# Nano-electro-mechanical-systems (NEMS) and Energy-efficient Electronics and The Emergence of Two-dimensional Layered Materials Beyond Graphene

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## ABSTRACT

Carbon-based nanomaterials such as graphene, a layered two-dimensional (2D) crystal, carbon nanotubes and carbon nanofibers have been explored extensively by researchers as well as the semiconductor industry as viable alternatives to silicon-based complimentary metal-oxide semiconductor transistors. Besides nanoscale transistors, the exceptional properties of carbon-based nanomaterials has stirred intense interest in considering these materials for applications ranging from interconnects, field-emission displays, photo-voltaics and nano-electro-mechanical-systems (NEMS). Recently, the emergence of other layered 2D crystals where the bonding between layers is held together by the weak van der Waals interaction, has opened up new avenues of research and exploration. Such material systems display a diverse array of properties ranging from insulating hexagonal-BN, metallic $NbS_2$ to semiconducting $MoS_2$. The ability to engineer the materials properties in these 2D layered materials provides promising prospects for their use in a wide variety of applications ranging from electronics, photonics, sensing, energy harvesting, flexible electronics and related applications over the coming years.

## 1. INTRODUCTION

The semiconductor industry based on complementary metal-oxide-semiconductor (CMOS) Silicon (Si) transistors faces major obstacles to continued scaling according to Moore's law. Such performance limitations arise from physical scaling limits with gate dielectrics that are 1 - 2 (nm) in thickness, as well as source-drain channel lengths which will soon approach 10 nm by 2016. New materials and novel logic devices are thus vigorously being explored beyond Si, in order to overcome performance limitation issues that are now impeding Si transistor scaling [1]. Among these materials, carbon-based nanostructures are gaining increasing attention from the semiconductor industry as viable alternatives to traditional materials used in the Si integrated-circuit (IC) industry. Such materials include the exploration of carbon nanotubes (CNTs), carbon nanofibers (CNFs), Y-junctions, graphene and graphene nanoribbons (GNRs), which either enable new device functionality or enhance the performance of established architectures in electronics. Besides transistor applications [2,3,4], the remarkable properties of carbon-based nanostructures [5] has stirred intense interest in considering these materials for a variety of other applications ranging from rf electronics [6,7], interconnects [8], ultra-capacitors [9], biosensors [10], stretchable electronics [11], thermo-electrics [12], photo-voltaics [13,14], optical applications and plasmonics [15,16], as well as nano-electro-mechanical-systems (NEMS) [17,18,19,20,21] given their remarkable mechanical properties [22,23,24].

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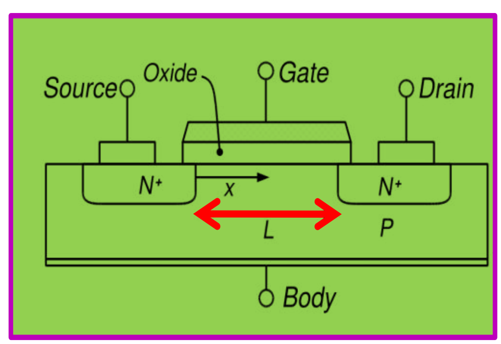
While over the past several decades, scaling in semiconductor transistors has enabled enhancement in performance of CMOS by increasing switching speed, density, functionality and cost, it is anticipated that further miniaturization will soon create performance limitations in these devices as mentioned. New materials and technologies are thus vigorously being explored beyond Si, in order to overcome performance limitations from ultra-miniaturized Si-CMOS [25] to enable more energy-efficient green electronics. This paper presents a discussion for the need for energy-efficient electronics which are under consideration for enabling green transistors that exhibit a steep sub-threshold switching characteristic; in this context nano-electro-mechanical-systems (NEMS) [26] are discussed for the realization of low-power, energy-efficient green transistors, with a particular emphasis on the role of carbon-based nanomaterials in such systems. Amongst the carbon-based systems, graphene, a 2D-layered material, has been widely explored for nanoelectronics and related applications. The emergence of other 2D-layered materials beyond graphene is discussed in the latter part of the paper. The field of 2D-layered materials beyond graphene is poised to open up new avenues for research and exploration in the coming years which can enable exciting applications in electronics, photonics, sensing, energy and flexible electronics applications.

