LARGE AREA CVD GROWTH AND CHARACTERIZATION OF MoS_2 LAYERS AND THE EFFECT OF GAMMA IRRADIATION ON ITS PROPERTIES

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by

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Submitted
in fulfilment of the requirements of the degree of Doctor of Philosophy
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Dedicated to my parents for their unconditional love and support

Certificate

This is to certify that the thesis entitled **Large area CVD growth and characterization of MoS_2 layers and the effect of gamma irradiation on its properties** being submitted by **Mr. Aditya Singh** to **Indian Institute of Technology Delhi** for the award of the degree of **Doctor of Philosophy** is a record of bonafide research work carried out by him. He has worked under my guidance and supervision, and has fulfilled the requirements, which to our knowledge have reached the requisite standard for the submission of the thesis. The results contained in this thesis have not been submitted in part or full to any other University or Institute for the award of any degree or diploma.

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"Your assumptions are your windows on the world. Scrub them off every once in a while, or the light won't come in." — Isaac Asimov

Aditya Singh

Abstract

Two-dimensional (2D) materials, namely graphene, hexagonal boron nitride (hBN), and transition metal dichalcogenides (TMDs), have gained incredible attention due to their unique optical, electrical, and mechanical properties. Graphene being a zero bandgap 2D-material, has limited applications in opto-electronics devices [1]. Possible ideal materials for replacement of graphene in the future optoelectronics are TMDs, depicted by MX_2, where M and X are transition metal (Mo, W, Nb, Ti, etc.) and chalcogen (S, Se and Te), respectively, e.g., MoS_2, $MoSe_2$, $MoTe_2$, etc [2]. In MX_2 type TMDs, a transition from an indirect bandgap to a direct bandgap has been observed as a number of layers decrease due to the quantum confinement effect [2] [3] [4]. Molybdenum disulfide (MoS_2), a member of the TMDs family, has been widely explored due to tunability of bandgap (1.3 eV in bulk and 1.8 eV in monolayer) [4], high elastic modulus (∼170 N/m) [5], high on/off ratio (∼10^8) [6], high carrier mobility (40-480 cm^2/V-s) [7] and lack of short channel effect [7], which makes it appropriate for application in flexible devices [5] [7], photodetectors [8] [9] [10] [11], field-effect transistors [7] [12] [13], space applications [14] [15], gas sensors [16], neuromorphic computing [17] [18] [19], biomimetic sensing [18] [19], etc.

There are various methods to synthesize TMDs, but powder-based chemical vapor deposition (CVD) has shown the potential to produce high-quality films at a lower cost. Synthesis of MoS_2 by CVD has already been reported, but there were several lackings where significant improvements in growth were required to utilize full potential of MoS_2 film. Precise control over precursors, temperature, substrate and boundary layer is paramount to achieve desired CVD growth of MoS_2, but, unfortunately, these issues were not addressed adequately. Most of the reported work was focused and limited to low-pressure and high-temperature CVD, SiO_2/Si substrate, pre-growth treatment of the substrate, multi-zone CVD furnace, etc. However, these requirements make the growth process expensive, time-taking and less suitable for batch production in industry. In order to overcome some of the aforementioned limitations/challenges, in the first three objectives of the thesis, we addressed various questions and limitations like which precursors are best for CVD 1L-MoS_2, reducing the growth temperature, extending CVD of 1L-MoS_2 on different types of substrates, low-temperature large-area growth of MoS_2 without do-

ing pre-growth treatment of substrates and understanding the role of the concentration boundary layer, etc.

