graphene, however, the conduction and valence bands touch at a single point as shown in Fig.2 [36, 51]. As a result, graphene has no band gap (small band gaps of a few hundred MeV can be introduced in bilayer graphene) [58]. The absence of a band gap is also interesting in the context of the material's optical properties and those implications. The absence of a band gap allows for the absorption of light over a large range of the electromagnetic spectrum, ranging from infrared ($< 1.65\text{ eV}$) to ultraviolet ($> 3.2\text{ eV}$), giving potential for electronic-photonic device applications [13, 52, 56].

Graphene's mechanical properties have been of much interest over the last decade. Graphene has a Young's modulus of $\sim 1000\text{ GPa}$ with a breaking strength that is 13% of that [1, 4]. It can also sustain elastic deformations of 20% due to its two-dimensional nature and it has high pliability [36]. Mechanically, graphene is an exciting material due to the fact it lies in the extreme ranges of some metrics, considering its size and dimensionality.

The mobility in graphene is another property that initially made the material so appealing (and still quite appealing to some degree). Graphene's mobility is about 1000 times that of silicon's [1, 9]. The outstanding crystal quality in large scale (a few microns) is the major contributing factor. Without many defects or imperfections, the electrons can travel long distances, as much as several micrometers, without being scattered even on rough substrates [12, 36]. The average electron mobility obtained in graphene varies depending on temperature, but the most commonly measured

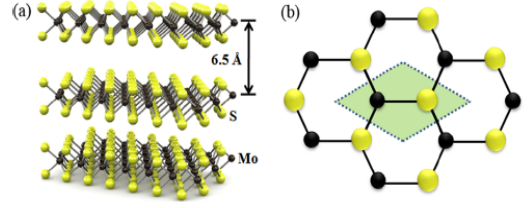


FIG. 3. (a) The atomic structure of layered MoS_2 . Different sheets are composed of three atomic layers S-Mo-S, where Mo and S are covalently bonded [44, 58]. (b) Top view of the honeycomb lattice [58].

value is $\mu = 100,000\text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ with values up to $\mu = 500,000\text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ obtainable at low temperatures [18]. Though graphene exhibits a high mobility, the main limiting factor in integration is the lack of band gap in material. This fact does not allow for integration and use in digital transistors. As a result, researchers, though focused still on the potential applications to other devices based upon its optical and mechanical properties, have moved on to other two-dimensional materials for integration in digital circuits. Ongoing research also includes graphene-like nano materials like silicene and germanene, which are the silicon and germanium-based versions of graphene found to show properties that are similar to graphene [6, 50]. These two-dimensional materials are becoming increasingly attractive for a wide-range of applications due to their distinct properties.

III. TRANSITION METAL DICALCOGENIDES

Graphene is being studied for its unique properties, however, many other two-dimensional materials are known. Some of the two-dimensional materials being studied in addition to graphene are known as transition metal dichalcogenides (TMDs) [37, 55]. TMDs consist of hexagonal layers of metal atoms (M) in between two layers of chalcogen atoms (X), such that the stoichiometry of the material is MX_2 [58]. The material is dependent on the combination of transition metal, typically one of: Mo, W, Nb, Re, Ni, or V and chalcogen, plus typically one of: S, Se, or Te [55]. These materials are commonly stacked together which involves van der Waals interactions between adjacent sheets and covalent bonding within each individual sheet (see Fig.3) [58]. There are wide variety of properties exhibited by these structures, which include insulator or metal. In addition, they can also display some interesting properties like the topological insulator effect, superconductivity, and thermoelectricity [17, 30, 57, 59].

A. Properties of MoS₂

As discussed in Sec. II A, pristine graphene has no band gap. Though it is possible to introduce a band gap in bilayer graphene and graphene nanoribbons, the appeal of many TMDs is that they have direct band gaps which make ideal candidates for electronic material applications [58]. One such example of a semiconducting TMD is MoS₂ (molybdenum disulphide). TMDs, and more specifically MoS₂ and the properties it exhibits, have been studied to some extent for several decades with electrical measurements dating back to the 1960s [14, 16]. However, as of late there has been renewed interest in several TMDs and their potential applications.