## 2. Nano-electro-mechanical-systems (NEMS) for Energy-efficient Electronics

The pervasive use of computer systems, either in large information technology (IT) data centers or portable devices, is a leading contributor to global energy usage and the growing carbon footprint [27]. Analysis shows that efficient use of energy in the IT industry, as in server farms shown in Fig. 1a, is expected to reduce green house gas emissions by 30% / year, which will amount to more than $300 billion in energy savings. In order to realize this saving, it is important to increase the efficiency of computer systems by developing low-power and energy-efficient green transistors for enabling green computing or green electronics which can ultimately increase energy savings [28]. Shown in Fig. 1b is a CMOS transistor and with continued scaling of the channel length $L$ to dimensions as low as 10 nm by 2016, and gate oxide thickness ~ 1 nm, conventional CMOS is inherently an energy inefficient device at nanoscale dimensions. Both tunneling transistors and NEMS are being proposed for enabling energy efficient green transistors due to their abrupt switching transitions; here we discuss the use of NEMS in more detail.

(a)

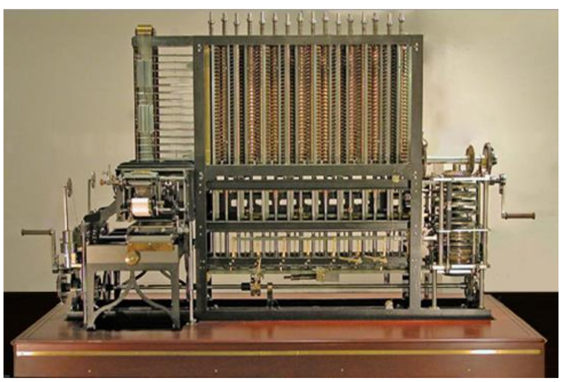


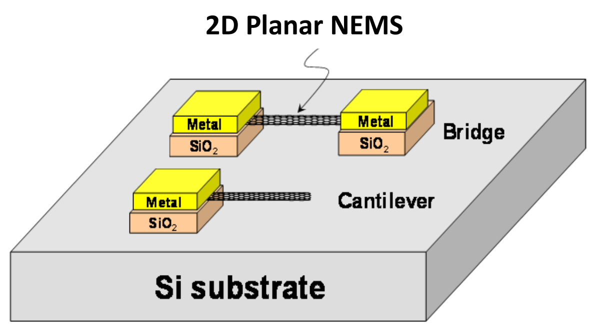

(b)

Figure 1. (a) Large server farms in the IT industry consume a significant amount of energy. (b) CMOS transistor structure where the decreasing channel lengths $L$ and oxide thickness are contributing to the degraded performance and energy inefficiency. The energy efficiency at the device level directly translates to energy efficiency at the system level in large server farms.

NEMS are another class of devices which have the potential to enable low-power, energy efficient, green switching devices that exhibit abrupt switching transitions with steep sub threshold characteristics. The idea of using mechanical components for computation dates back to the 1800s when Charles Babbage proposed the difference engine which occupied a table top as depicted in Fig. 2a. While the idea of mechanical computation is being revisited two centuries later, the dimensions of the components are now far smaller, in the nanoscale regime. The mechanical construct of NEMS devices indicates that they offer near zero leakage characteristics [29]. In particular, carbon-based materials are extremely attractive for NEMS since they offer the potential for ultra-high switching speeds due to their ultra-high elastic modulus (> 1TPa) and which far exceeds Si [18,20,23,24]. NEMS devices also have the potential to operate in high temperature and highly radiating environments unlike solid-state CMOS transistors which are inherently susceptible to radiation. Shown in Fig. 2b are two commonly explored 2D planar NEMS architectures, the bridge and cantilever. NEMS have been shown to have an abrupt switching transition with a sub threshold swing approaching 2 mV/decade, unlike nanoscale CMOS which can exceed 90 mV/decade depending on the operating conditions of the transistor.

The challenges with NEMS lie in reducing the pull-in voltage and to increase the low ON-state current. In addition, the reliability of such devices also needs to be increased by eliminating stiction issues that are commonly seen in these devices.