Initial work primarily focused on finding the best-suited molybdenum (Mo) source precursor for high-quality CVD of 1L-MoS_2 and lowering the growth temperature. We did a quantitative comparison of CVD synthesis of MoS_2 on SiO_2/Si substrate using three different precursors/growth promoters viz., molybdenum trioxide (MoO_3), ammonium heptamolybdate (AHM) and tellurium (Te). A strategy based on growth temperature and the ratio of precursors was developed to control the thickness and growth area of MoS_2 flakes systematically. Highly crystalline large-sized 1L-MoS_2 flakes were obtained at S to MoO_3 particles ratio of ∼30:1. Furthermore, using Raman spectroscopy, we proposed a three-step chemical reaction mechanism for the evolution of MoS_2 from MoO_3 micro-crystals. Our findings showed that for large-sized crystalline 1L-MoS_2 flakes, MoO_3 is a better choice than AHM and Te-assisted synthesis. Finally, with the introduction of Te, MoS_2 growth temperature was lowered down by ∼250°C, and monolayer and bulk MoS_2 flakes were obtained.

To reduce the cost of CVD synthesis, there was a pressing need to lower the growth temperature and achieve TMD growth over various substrates for different device applications. So, our second objective was the low-temperature synthesis of high-quality 1L-MoS_2 films over different substrates, particularly flexible mica. But Te-assisted growth was limited to SiO_2/Si only and over mica, Te-assisted growth produced bulk MoS_2 only. So, we replaced Te with sodium chloride (NaCl), which is very cheap compare to Te. NaCl-assisted growth of 1L-MoS_2 films and flakes were carried out on amorphous (SiO_2/Si and fused quartz), crystalline (sapphire and silicon) and layered substrates (mica). Significantly, we reduced the growth temperature from ∼ 900 to 650°C, and the crystalline quality of film/flakes was enhanced. 1L-MoS_2 flakes grown over SiO_2/Si and sapphire substrate were large-sized and had sharp edges (up to ∼ 150 μm).

These as-grown 1L-MoS_2 samples were characterized by various techniques, and Raman/PL showed that 1L-MoS_2/sapphire has relatively better optical properties and least structural disorder than 1L-MoS_2 on other substrates. In contrast to large-sized 1L-MoS_2 flakes grown over sapphire, a continuous film of 1L-MoS_2 was observed over the entire mica substrate, attributed to the mica substrate's layered nature, which has facili-

tated the growth. Furthermore, growth mechanism was discussed based on NaCl-assisted formation of the seeding layer of Na_2S and/or Na_2SO_4, which enhanced 2D planar nucleation. The study depicted that the NaCl assisted in forming seeding promoters such as a water-soluble layer of Na_2S and/or Na_2SO_4 on the substrate that helped in 2D planar nucleation of MoS_2. The formation of such intermediate seeding layers also helped in MoS_2 layer transfer owing to its easy water solubility.

After synthesizing high-quality 1L-MoS_2 film/flakes at low-temperature, our next goal was to achieve large-area growth of layered MoS_2, and for that, we developed a novel approach. Controlling the concentration boundary layer formation by tuning separation between the precursors and growing face of the substrate, we can control layer number, growth area coverage and nucleation density easily. So in our third objective, we synthesized high-quality large-area trilayer (3L)-MoS_2 (up to $\approx$ 4 cm^2) at low temperature (650°C) by controlling the concentration boundary layer. The physical and chemical properties of 3L-MoS_2 were analyzed by optical microscopy (OM), Raman spectroscopy, atomic force microscopy (AFM), X-ray photoelectron spectroscopy (XPS), X-ray diffraction (XRD), transmission electron microscopy (TEM), etc. High uniformity and low roughness of large area 3L-MoS_2 were confirmed by Raman scattering and AFM measurements, respectively. UV-vis spectroscopy in reflectance mode was carried to calculate the bandgap of MoS_2 film, and it was found to be 1.7 eV, indicating the trilayer MoS_2. Our as-grown 3L-MoS_2 films were single crystalline as identified by XRD and TEM measurements. We believe that regulated control over concentration boundary can lead to high-quality wafer-scale growth of other TMDs for engineering future nanoelectronics.

