

Applications of MoS₂ as a Two-Dimensional Material Beyond Graphene

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An article usually includes an abstract, a concise summary of the work covered at length in the main body of the article.

I. INTRODUCTION

II. GRAPHENE AS A NEW TWO-DIMENSIONAL MATERIAL

A. The Discovery of Graphene

By the end of the last century microelectronics had revolutionized the world, the majority 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 [13, 16, 27]. A decade after the first device, 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 [20, 27]. This 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 [27]. 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 before. The search for alternatives to silicon resulted in research into many new, nontraditional materials. Several notable examples are organic conductors and carbon nanotubes [1, 3]. Arguably one of the most interesting nontraditional materials to come out of such research was graphene.

In 1985, with the discovery of fullerenes the amount of known carbon allotropes increased [14, 18]. Fullerenes

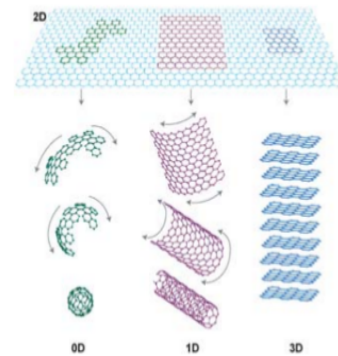


FIG. 1. Graphene can be envisioned in several dimensions. 0-dimensional buckyballs, 1-dimensional nanotubes, or 3-dimensional graphite [24].

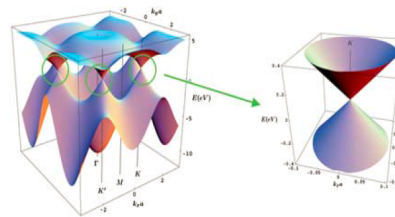


FIG. 2. 3D representation of the electronic band structure of graphene. The right side shows an enlarged view near the Fermi level in one k point [18].

suggested the existence of a one-dimensional form of carbon, known as carbon nanotubes, which were first demonstrated in 1991 [12]. 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 [21, 22]. 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 several carbon-based materials (graphite, fullerenes, nanotubes, etc..., see Fig.1) [4, 21, 28]. 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 [18].

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B. 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 properties are primarily a result of its low dimensionality and its band structure that allow electrons to mimic relativistic particles [10]. 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 [23, 33, 39]. However, it is worth noting that this peculiar band structure can be modified by stacking three or more layers of graphene [18].

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 [18, 31]. As a result graphene has no band gap (small band gaps of a few hundred MeV can be introduced in bilayer graphene) [37]. The absence of a band gap is also interesting in the context of the material's optical properties and the implications of these. 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 [5, 32, 35]. Due to the material's thickness...

III. TRANSITION METAL DICHALCOGENIDES

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) [19, 34]. 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 [37]. The material is dependent on the combination of transition metal, typically one of: Mo, W, Nb, Re, Ni, or V, and chalcogen, typically one of: S, Se, or Te [34]. 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) [37]. 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 [9, 15, 36, 38]. Ongoing research also includes graphene-like nano materials like silicene and germanene, which are the silicon and germanium-based versions of graphene and are found to show properties that are simi-

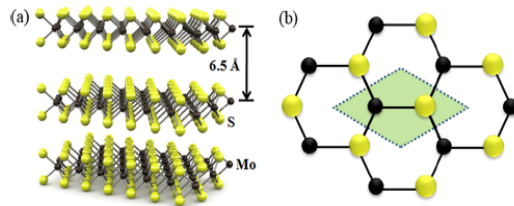


FIG. 3. (a) The atomic structure of layered MoS_2 . Different sheets are composed of three atomic layers S-Mo-S, where Mo and S are covalently bonded [25, 37]. (b) Top view of the honeycomb lattice [37].

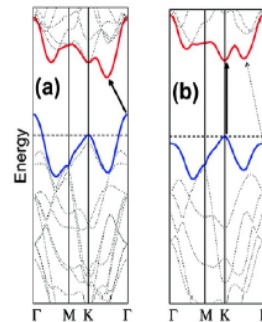


FIG. 4. Calculated band structures of bulk (a) and monolayer (b) MoS_2 and the arrows indicate the lowest energy transition [29].

lar to graphene [2, 30]. These two-dimensional materials are becoming increasingly attractive for a wide-range of applications due to their distinct properties.

A. Properties of MoS_2

As discussed in sec. II B, 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 them ideal candidates for electronic material applications [37]. One such example of a semiconducting TMD is MoS_2 (molybdenum disulphide). TMDs, and more specifically MoS_2 and the properties it exhibits have been studied to some extent for several decades with electrical measurements dating back to the 1960s [6, 8]. However, as of late there has been renewed interest in several TMDs and their potential applications.

sheet	theoretical E_{gap}	experimental E_{gap}
graphene	0	0
bilayer graphene	0	0
monolayer MoS ₂ ^a	1.9 [7]	1.9 [7]
bulk MoS ₂	1.2 [11, 17]	1.0-1.29 [11, 17]

^a Bilayer MoS₂ is an indirect band gap semiconductor [26]

TABLE I. Table of energies for monolayer and bilayer graphene and monolayer and bulk MoS₂ given in units of eV. Table adapted from table in [37].

IV. SYNTHESIS METHODS

V. APPLICATIONS OF MOS₂

VI. STATE OF THE ART

VII. PROBLEMS AND OUTLOOK

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