(a) 



(b)

Figure 2. (a) The difference engine is depicted here where Charles Babbage proposed the idea of using mechanical components for computation as early as the 1800's. (b) In the nanoscale regime, nano-mechanical relays or NEMS are being considered as alternative approaches to electronic computation. The bridge and cantilever architectures have been commonly explored for 2D planar NEMS.

## 3. Graphene and Other 2D-layered Materials for Device Applications

Although great strides have been made recently for applications of graphene that have stemmed from its unique electrical, mechanical and optical properties, the absence of an intrinsic band-gap in pristine graphene poses concerns for its attractiveness in electronics applications, specifically digital electronics, where high ON/OFF ratios are desired. While a band-gap in graphene is induced through quantum confinement by creating graphene nanoribbons (GNRs) [30], chemical functionalization [31], and through the application of an electric field in bilayer graphene [32], the band gaps nonetheless are small (few hundred meV); in the case of GNRs, it is challenging to maintain pristine edge chirality due to defects that are induced during nanofabrication of the ribbons. The methods used to induce a band-gap in graphene also reduces the mobilities that pristine graphene has to offer. Recently, layered 2D crystals of other materials similar to graphene have been realized which include the transition metal di-chalcogenides, transition metal oxides and other 2D compounds such as insulating hexagonal-BN, $Bi_2Te_3$ and $Bi_2Se_3$. These 2D crystals exhibit a diverse spectrum of properties; for example, $NbS_2$ is metallic while $MoS_2$ is semiconducting with an intrinsic band gap unlike graphene. The transition metal di-chalcogenides consist of hexagonal layers of metal M atoms sandwiched between two layers of chalcogen atoms X with stoichiometry $MX_2$ as shown in Fig. 3 for the case of $MoS_2$ (M = Mo, X = S). As with transition metal di-chalcogenides in general, the interatomic binding in $MoS_2$ is strong arising from the covalent in-plane bonding but the subsequent layers interact through the weaker van der Waals interlayer forces.

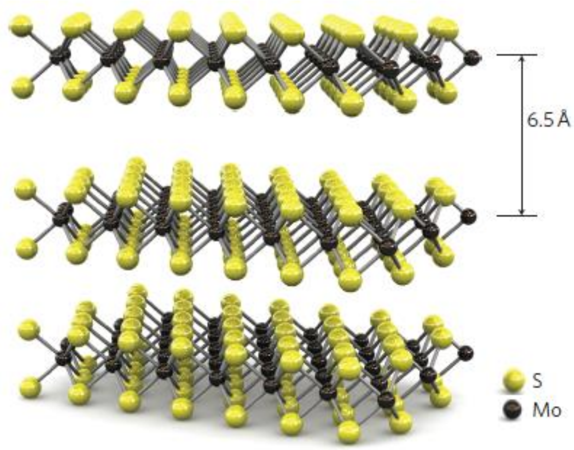



Figure 3. Crystalline structure of layered $MoS_2$ where the Mo atom is sandwiched between the S atoms. The interlayer bonding occurs via the weak van der Waals interaction. Unlike graphene, monolayers of $MoS_2$ exhibit a large band-gap ~ 1.8eV and it is also a direct-band gap semiconductor.

Depending on the combination of the transition metal atom and the chalcogen (S, Se or Te), a wide variety of transition metal di-chalcogenides are possible, as illustrated in Fig. 4, each offering a unique set of properties. The coordination and oxidation state of the metal atoms determines whether the transition metal di-chalcogenide will be metallic, semi metallic or semiconducting. Superconductivity and charge density wave effects have also been observed in some transition metal di-chalcogenides. Besides the transition metal dichalcogenides, the chalcogenides of group III (GaSe, GaTe, InSe), group IV (GeS, GeSe, SnS, SnSe, etc.) and group V ($Bi_2Se_3$, $Bi_2Te_3$) also show a graphite like layered structure and offer promise in electronics, photonics and energy harvesting.