After achieving significant improvement in the CVD of MoS_2, we focussed our attention on investigating the properties of as-grown 1L-MoS_2 flakes. Since these 2D-TMDs have a high surface-to-volume ratio and ultra-low thickness, fabricated devices are susceptible to surrounding environments such as air and radiation. This radiation may degrade device performance too. So, understanding the radiation hardness of 2D-TMDC was extremely important for space instrumentations. So, our fourth objective was to study the impact of gamma irradiation on 1L-MoS_2 flakes and corresponding changes in their chemical and structural properties. 1L-MoS_2 flakes on sapphire were irradiated by the Cobalt-60 gamma source ($\sim$1.25 MeV) at various doses (1-1000 kGy) with a dose rate $\sim$3.2 kGy/hr.

We estimated that the temperature of MoS_2 increases by 1.3°C per kGy of gamma-ray dose. It was observed that up to 130 kGy, gamma exposure has no significant impact on the morphology and chemical properties of MoS_2. However, XPS showed that from 275 kGy, MoS_2 started converting into MoO_x. Raman spectroscopy showed that at low gamma doses, the crystallinity of MoS_2 was increased, while at higher doses, a traceable amount of MoS_2 started converting into amorphous MoS_2. Our findings showed that both E^1_{2g} and A_{1g} Raman mode of MoS_2 show a blue shift as gamma irradiation dose increases owing to the combined effect of sulfur vacancies creation and strain caused by thermal expansion of MoS_2.

As graphene (Gr) is an atomically thin material, it has a very high surface-to-volume ratio that makes it prone to the surrounding environment. So to support or encapsulate graphene, we can use various substrates like Si- or Al-based oxides, but unfortunately, it incorporates surface roughness, charged impurities, dangling bonds, which ultimately cause ripples, disorder [20] and doping fluctuations [21] in graphene. Like graphene, TMDs are atomically thin and very flat materials with a high dielectric constant. So, in last thesis work, the idea was to use various TMDs as encapsulating layers for graphene and unravel the behavior of Raman 2D-mode of graphene under various dielectric environments, which ultimately led to understand the smearing of Kohn anomaly near **Γ**- and **K**- points. We used different kinds of mechanically exfoliated verticle heterostructure samples like suspended 1L-WSe_2/Gr, which has four different interesting regions (suspended Gr on the hole, SiO_2/Gr, SiO_2/Gr/WSe_2 and suspended WSe_2/Gr); the second sample was hBN-supported 1L-$MoSe_2$/Gr and the third sample was hBN-capped 1L-$MoSe_2$/Gr.

Raman scattering measurements showed that unlike G-mode (ω_G), Raman 2D-mode (ω_{2D}) of graphene strongly depends upon the dielectric environment and incident photon energy. The higher the dielectric screening for graphene, the lesser the electron-phonon coupling, leading to the blue-shift in ω_{2D}. Dispersion of ω_{2D} increased as incident photon energy were increased. Also, at a particular incident photon energy, as the screening for graphene increases, ω_{2D} upshifts accordingly. Our Raman findings showed that a single layer of TMD is as effective as two layers of monolayer hBN.

