



Article Controlled p-Type Doping of MoS₂ Monolayer by Copper Chloride

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Abstract: Electronic devices based on two-dimensional (2D) MoS₂ show great promise as future building blocks in electronic circuits due to their outstanding electrical, optical, and mechanical properties. Despite the high importance of doping of these 2D materials for designing field-effect transistors (FETs) and logic circuits, a simple and controllable doping methodology still needs to be developed in order to tailor their device properties. Here, we found a simple and effective chemical doping strategy for MoS₂ monolayers using CuCl₂ solution. The CuCl₂ solution was simply spin-coated on MoS₂ with different concentrations under ambient conditions for effectively p-doping the MoS₂ monolayers. This was systematically analyzed using various spectroscopic measurements using Raman, photoluminescence, and X-ray photoelectron and electrical measurements by observing the change in transfer and output characteristics of MoS₂ FETs before and after CuCl₂ doping, showing effective p-type doping behaviors as observed through the shift of threshold voltages (Vth) and reducing the ON and OFF current level. Our results open the possibility of providing effective and simple doping strategies for 2D materials and other nanomaterials without causing any detrimental damage.

Keywords: MoS₂ monolayer; copper chloride; transition metal chloride; p-type doping; spin coating

1. Introduction

Monolayer transition metal dichalcogenides (TMDCs) have been considered to be the next-generation semiconducting channel materials because of their incredible electronic and mechanical properties that make them suitable for flexible, wearable, and transparent devices [1–5]. In addition, their ideally dangling bond-free surface and atomic thickness show promise for van der Waals integration on various substrates/materials and in reducing short channel effect, thus becoming candidates for the semiconducting channel materials in nano-scaled electronics and optoelectronics devices [2,6–8]. Especially, the field-effect transistors (FETs) composed of TMDC monolayers show high carrier mobility, large On/Off ratio (>10⁸), and low power consumption, which have inspired experimental research in advancing FET performance of these devices [5,9–14].

To implement the TMDC monolayers for practical electronic device applications, the device properties need to be tailored to show the desired output characteristics of electronic devices. One way to achieve the desired device characteristics is through doping [3,15–19]. The doping of 2D materials is recognized to be the key to precisely controlling their fundamental properties, based on the history of the contemporary Si or III–V-based semiconductors. Ion implantation is one of the possible doping techniques. However, this uses high energy and can be detrimental to atomically thin 2D crystals. On the other hand, chemical doping is potentially more advantageous compared to the ion implantation method, as the chemical doping is generally based on a charge transfer by chemical potential of adsorbed organic molecules and leads to less damage in 2D crystal structures [18,20–23]. The chemical doping of 2D TMDCs have been mostly relied on employing self-assemble monolayer (SAM) techniques [3,9], substitutional doping [17,24], and passivation of sulfur vacancy defects [5,25,26]. However, using such techniques, it is difficult to tune the amount



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Copyright: © 2022 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). of doping, and they generally require a controlled doping environment. Therefore, it is required to find a convenient method to modulate electrical/optical properties, as well as the electronic device properties.

Herein, we report a simple and controllable doping method for 2D MoS₂ using copper (II) chloride (CuCl₂) performed at ambient conditions. In this process, the CuCl₂ is dissolved in ethanol, and the solution is simply spin-coated onto 2D MoS₂ to effectively modulate charge carrier densities without any damage to MoS₂ crystals and their devices. The change in doping was analytically confirmed through Raman, photoluminescence (PL), and X-ray photoelectron spectroscopy (XPS), showing the p-type doping effect on 2D MoS₂. We further confirmed the feasibility of this doping process by simply coating the different concentrations of CuCl₂ solution onto the back-gated MoS₂ transistors, showing effective p-type doping behaviors as observed through the shift of threshold voltages (Vth) and reducing the ON and OFF current levels. These findings pave an important pathway toward modulating 2D materials and devices and designing logic devices based on 2D materials.

2. Materials and Methods

Synthesis of monolayer MoS₂: Monolayer MoS₂ was synthesized on a SiO₂ (300 nm)/Si substrate using the previously reported thermal chemical vapor deposition (CVD) method [27,28]. Here, 0.05 mg of MoO₃ precursors were prepared by dissolving the MoO₃ powders into ammonium hydroxide (NH₄OH) solution and loading the MoO₃ onto alumina boats using a micropipette. The SiO₂/Si substrate was placed above the alumina boat with the substrate placed faced down. The growth was carried in a 2-inch quartz tube, an alumina boat containing 100 mg of sulfur powder was placed upstream, while the alumina boat containing 0.05 mg of MoO₃, and substrate was placed downstream in the middle of the CVD furnace. The growth was carried out at 750 °C for 10 min, and the furnace was naturally cooled down to room temperature. MoS₂ crystal sizes around 30–50 µm were obtained from the CVD synthesis.