Like graphene, and many other two-dimensional materials, MoS₂ has a Young's modulus that is comparable to steel (~ 205 GPa) [48]. The Young's modulus of single-layer MoS₂ is ~ 270 GPa. The Young's modulus of bulk MoS₂ is ~ 240 GPa. The fact that monolayer MoS₂ has a higher Young's modulus than its bulk material counterpart is thought to be mostly due to defects in the material, interlayer sliding or the absence of stacking faults in monolayer samples [31]. In a further study it was found that the Young's modulus of multilayer MoS₂ ranging in thickness from 5 to 25 layers was 330 ± 70 GPa [8]. In addition, both single and bilayer MoS₂ have a breaking strength of about 6% and 11% of their Young's modulus, respectively [4]. This is an indication that MoS₂ is quite flexible compared to other commonly used engineering materials (stainless steel $\sim 0.4\%$, kevlar $\sim 2.6\%$) [19].

As stated before, MoS₂ and some other TMDs are appealing for applications, specifically for use in integrated circuits and logic applications (see sec.V for more on applications). Monolayer MoS₂ has an indirect band gap of 1.8 eV and few layer (bulk) MoS₂ has a direct band gap of 1.3 eV [15, 22, 27, 35, 58]. This change in transition from an indirect band gap semiconductor to a direct band gap semiconductor is shown in Fig.4. The unusual electronic structure of mono and few-layer MoS₂ which ultimately results in some unique optical properties, are due to the composition of the material's conduction and valence bands. The valence band maximum at the Γ point shifts downward to the K point of the Brillouin zone as the number of layers decreases [35, 49]. The change in the band structure as a function of the amount of layers is due to quantum confinement and the change in hybridization between p_z orbitals on S atoms and d orbitals on Mo atoms [33, 35, 49]. Using quantum mechanical modeling systems to investigate the many-body electronic structure of MoS₂ (density functional theory), it has been shown that the conduction band states at the K point are primarily the result of d -orbital electrons localized on the Mo atoms in between layers and are relatively unaffected by interlayer coupling [23, 53]. Conversely, states near the Γ -point

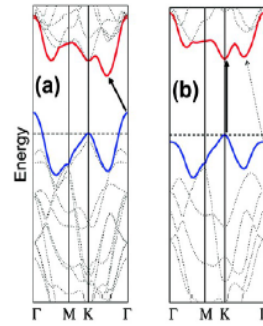


FIG. 4. Calculated band structures of bulk (a) and monolayer (b) MoS₂ and the arrows indicate the lowest energy transition [49].

are strongly affected by interlayer coupling due to the effects of antibonding p_z -orbitals on the S atoms and the d orbitals on the Mo atoms [49]. The result of this is that the states near the K -point are, for the most part, unchanged while the states near the Γ -point are shifted, causing the change from an indirect to a direct band gap as the amount of layers of the material is decreased.

Carrier mobility in two-dimensional TMDs are affected by scattering. The amount by which the scattering affects the mobility is dependent on a number of factors, namely: material thickness, carrier density, effective mass, temperature and electronic and phonon band structure [53]. The main sources of scattering in 2-D TMDs are acoustic and optical phonon scattering and Coulomb scattering [2, 45].

IV. MECHANICAL EXFOLIATION AND CHARACTERIZATION OF MoS₂ NANOSHEETS

Several methods exist that can be used to prepare atomically thin nanosheets of MoS₂ (and other TMDs). Among these several methods are mechanical exfoliation, chemical exfoliation, chemical vapor deposition and sonication [58]. The method of mechanical exfoliation used to synthesize monolayer and few-layer MoS₂ is very similar to the method used by Geim et al. to synthesize their samples of graphene from 3-D graphite [41].