Recently, it has been shown that bulk $MoS_2$ films are indirect band-gap semiconductors with a band gap of ~1.2 eV and a transformation takes place to a direct band gap semiconductor with a gap of ~1.8 eV for single-layers. Already, the device applications of such systems show promising characteristics; for example transistors derived from 2D monolayers of $MoS_2$ show ON/OFF ratios many orders of magnitude larger than the best graphene transistors at room temperature, with comparable mobilities [33]. The intrinsic band gap in these layered materials can be tuned depending on the choice of materials and implies possible applications in photonics, sensing and energy harvesting. The field of 2D materials beyond graphene is likely to grow at a rapid pace in the near future and while the many device applications that have emerged recently have been reported for mechanically exfoliated layers, progress in the nanomanufacturable synthesis of these materials will prove to be a key factor for propelling this field forward in the coming years.

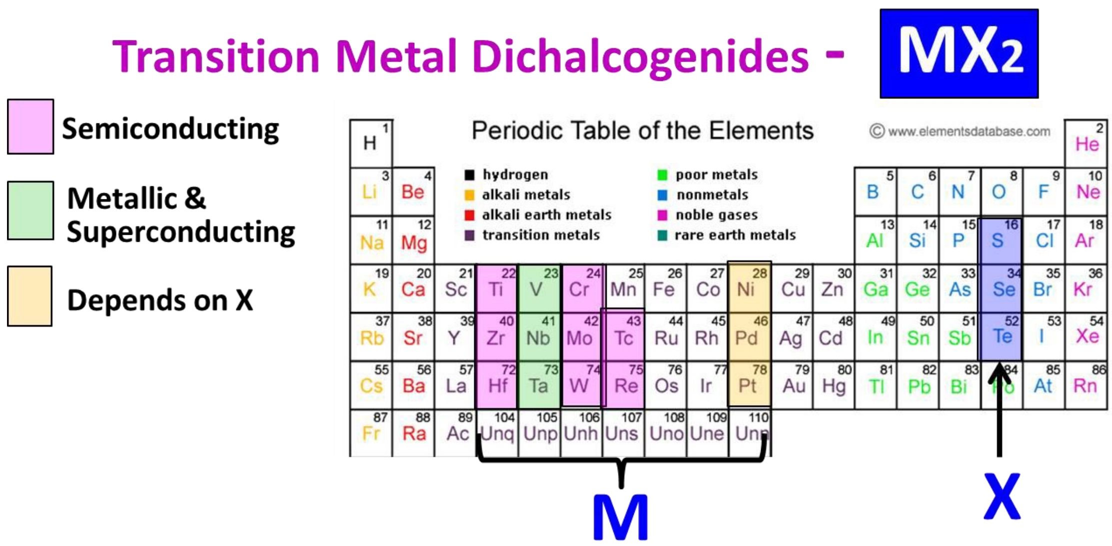



Figure 4. The transition metal di-chalcogenides are an example of 2D layered materials. Depending on the combination of the transition metal M, and the chalcogen atom X (S, Se, Te), a wide range of properties can arise.

Given the tunable, direct band gaps of some of the 2D TMDCs and their relative earth abundance, they appear to be a promising choice for solar cells or light-absorbing components, photo detectors, in addition to light-emitting devices. Also, given the thinness of these materials, the devices could be made transparent, light and flexible, and could provide an alternative choice to organic semiconductors, given their degradation at ambient conditions. For flexible and transparent optoelectronics applications such as displays and wearable electronics, materials such as conductors, semiconductors, optical absorbers, light emitters and dielectrics are desired. Semiconducting 2D TMDCs, combined with other 2D materials such as conducting graphene and insulating BN, can enable 2D electronic circuits to be fabricated on flexible substrates. In addition, the mechanical properties of $MoS_2$ also appear to be very attractive; it has been found to be 30 times as strong as steel and can tolerate deformations of up to 11% before breaking [34]. Such mechanical properties makes $MoS_2$ one of the strongest semiconducting materials and very attractive for flexible electronics applications.

## 4. Summary

An overview of carbon-based nanomaterials was provided and the role they play in enabling energy-efficient green electronics, with particular emphasis given to NEMS. Other 2D layered materials similar to graphene were also introduced, but some of these materials such as $MoS_2$ have an intrinsic band-gap unlike pristine graphene. In general, the 2D layered material systems exhibit a diverse array of properties which have promise in enabling applications in electronics, photonics, sensing, energy harvesting and flexible electronics in the near future.

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*Any opinion, findings, and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the National Science Foundation.*

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