Fabrication and measurement of MoS₂ transistors: The synthesized MoS₂ monolayers were transferred onto HfO_2/Si substrate using polystyrene (PS) film as the transferring medium. The PS film (M_W~192,000) was spin-coated onto MoS₂/SiO₂/Si substrate and the film was detached during the transfer process while the film was floated on DI water. The detached PS film with MoS₂ was dried in air for 2 h and transferred onto HfO₂/Si substrate for device fabrication. The source and drain electrode pads were patterned using photolithography, and 5 nm Ti/40 nm Au electrodes were deposited using a thermal evaporator. The devices were annealed at 150 °C for 1 h under vacuum conditions. The electrical properties were measured using semiconductor parameter analyzer (Keithley 4200A-SCS) and MS Tech probe station.

Characterization of MoS_2 : The Raman and PL measurements were carried out using Alpha 300 R confocal Raman spectroscopy with 532 nm laser. AFM measurement was carried out using XE7 (Park Systems, Suwon, Korea). XPS measurement was performed using NEXSA (Thermofisher Scientific, Waltham, MA, USA).

3. Results

MoS₂ monolayers were synthesized on a SiO₂ (300 nm)/Si substrate using a chemical vapor deposition (CVD). Figure 1a shows the CVD-grown monolayered MoS₂ profiled by atomic force microscopy (AFM) height measurement. The morphology and thickness of the as-grown MoS₂ show its thickness around 0.7 nm, confirming the single-layered thickness. For doping of MoS₂, CuCl₂ was employed in this study as the metal chlorides offer a wide range of doping molecules, have been frequently employed to modulate electrical properties of graphene, and are known to be strong electron acceptors [29–31]. The metal chloride generally acts as a strong electron acceptor due to the high electronegativity of chlorine compared to molybdenum or sulfur [31]. It should be noted that CuCl₂ has never been used for doping 2D MoS₂. Figure 1b illustrates our simple CuCl₂ doping process. CuCl₂ was firstly dissolved in ethanol at different molar concentrations (0.5 M and 1 M).

The as-grown MoS_2 layer on SiO_2 was then placed on a spin coater, and $CuCl_2$ solution was dropped onto the as-grown $MoS_{2,}$ followed by the spin coating at 3000 RPM. The doped MoS_2 samples were then dried on a hot plate at a mild temperature below 90 °C. All of the doping processes were performed in ambient conditions.



Figure 1. CuCl₂ doping process for MoS₂ monolayers. (a) AFM topography image of MoS₂ monolayers showing its atomic thickness around 0.7 nm. Scale bar: 5 μ m. (b) Schematic illustration of CuCl₂ doping process. The as-synthesized MoS₂ monolayers on SiO₂/Si substrate were placed on a spin coater, and CuCl₂ solution was dropped onto the substrate for spin coating at 3000 RPM.

In order to understand the effect of CuCl₂ doping on MoS₂ monolayers, we first performed Raman and PL analysis of the pristine MoS₂ and CuCl₂-doped MoS₂ as shown in Figure 2a,b. Figure 2a shows the Raman spectrum of pristine MoS_2 (dotted grey line), 0.5 M CuCl₂-doped MoS₂ (purple line), and 1 M CuCl₂-doped MoS₂ (magenta). The Raman spectrum of pristine MoS_2 shows two characteristic peaks located at around 381 cm⁻¹ and 400 cm⁻¹, which correspond to the in-plane E_{2g}^{1} and out-of-plane A_{1g} vibrational modes, respectively. As the CuCl₂ is doped onto MoS₂, the Raman peaks of MoS₂ were monotonically blue shifted with increasing the CuCl₂ doping concentrations. Such a trend of shifting in Raman peaks is a clear signature that carrier concentrations were changed without damaging the crystal structure, and can be understood as a CuCl₂-induced p-type doping effect, which is in agreement with the previous studies [9,32]. Figure 2b shows PL spectra measured for the pristine MoS_2 and $CuCl_2$ -doped MoS_2 . The pristine MoS_2 shows direct bandgap PL emission at around 1.82 eV. As the MoS₂ monolayers were doped with CuCl₂, the PL intensity was largely increased. It has been widely accepted that the PL intensity of 2D MoS₂ is strongly affected by carrier concentrations. The increased PL intensity of MoS₂ monolayer can be due to the reduced trion formation and strongly increased exciton radiative recombination rates through decreasing the carrier concentrations of $CuCl_2$ -doped MoS₂ monolayers [33]. Therefore, $CuCl_2$ doping of MoS₂ monolayer decreases carrier concentrations due to the strong electron accepting nature of CuCl₂, which was observed through Raman and PL measurements.