To date, mechanical exfoliation remains the best method to synthesize MoS₂ crystals of the highest quality. The process involves taking bulk MoS₂ crystals and peeling thin layers from the bulk material using some adhesive material. Commonly, the adhesive material is Scotch tape, though there have been variations such as a silicone stamp [7]. This leaves a number of flakes attached to the surface of the adhesive. The flakes that are attached to the adhesive are then placed onto a substrate using instruments like plastic tweezers to further separate the flakes from the adhesive material.



FIG. 5. Color image of a MoS_2 deposited on a 90 nm SiO_2/Si substrate. The digits indicate the layer numbers of MoS_2 nanosheets [32]

The process results in mono and few-layer flakes of MoS_2 being deposited on the substrate [32]. In addition to mono and few-layer flakes of MoS_2 being deposited on the substrate, the most common substrate being SiO_2/Si , a quantity of thicker flakes of MoS_2 are deposited as well [5]. This is demonstrated in Fig.5, showing the varying thicknesses of MoS_2 flakes on a substrate. As a result a method is needed to further differentiate between the flakes of varying thicknesses on that have been deposited on the substrate before any type of fundamental research can be done on the material.

Determining the size of synthesized two-dimensional materials is inherently challenging due to the small sample sizes. Several methods have been developed throughout the years to identify and characterize these materials. The method used is dependent on the desired properties of the material that are of interest. For locating and subsequently determining the thickness of MoS_2 , optical microscopy is one technique that does well to identify single and multi-layer flakes [5]. In addition, to identify the thickness of these flakes, a common technique involves the use of atomic force microscopy (AFM).

V. APPLICATIONS OF MoS_2 TO FIELD EFFECT TRANSISTORS

MoS_2 exhibits unique properties that make it an interesting candidate for several applications. Some of these applications include optoelectronic devices, namely devices that can interact with, detect, or control light. The electronic structure of MoS_2 is what makes it interesting for this application. In addition, MoS_2 is of interest for molecular sensing applications [53]. As compared to graphene, MoS_2 is appealing in this context because of the natural band gap and as a result it is an ideal candidate for use in field effect transistors (FETs).

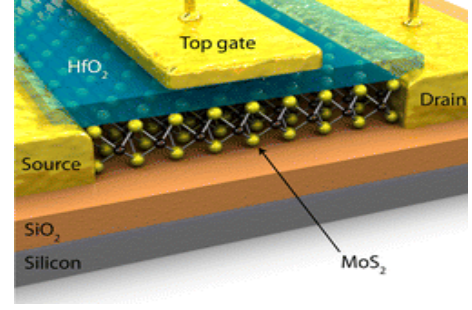


FIG. 6. Schematic view of a MoS_2 transistor with Au leads and encapsulated in 30 nm thick high κ dielectric HfO_2 acting as a top-gate dielectric [31, 44].

FETs are the most fundamental component of modern electronic circuits. These components are used primarily as a switch in digital circuits. Typically, FETs are composed of a source and a drain that serve as contacts for the channel, the area that connects them [38]. The channel has thin dielectric coating and has a metal electrode at the top, the top gate. By changing the carrier density through the use of this electrode one can control the channel's conductivity. Fig.6 shows a schematic of a single-layer MoS_2 FET, illustrating the positioning of the drain, source, top gate, and the commonly used SiO_2/Si substrate. A side image of a similar FET is shown in Fig.7, here the relative thicknesses and positions are shown more clearly. One of the ideal properties for a transistor channel would include high charge carrier mobility, a higher mobility would allow for fast switching between on and off states [31]. Another property that is necessary for use in transistors is the presence of a band gap, which eliminates the use of graphene, even though it exhibits high mobility the lack of a band gap does not allow for the fabrication of transistors that could be switched on or off.