सारांश

ग्राफीन, बोरॉन नाइट्राइड और संक्रमण धातु डाई चाल्कोजेनॉइड्स (TMDs) नामक द्विआयामी (2D) पदार्थों ने अपने अद्वितीय प्रकाशिक, वैद्युत और यांत्रिक गुणों के कारण अविश्वसनीय ध्यान आकर्षित किया। ग्राफीन के जीरो ऊर्जा अंतराल द्विआयामी (2D) पदार्थ होने के कारण प्रकाश-इलेक्ट्रॉनिक उपकरणों में सीमित उपयोग हैं **[1]**। भविष्य के प्रकाश-इलेक्ट्रॉनिकी में ग्राफीन के प्रतिस्थापन के लिए TMDs आदर्श पदार्थ हैं, जिन्हें MX_2 द्वारा दर्शाया जाता है। जहाँ M और X क्रमशः संक्रमण धातु (Mo, W, Nb, Ti, आदि) और चालकोजन (S, Se, Te,आदि) हैं ; उदाहरणार्थ: MoS_2, $MoSe_2$, $MoTe_2$, इत्यादि **[2]**। MX_2 प्रकार के TMDs में क्वांटम कन्फ़ाइनमेंट के कारण परतों की संख्या घटने से अप्रत्यक्ष ऊर्जा अंतराल से प्रत्यक्ष ऊर्जा अंतराल में संक्रमण देखा गया है **[2] [3] [4]**। TMDs परिवार के एक सदस्य, मोलिब्डनम डाई सल्फाइड (MoS_2) को ऊर्जा अंतराल की अनुकूलता (बल्क में १.३ इलेक्ट्रान वोल्ट और एक परत में १.८ इलेक्ट्रान वोल्ट) **[4]**, उच्च प्रत्यास्थता मापांक (लगभग १७० न्यूटन प्रति मीटर) **[5]**, उच्च ऑन/ऑफ अनुपात (लगभग $१०^{८}$) **[6]**, उच्च वाहक चालकता (४०-४८० वर्ग सेंटीमीटर प्रति वोल्ट-सेकंड) **[7]** और लघु चैनल प्रभाव **[7]**; जो कि इसे लचीले उपकरण **[5] [7]**, फोटोडिटेक्टर **[8] [9] [10] [11]**, फील्ड इफ़ेक्ट ट्रांजिस्टर **[7] [12] [13]**, अंतरिक्ष उपयोग **[14] [15]**, गैस सेंसर **[16]**, न्यूरोमॉर्फिक गणना **[17] [18] [19]** और बायोमिमेटिक संवेदन **[18] [19]** इत्यादि के लिए उपयुक्त बनाता है।

TMDs को संश्लेषित करने के विभिन्न तरीके हैं, लेकिन पाउडर-आधारित रासायनिक वाष्प निक्षेपण (CVD) ने कम लागत पर उच्च गुणवत्ता वाली फिल्म्स का उत्पादन करने की क्षमता दिखाई है। CVD के द्वारा MoS_2 के संश्लेषण की सूचना पहले ही दी जा चुकी है, लेकिन उनमें कई कमियाँ थीं, जहाँ MoS2 फिल्म की पूर्ण क्षमता का उपयोग करने के लिए उसके विकास में महत्वपूर्ण सुधार की आवश्यकता थी। MoS_2 का CVD के द्वारा वांछित विकास प्राप्त करने के लिए प्रणेता, तापमान, सब्सट्रेट और सीमावर्ती परत पर सटीक नियंत्रण सर्वोपरि है, लेकिन दुर्भाग्यवश इन मुद्दों को पर्याप्त रूप से सम्बोधित नहीं किया गया था। अधिकांश सूचित किये गए कार्य निम्न दाब और उच्च ताप CVD, SiO_2/Si सब्सट्रेट, सब्सट्रेट का

पूर्व-विकास उपचार, बहुक्षेत्रीय CVD भट्टी, इत्यादि, पर केंद्रित और सीमित थे। हालाँकि, ये आवश्यकताएँ विकास प्रक्रिया को महंगा, समय लगने वाला और उद्योग में थोक उत्पादन के लिए अनुपयुक्त बनाती हैं। उपरोक्त वर्णित कुछ सीमाओं/चुनौतिओं को दूर करने के लिए थीसिस के पहले तीन उद्देश्यों में हमने विभिन्न प्रश्नों और सीमाओं को सम्बोधित किया; जैसे कि कौन से प्रणेता एक परत (1L) MoS_2 CVD विकास के लिए सबसे अच्छे हैं, विकास तापमान को कम करने के लिए, विभिन्न प्रकार के सब्सट्रेटों पर 1L- MoS_2 का CVD विस्तार करना, सब्सट्रेट का पूर्व-विकास उपचार किये बिना निम्न ताप पर MoS_2 का व्यापक क्षेत्र पर विकास करना और सीमावर्ती परत सांद्रता की भूमिका समझना इत्यादि।