To further confirm the effect of CuCl₂ doping and the chemical state of CuCl₂ molecules, we performed X-ray photoelectron (XPS) analysis as shown in Figure 3a–d. XPS analysis was performed for both pristine MoS₂ and CuCl₂-doped MoS₂, and we compared any change in the binding energies. Figure 3a,b show the main binding energy of MoS₂, Mo 3d and S 2p peaks, and we compared the change of binding energies before and after CuCl₂ doping. It is clearly observable that the binding energies of both Mo 3d and S 2p peaks shifted toward lower binding energy by about 0.3 eV. The shift to a lower binding energy in semiconducting MoS₂ can be attributed to the shift of Fermi-level energy toward the valence band, which results in the change of binding energies in MoS₂, and the results agree with the Raman and PL analysis that show the p-type doping effect of CuCl₂ on MoS₂.



Figure 2. (a) Raman and (b) PL measurements before and after $CuCl_2$ doping. 0.5 M and 1 M $CuCl_2$ solutions were employed for doping. After $CuCl_2$ doping, the Raman spectrum of MoS_2 was blue-shifted and PL intensity was largely increased, showing p-type doping effect on MoS_2 .



Figure 3. X-ray photoelectron spectroscopy (XPS) measurements before and after $CuCl_2$ doping. XPS spectrum of (**a**) Mo 3d and (**b**) S 2p before and after $CuCl_2$ doping. The shift of the binding energies to lower energy indicates lowered Fermi level in MoS₂. XPS spectrum of (**c**) Cu 2p and (**d**) Cl 2p was found in CuCl₂ doped MoS₂ film, demonstrating the CuCl₂ is doped onto MoS₂.

XPS analysis on CuCl₂-doped MoS₂ also showed the chemical state of CuCl₂ as shown in Figure 3c,d. Figure 3c and d show the high-resolution XPS peaks of Cu 2p and Cl 2p peaks, respectively, which were recorded from the CuCl₂-doped MoS₂ sample. As shown in Figure 3c, it can be seen that the binding energies of Cu 2p are composed of the main characteristic doublet peaks centered at around 953 eV and 933.3 eV, which correspond to Cu $2p_{1/2}$ and Cu $2p_{3/2}$, respectively, and other satellite peaks [34]. The difference between the two peaks is around 19 eV, which is in good agreement with the value reported in the literature [35]. Cl 2p peaks can be deconvoluted into two main doublets, which are found at 200.6 eV and 198.9 eV and correspond to Cl $2p_{1/2}$ and Cl $2p_{3/2}$, respectively. The peak difference of the two peaks is around 1.7 eV, which is in good agreement with the value reported in the value reported in the literature [36]. The XPS results and the presence of Cu 2p and Cl 2p binding energies confirm the presence of CuCl₂ and the effective p-type doping on MoS₂.

To understand the effect of CuCl₂ doping on the electrical properties of FETs based on a 2D MoS₂ channel, the electrical properties were measured before and after doping the MoS₂ FETs with CuCl₂. The FET devices were fabricated on a HfO₂/Si substrate using photolithography and metal deposition using a thermal evaporator. Figure 4a shows the schematic description of the doping process of MoS₂ FETs. The as-fabricated MoS₂ FETs were spin-coated with CuCl₂ solution. Figure 4b shows the representative transfer curve, drain-source current, I_{DS} , as a function of the gate voltage, V_G , which is plotted on a logarithmic scale at the applied drain voltage of $V_{DS} = 0.1$ V. The inset of Figure 4b shows the transfer curve in a linear scale. The as-fabricated MoS₂ FET showed n-type transfer characteristics and a large ON/OFF ratio above 10^7 . From the transfer characteristics, we have estimated a field effect mobility using $\mu_{FE} = \frac{L}{WC_{ox}V_{ds}} \frac{dI_{ds}}{dV_{gs}}$, where L is channel length, W is channel width, and C_{ox} is the gate capacitance of 309.9 nF cm⁻². The field effect mobility was measured to be 12.3 cm²/Vs, which is in good agreement with reported values for a back-gated transistor using CVD-grown MoS₂ monolayers. It can be observed from Figure 4b that the CuCl₂-doped MoS₂ FETs shows a gradual decrease in both ON and OFF current as the CuCl₂ is doped onto the MoS₂ FETs.