The use of gate dielectric is of importance in FETs in the context of mobility. Electrical measurements of single layer MoS_2 have shown a room temperature mobility in the range of $0.5 - 3 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$, whereas the mobility of bulk MoS_2 under room temperature conditions is measured in the range of $200 - 500 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$ [14, 20, 41]. However, by using HfO_2 , a material that has a high κ , the room temperature mobility of single layer MoS_2 can be increased to around $200 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$. In addition, this device showed a current on/off ratio near 10^8 [44]. Here on/off ratio is referring to the ratio of value of current needed for the device to be considered switched on as compared to the value of current needed for the device to be considered switched off. The reported mobility of monolayer MoS_2 is much lower than that of graphene or Si [28]. This fact presents a problem for use in high-performance applications that could limit the use of MoS_2 to low power devices.

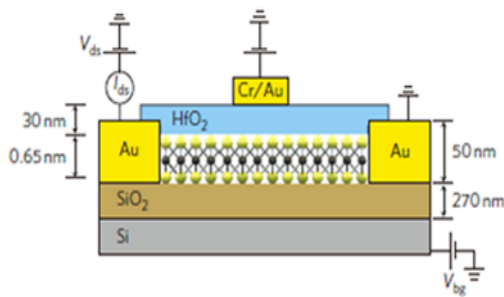


FIG. 7. A cross-sectional view of the monolayer MoS₂ FET of thickness 6.5 Å. The monolayer is separated from the top gate by 30 nm of HfO₂ [58].

VI. CONCLUSIONS AND FUTURE WORK

The field of condensed matter physics as it pertains to two-dimensional materials has grown rapidly in the previous years. Graphene offers some potential applications based upon its unique properties. However,

the lack of a band gap led researchers to search for other materials that would allow the devices it comprised to be switched on and off. This, in part, renewed research in TMDs, and among them MoS₂, which had previously been studied to some extent.

MoS₂ has an electronic structure that is interesting, the band gap for few-layer MoS₂ is indirect and the band gap increases and becomes a direct band gap for monolayer MoS₂. In addition, MoS₂ exhibits high current on/off ratios. The presence of a relatively large band gap and a high current on/off ratio led to the study of MoS₂ as a material in FET channels.

To date, there is much ongoing research that looks to address some of problems that still remain in the study of MoS₂ as a two-dimensional material and its applications. One such problem that needs to be addressed in the coming years is improvements in mobility. The low mobility measurements in MoS₂ FETs are limits to the applications such FETs can be used for. Theoretical predictions show that mobility could still be improved significantly [25]. Much of the challenge in this problem lies in decreasing the scattering.