प्रारंभिक कार्य मुख्य रूप से 1L-MoS_2 के उच्च गुणवत्ता वाले CVD के लिए सबसे उपयुक्त मॉलिब्डेनम (Mo) स्रोत प्रणेता प्राप्त करने और विकास ताप को कम करने पर केंद्रित था। हमने SiO_2/Si सब्सट्रेट पर MoS_2 के संश्लेषण की CVD विकास की परिणात्मक तुलना तीन विभिन्न प्रणेता/विकास प्रवर्तकों मॉलिब्डेनम ट्राईऑक्साइड (MoO_3), अमोनियम हेप्टामॉलीब्डेट (AHM) और टेल्यूरियम (Te) का उपयोग करते हुए की। MoS_2 शल्क की मोटाई और विकास क्षेत्रफल को व्यवस्थित रूप से नियंत्रित करने के लिए विकास तापमान और प्रणेता अनुपात पर आधारित एक रणनीति विकसित की गयी। अत्यधिक क्रिस्टलीय दीर्घाकार 1L-MoS_2 शल्क S और MoO_3 के ३०:१ कण अनुपात पर प्राप्त हुये। इसके आलावा, रमन स्पेक्ट्रोस्कोपी का उपयोग करते हुए हमने MoO_3 सूक्ष्म क्रिस्टल से MoS_2 के विकास के लिए तीन चरणीय रासायनिक अभिक्रिया तंत्र का प्रस्ताव रखा। हमारे अन्वेषण निष्कर्षों से पता चला है कि दीर्घाकार क्रिस्टलीय 1L-MoS_2 शल्क प्राप्त करने के लिए AHM और Te आधारित संश्लेषण कि तुलना में MoO_3 एक अच्छा विकल्प है। अंततः Te के परिचय के साथ MoS_2 का विकास तापमान २५० डिग्री सेंटीग्रेट तक कम कर लिया गया और एक परतीय और विस्तृत MoS_2 शल्क प्राप्त कर लिए गए।

CVD संश्लेषण की लागत कम करने के लिए विकास तापमान को कम करने और विभिन्न उपकरणीय उपयोगों के लिए TMD का विभिन्न सब्सट्रेटों पर विकास प्राप्त करने की तत्काल आवश्यकता थी। इसलिए

किया। प्रणेता और सब्सट्रेट के विकासशील चेहरे के बीच दूरी के समंजन द्वारा सीमावर्ती सतह निर्माण की सांद्रता को नियंत्रित करते हुए हम आसानी से सतह संख्या, आवृत्त विकास क्षेत्र और केन्द्रीकरण घनत्व को नियंत्रित कर सकते हैं। इसलिए अपने तीसरे उद्देश्य में हमने सीमावर्ती सतह सांद्रता को नियंत्रित करते हुए निम्न ताप पर उच्च गुणवत्तापूर्ण दीर्घ क्षेत्र (४ वर्गसेंटीमीटर तक) त्रिस्तरीय (TL)-MoS_2 संश्लेषित किया। 3L-MoS_2 के भौतिक और रासायनिक गुण प्रकाशिक सूक्ष्मदर्शी (OM), रमन स्पेक्ट्रोस्कोपी, परमाणु बल सूक्ष्मदर्शी (AFM), X-किरण प्रकाश इलेक्ट्रॉन स्पेक्ट्रोस्कोपी (XPS), X-किरण विवर्तन (XRD), अपवर्तन इलेक्ट्रॉन सूक्ष्मदर्शी (TEM) इत्यादि के द्वारा विश्लेषित किये गए। 3L-MoS_2 की उच्च एकरूपता और निम्न रूक्षता की पुष्टि क्रमशः रमन प्रकीर्णन और AFM मापन द्वारा की गयी। MoS_2 के ऊर्जा अंतराल की गणना के लिए UV-VIS स्पेक्ट्रोस्कोपी परावर्तन तरीके में की गयी और यह १.७ eV प्राप्त हुआ जो कि 3L-MoS_2 के संगत है। हमारी यथा विकसित 3L-MoS_2 फिल्में एक क्रिस्टलीय थीं, जैसा कि XRD और TEM मापन के द्वारा पता लगाया गया। हमारा विश्वास है कि सीमावर्ती सांद्रता पर नियंत्रित नियंत्रण भविष्य में व्यवहारिक नैनो इलेक्ट्रॉनिकी के लिए उच्च गुणवत्ता पूर्ण अन्य TMDs के वेफर स्केल विकास को जन्म दे सकता है।