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- [1] Deji Akinwande, Nicholas Petron, and James Hone. Two-dimensional flexible nanoelectronics. *Nature Communications*, 5, 2014.
 - [2] Tsuneya Ando, Alan B. Fowler, and Frank Stern. Electronic properties of two-dimensional systems. *Rev. Mod. Phys.*, 54:437–672, Apr 1982.
 - [3] Ray H. Baughman, Anvar A. Zakhidov, and Walt A. de Heer. Carbon nanotubes—the route toward applications. *Science*, 297(5582):787–792, 2002.
 - [4] Simone Bertolazzi, Jacopo Brivio, and Andras Kis. Stretching and breaking of ultrathin mos2. *ACS Nano*, 5(12):9703–9709, 2011. PMID: 22087740.
 - [5] Sheneve Z. Butler, Shawna M. Hollen, Linyou Cao, Yi Cui, Jay A. Gupta, Humberto R. Gutierrez, Tony F. Heinz, Seung Sae Hong, Jiaying Huang, Ariel F. Ismach, Ezekiel Johnston-Halperin, Masaru Kuno, Vladimir V. Plashnitsa, Richard D. Robinson, Rodney S. Ruoff, Sayeef Salahuddin, Jie Shan, Li Shi, Michael G. Spencer, Mauricio Terrones, Wolfgang Windl, and Joshua E. Goldberg. Progress, challenges, and opportunities in two-dimensional materials beyond graphene. *ACS Nano*, 7(4):2898–2926, 2013. PMID: 23464873.
 - [6] S. Cahangirov, M. Topsakal, E. Aktürk, H. Şahin, and S. Ciraci. Two- and one-dimensional honeycomb structures of silicon and germanium. *Phys. Rev. Lett.*, 102:236804, Jun 2009.
 - [7] A Castellanos-Gomez, N Agrat, and G Rubio-Bollinger. Optical identification of atomically thin dichalcogenide crystals. *Applied Physics Letters*, 96(21):–, 2010.
 - [8] A. Castellanos-Gomez, M. Poot, G. Steele, H.S.J. van der Zant, N. Agrait, and G. Rubio-Bollinger. Elastic properties of freely suspended mos2 nanosheets. *Adv. Mater.*, 24:772–775, 2012.
 - [9] A. Dargys and J. Kundrotas. *Handbook on physical properties of Ge, Si, GaAs, InP*. Science and Encyclopedia Publishers, Vilnius, Lithuania, 1994.
 - [10] C.D. Dimitrakopoulos and D.J. Masearo. Organic thin-film transistors: A review of recent advances. *IBM Journal of Research and Development*, 45(1):11–27, Jan 2001.
 - [11] M. S. Dresselhaus and G. Dresselhaus. Intercalation compounds of graphite. *Advances in Physics*, 51(1):1–186, 2002.
 - [12] X. Du, I. Skachko, A. Barker, and E.Y. Andrei. Approaching ballistic transport in suspended graphene. *Nature Nanotech.*, 3:491–495, 2008.
 - [13] T.J. Echtermeyer, L. Britnell, P.K. Jasnós, A. Lombardo, R.V. Gorbachev, A.N. Grigorenko, A.K. Geim, A.C. Ferrari, and K.S. Novoselov. Strong plasmonic enhancement of photovoltage in graphene. *Nat. Commun.*, 2:458, 2011.
 - [14] R. Fivaz and E. Mooser. Mobility of charge carriers in semiconducting layer structures. *Phys. Rev.*, 163:743–755, Nov 1967.
 - [15] E. Fortin and W.M. Sears. Photovoltaic effect and optical absorption in mos2. *Journal of Physics and Chemistry of Solids*, 43:881–884, 1982.
 - [16] R. F. Frindt and A. D. Yoffe. Physical properties of layer structures: Optical properties and photoconductivity of thin crystals of molybdenum disulphide. *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 273(1352):69–83, 1963.
 - [17] F. R. Gamble and B. G. Silbernagel. Anisotropy of the proton spinlattice relaxation time in the superconducting intercalation complex tas2(nh3): Structural and bonding implications. *The Journal of Chemical Physics*,