MoS_2 के CVD में महत्वपूर्ण सुधार प्राप्त करने के बाद हमने अपना ध्यान यथा विकसित 1L-MoS_2 शल्क के गुणों के अन्वेषण पर केंद्रित किया। चूँकि इन TMDs में उच्च सतह से आयतन अनुपात और अत्यंत अल्प मोटाई पायी जाती है और इनसे बने हुए उपकरण, परिवेश जैसे हवा और विकिरण से अति संवेदनशील हैं। ये विकिरण, उपकरण के प्रदर्शन को भी हानि पहुँचा सकता है। इसलिए 2D-TMDC की विकिरण कठोरता को समझना अंतरिक्ष उपकरणों के लिए अत्यंत महत्वपूर्ण था। इसलिए हमारा चतुर्थ उद्देश्य 1L-MoS_2 शल्क पर गामा विकिरण का प्रभाव और इसके संगत उनके रासायनिक और संरचनात्मक गुणों में होने वाले परिवर्तन का अध्ययन करना था। नीलम सब्सट्रेट पर 1L-MoS_2 शल्क Co-६० गामा स्रोत (लगभग १.२५ MeV) द्वारा विभिन्न खुराकों (लगभग १-१००० kGy) पर एक नियत खुराक दर (लगभग ३.२ kGy/ घंटा) से विकरित किये गए। हमने अनुमान लगाया कि MoS_2 का तापमान गामा

किरणों के प्रति एक kGy खुराक से १.३ ^{o}C तक बढ़ जाता है। यह देखा गया कि १३० kGy तक गामा अनावरण का MoS_2 के रूपात्मक और रासायनिक गुणों पर कोई महत्वपूर्ण प्रभाव नहीं हुआ। हालाँकि XPS ने दर्शाया कि २७५ kGy से MoS_2, MoO_x में परिवर्तित होना शुरू हो गया। रमन स्पेक्ट्रोस्कोपी ने दिखाया कि गामा की कम खुराकों पर MoS_2 की क्रिस्टलीयता बढ़ गयी थी जबकि उच्च खुराकों पर MoS_2 की एक अनुरेखणीय मात्रा आकारहीन MoS_2 में परिवर्तित होना शुरू हो गयी। हमारे निष्कर्षों से पता चला कि MoS_2 के दोनों रमन मोड गामा विकिरण की खुराक बढ़ने के साथ-साथ MoS_2 के तापीय विस्तार से उत्पन्न खिंचाव और सल्फर रिक्तियों के निर्माण के संयुक्त प्रभाव के कारण नीला खिसकाव दिखाते हैं।