- 63(6):2544–2552, 1975.
- [18] A.K. Geim and I.V. Grigorieva. van der waals heterostructures. *Nature*, 499:419–425, 2013.
 - [19] James M. Gere and 1878-1972 Timoshenko, Stephen P. *Mechanics of materials*. Boston PWS Pub Co, 4th ed edition, 1997. Includes indexes.
 - [20] Subhamoy Ghatak, Atindra Nath Pal, and Arindam Ghosh. Nature of electronic states in atomically thin mos2 field-effect transistors. *ACS Nano*, 5(10):7707–7712, 2011. PMID: 21902203.
 - [21] A. K. Giem and K. S. Novoselov. The rise of graphene. *Nature Materials*, 6:183–191, 2007.
 - [22] E. Gourmelon, O. Lignier, H. Hadouda, G. Couturier, J.C. Bernede, J. Teddb, J. Pouzeta, and J. Salardenneb. Ms2 (m = mo, w) photosensitive thin films for solar cells. *Solar Energy Materials and Solar Cells*, 46:115–121, 1997.
 - [23] P. Hohenberg and W. Kohn. Inhomogeneous Electron Gas. *Physical Review*, 136:864–871, nov 1964.
 - [24] Sumio Iijima. Helical microtubules of graphitic carbon. *Nature*, 354:56–58, 1991.
 - [25] Kristen Kaasbjerg, Kristian S. Thygesen, and Antti-Pekka Jauho. Acoustic phonon limited mobility in two-dimensional semiconductors: Deformation potential and piezoelectric scattering in monolayer mos₂ from first principles. *Phys. Rev. B*, 87:235312, Jun 2013.
 - [26] D. Kahng and M. Atalla. Us patents 3206670 and 3102230, 1960.
 - [27] K. Kam and B.A. Parkinson. Detailed photocurrent spectroscopy of the semiconducting group-vi transition-metal dichalcogenides. *J. Phys. Chem.*, 86:463–467, 1982.
 - [28] Kinam Kim, Jae-Young Choi, Taek Kim, Seong-Ho Cho, and Hyun-Jong Chung. A role for graphene in silicon-based semiconductor devices, 2011.
 - [29] H. W. Kroto, J. R. Heath, S. C. O’Brien, R. F. Curl, and R. E. Smalley. C₆₀: Buckminsterfullerene. *Nature*, 318:162–163, 1985.
 - [30] Murong Lang, Liang He, Faxian Xiu, Xinxin Yu, Jianshi Tang, Yong Wang, Xufeng Kou, Wanjun Jiang, Alexei V. Fedorov, and Kang L. Wang. Revelation of topological surface states in bi₂se₃ thin films by in situ al passivation. *ACS Nano*, 6(1):295–302, 2012. PMID: 22147687.
 - [31] Dominik Lembke, Simone Bertolazzi, and Andras Kis. Single-layer mos2 electronics. *Accounts of Chemical Research*, 48(1):100–110, 2015. PMID: 25555202.
 - [32] Hai Li, Jumiati Wu, Zongyou Yin, and Hua Zhang. Preparation and applications of mechanically exfoliated single-layer and multilayer mos2 and wse2 nanosheets. *Accounts of Chemical Research*, 47(4):1067–1075, 2014. PMID: 24697842.
 - [33] T. Li and G. Galli. Electronic properteis of mos2 nanoparticles. *J. Phys. Chem. C*, 111:3042–3047, 2007.
 - [34] J.E. Lilienfeld. Us patent 174175, 1925.
 - [35] Kin Fai Mak, Changgu Lee, James Hone, Jie Shan, and Tony F. Heinz. Atomically thin mos₂: A new direct-gap semiconductor. *Phys. Rev. Lett.*, 105:136805, Sep 2010.
 - [36] Ruben Mas-Balleste, Cristina Gomez-Navarro, Julio Gomez-Herrero, and Felix Zamora. 2d materials: to graphene and beyond. *Nanoscale*, 3:20–30, 2011.
 - [37] L. F. Mattheiss. Band structures of transition-metal-dichalcogenide layer compounds. *Phys. Rev. B*, 8:3719–3740, Oct 1973.
 - [38] J. Millman and C.C. Halkias. *Electronic devices and circuits*. McGraw-Hill, New Delhi, 1991.
 - [39] G. Moore. Cramming more components onto integrated circuits. *Electronics*, 38(8), 1965.
 - [40] K. S. Novoselov, A. K. Geim, S. V. Morozov, D. Jiang, Y. Zhang, S. V. Dubonos, I. V. Grigorieva, and A. A. Firsov. Electric field effect in atomically thin carbon films. *Science*, 306(5696):666–669, 2004.