जैसा कि ग्राफीन एक परमाणु के जितना पतला पदार्थ है, इसके सतह से आयतन का अनुपात अत्यंत उच्च है जो इसे आस-पास के परिवेश के लिए प्रवण बनाता है। इसलिए ग्राफीन के समर्थन अथवा एनकैप्स्यूलेशन के लिए हम सिलिकॉन या एल्युमीनियम आधारित ऑक्साइड के समान विभिन्न सब्सट्रेटों का प्रयोग कर सकते हैं, लेकिन दुर्भाग्यवश इसमें सतह खुरदुरापन, आवेशित अशुद्धियाँ, डैंगलिंग बंधन शामिल हैं जो अंततः ग्राफीन में तरंग, विकार और अपमिश्रण उतर-चढ़ाव का कारण बनते हैं। ग्राफीन के समान ही TMDs उच्च डाई इलेक्ट्रिक नियतांक युक्त अत्यंत समतल और परमाणु के समान पतले पदार्थ हैं। इसलिए थीसिस के अंतिम कार्य में विभिन्न TMDs को ग्राफीन के लिए एनकैप्सूलेटिंग तहों के रूप में प्रयोग करने और विभिन्न डाई इलेक्ट्रिक परिवेश में ग्राफीन के 2D मोड के व्यवहार को उजागर करने की योजना थी, जिससे अंततः Γ- और K- बिंदुओं के पास कोन (Kohn) विसंगति के धब्बों को समझने में मदद मिली। हमने निलंबित 1L-WSe_2/Gr के समान विभिन्न प्रकार के यांत्रिक रूप से एक्सफोलिएटेड ऊर्ध्वाधर विषम संरचना युक्त नमूने प्रयुक्त किये, जिनमें चार विभिन्न दिलचस्प क्षेत्र (कोटर पर निलंबित Gr, SiO_2/Gr, SiO_2/Gr/WSe_2 और निलंबित WSe_2/Gr) हैं; द्वितीय नमूना hBN समर्थित 1L-$MoSe_2$/Gr था और तृतीय नमूना hBN छायित 1L-$MoSe_2$/Gr था।

रमन प्रकीर्णन मापों से पता चला कि G-मोड (ω_G) के विपरीत, ग्राफीन के रमन 2D-मोड (ω_{2D}) आपतित फोटॉन कि ऊर्जा और डाई इलेक्ट्रिक परिवेश पर दृढ़तापूर्वक निर्भर करते हैं। ग्राफीन के लिए जितना अधिक डाई इलेक्ट्रिक स्क्रीनिंग होगा उतना ही कम लेक्ट्रोन-फोनॉन युग्मन होगा जो कि ω_{2D} में नीले खिसकाव को परिणत करते हैं। जैसे ही फोटॉन कि ऊर्जा बढ़ा दी गयी, ω_{2D} का विक्षेपण बढ़ गया। इसके अलावा एक विशेष आपतित फोटॉन ऊर्जा पर जैसे-जैसे स्क्रीनिंग बढ़ता है तदनुसार ω_{2D} ऊपर की और खिसकता है। हमारे रमन निष्कर्षों से पता चला है कि TMD की एक तह उतनी ही प्रभावी है जितनी कि एक सतही hBN की दो तह।

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List of Symbols and Abbreviations

Symbols

q	Charge
h	Plank constant
ν	Frequency of photon
c	Speed of light
λ	Wavelength
T	Temperature
E_g	Energy bandgap
γ	Gamma
$\mathring{A}$	Angstrom
m_0	Rest mass of electron
°C	Degree Celsius
K	Kelvin
J	Joule
θ	Incident angle of x-ray with crystal plane
Φ	Rotation angle with normal to the crystal plane
V_{CPD}	Contact potential difference
ϕ_{tip}	Work function of the tip
ϕ_{sample}	Work function of the sample
kGy	Kilo Gray

Abbreviations

2D	Two-dimensional
3D	Three-dimensional
CVD	Chemical vapor deposition
MOCVD	Metal-organic chemical vapor deposition
1L/2L/3L	monolayer/bilayer/trilayer
AHM	Ammonium heptamolybdate
TMDs	Transition metal dichalcogenides
FET	Field effect transistor
MSM	Metal-semiconductor-metal
MOS	Metal oxide semiconductor
VBM	Valence band maximum
PLD	Pulsed laser deposition
TEM	Transmission electron microscope
HRTEM	High resolution transmission electron microscope
SAED	Selected-area electron diffraction
XRD	X-ray diffraction
OM	Optical microscopy
UV-vis	UV-Visible absorption
PL	Photoluminescence
SPM	Scanning probe microscopy
SEM	Scanning electron microscopy
FESEM	Field-emission scanning electron microscopy
AFM	Atomic force microscopy
KPFM	Kelvin probe force microscopy
PL	Photoluminescence
XPS	X-ray photoelectron microscopy
FWHM	Full-width-at-half-maximum