 - [41] K. S. Novoselov, D. Jiang, F. Schedin, T. J. Booth, V. V. Khotkevich, S. V. Morozov, and A. K. Geim. Two-dimensional atomic crystals. *Proceedings of the National Academy of Sciences of the United States of America*, 102(30):10451–10453, 2005.
 - [42] K.S. Novoselov, A. K. Geim, S.V. Morozov, D. Jiang, M.I. Katsnelson, I.V. Grigorieva, S.V. Dubonos, and A.A. Firsov. Two-dimensional gas of massless dirac fermions in graphene. *Nature*, 438:197–200, 2005.
 - [43] K.S. Novoselov and A.K. Geim. The rise of graphene. *Nature Materials*, 6:183–191, 2007.
 - [44] B. Radisavljevic, A. Radenovic, J. Brivio, V. Giacometti, and A. Kis. Single-layer mos2 transistors. *Nat. Nano.*, 6:147–150, 2011.
 - [45] B K Ridley. The electron-phonon interaction in quasi-two-dimensional semiconductor quantum-well structures. *Journal of Physics C: Solid State Physics*, 15(28):5899, 1982.
 - [46] Max Schulz. The end of the road for silicon? *Nature*, 399:729–730, 1999.
 - [47] O. A. Shenderova, V. V. Zhirnov, and D. W. Brenner. Carbon nanostructures. *Critical Reviews in Solid State and Materials Sciences*, 27(3-4):227–356, 2002.
 - [48] M. Spittel and T. Spittel. 4.2 young’s modulus of steel. In H. Warlimont, editor, *Metal Forming Data of Ferrous Alloys - deformation behaviour*, volume 2C1 of *Landolt-Brnstein - Group VIII Advanced Materials and Technologies*, pages 85–88. Springer Berlin Heidelberg, 2009.
 - [49] Andrea Splendiani, Liang Sun, Yuanbo Zhang, Tianshu Li, Jonghwan Kim, Chi-Yung Chim, Giulia Galli, and Feng Wang. Emerging photoluminescence in monolayer mos2. *Nano Letters*, 10(4):1271–1275, 2010. PMID: 20229981.
 - [50] Kyoazaburo Takeda and Kenji Shiraishi. Theoretical possibility of stage corrugation in si and ge analogs of graphite. *Phys. Rev. B*, 50:14916–14922, Nov 1994.
 - [51] P. R. Wallace. The band theory of graphite. *Phys. Rev.*, 71:622–634, May 1947.
 - [52] Feng Wang, Yuanbo Zhang, Chuanshan Tian, Caglar Girit, Alex Zettl, Michael Crommie, and Y. Ron Shen. Gate-variable optical transitions in graphene. *Science*, 320(5873):206–209, 2008.
 - [53] Qing Hua Wang, Kourosh Kalantar-Zadeh, Andras Kis, Jonathan N. Coleman, and Michael S. Strano. Electronics and optoelectronics of two-dimensional transition metal dichalcogenides. *Nature Nanotechnology*, 7:699–712, 2012.
 - [54] J. R. Williams, L. DiCarlo, and C. M. Marcus. Quantum hall effect in a gate-controlled p-n junction of graphene. *Science*, 317(5838):638–641, 2007.
 - [55] J.A. Wilson and A.D. Yoffe. The transition metal dichalcogenides discussion and interpretation of the observed optical, electrical and structural properties. *Advances in Physics*, 18(73):193–335, 1969.
 - [56] F.N. Xia, T. Mueller, Y.M. Lin, A. Valdes-Garcia, and P. Avouris. Ultrafast graphene photodetector. *Nat. Nanotechnol.*, 4:839–843, 2009.

- [57] Wenjie Xie, Xinfeng Tang, Yonggao Yan, Qingjie Zhang, and Terry M. Tritt. Unique nanostructures and enhanced thermoelectric performance of melt-spun bisbte alloys. *Applied Physics Letters*, 94(10):-, 2009.
- [58] Mingsheng Xu, Tao Liang, Minmin Shi, and Hongzheng Chen. Graphene-like two-dimensional materials. *Chemical Reviews*, 113(5):3766–3798, 2013. PMID: 23286380.
- [59] Hong Bin Zhang, Hai Lin Yu, Ding Hua Bao, Shu Wei Li, Cheng Xin Wang, and Guo Wei Yang. Magnetoresistance switch effect of a sn-doped bi₂te₃ topological insulator. *Advanced Materials*, 24(1):132–136, 2012.
- [60] L. Zhang, Y. Zhang, J. Camacho, M. Khodas, and I. Zaloznyak. The experimental observation of quantum hall effect of l=3 chiral quasiparticles in trilayer graphene. *Nat. Phys.*, 7:953–957, 2011.