Figure 4. (**a**) Schematic description of CuCl₂ doping on MoS₂ FETs. (**b**) The transfer characteristics, (**c**) output characteristics, (**d**) threshold voltages of MoS₂ FETs before and after CuCl₂ doping.

Such behavior was also found when an output curve, the drain-source current versus drain-source voltage on a linear scale, was measured as shown in Figure 4c (inset image shows the output curve of 1 M CuCl₂ doped MoS₂ FET). The output curve of as-fabricated MoS₂ FET shows a high ON current and a linearly dependent drain current showing good Ohmic contact between MoS₂ and electrodes. As the CuCl₂ is doped onto MoS₂ FETs, the channel conductance is largely decreased, showing a p-type doping effect of CuCl₂ on MoS₂, in accordance with transfer curve measured in Figure 4b.

Following the reduced ON current and channel conductance, it was also shown that as CuCl₂ was doped onto MoS₂ FETs, threshold voltage (V_{th}) was shifted towards positive voltages from -2.85 V to -1.45 V and -0.9 V as 0.5 M and 1 M CuCl₂ was doped onto MoS₂ FETs as shown in Figure 4d. Using the changes in the V_{th}, the change in carrier concentrations upon CuCl₂ doping can be calculated using the parallel-plate capacitor model [3,9], $N_{doping} = \frac{C|\Delta Vth|}{e}$, where *C* is the gate capacitance, ΔV_{th} is the change in the V_{Th} after the CuCl₂ is doped onto the device compared to the as-fabricated MoS₂ FET, and *e* is the elementary charge. The amount of doping concentration was estimated to be 2.72×10^{12} cm⁻² and 3.77×10^{12} cm⁻² when 0.5 M CuCl₂ and 1 M CuCl₂ were doped onto MoS₂ FETs, respectively. The electrical analysis of MoS₂ FETs before and after CuCl₂ doping show that CuCl₂ is an effective p-type dopant for MoS₂ that can be easily employed using simple spin coating of different concentrations of CuCl₂ solution.

4. Conclusions

To conclude, we have demonstrated simple and effective p-type doping on the 2D MoS₂ FETs by simply spin coating the device with CuCl₂ solution at ambient conditions. The effect of CuCl₂ doping was confirmed analytically through Raman, PL, and XPS measurements. The p-type doping on the MoS₂ channel showed largely decreased channel conductance and the shift in threshold voltages towards positive gate voltages in back-gated MoS₂ transistors. It was also shown that the amount of doping can be simply controlled by the CuCl₂ concentrations in a solution containing ethanol. The results and findings present an important pathway towards designing a CMOS circuit based on 2D FETs and other nanomaterials.

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References

- Pak, S.; Lee, J.; Lee, Y.-W.; Jang, A.-R.; Ahn, S.; Ma, K.Y.; Cho, Y.; Hong, J.; Lee, S.; Jeong, H.Y.; et al. Strain-Mediated Interlayer Coupling Effects on the Excitonic Behaviors in an Epitaxially Grown MoS₂/WS₂ van der Waals Heterobilayer. *Nano Lett.* 2017, 17, 5634–5640. [CrossRef] [PubMed]
- Pak, S.; Cho, Y.; Hong, J.; Lee, J.; Lee, S.; Hou, B.; An, G.H.; Lee, Y.W.; Jang, J.E.; Im, H.; et al. Consecutive Junction-Induced Efficient Charge Separation Mechanisms for High-Performance MoS₂/Quantum Dot Phototransistors. *ACS Appl. Mater. Interfaces* 2018, 10, 38264–38271. [CrossRef] [PubMed]
- Pak, S.; Jang, A.R.; Lee, J.; Hong, J.; Giraud, P.; Lee, S.; Cho, Y.; An, G.H.; Lee, Y.W.; Shin, H.S.; et al. Surface functionalizationinduced photoresponse characteristics of monolayer MoS₂ for fast flexible photodetectors. *Nanoscale* 2019, *11*, 4726–4734. [CrossRef] [PubMed]
- 4. Pak, S.; Lee, J.; Jang, A.R.; Kim, S.; Park, K.-H.; Sohn, J.I.; Cha, S. Strain—Engineering of Contact Energy Barriers and Photoresponse Behaviors in Monolayer MoS₂ Flexible Devices. *Adv. Funct. Mater.* **2020**, *30*, 2002023. [CrossRef]
- 5. Pak, S.; Jang, S.; Kim, T.; Lim, J.; Hwang, J.S.; Cho, Y.; Chang, H.; Jang, A.R.; Park, K.H.; Hong, J.; et al. Electrode-Induced Self-Healed Monolayer MoS₂ for High Performance Transistors and Phototransistors. *Adv. Mater.* **2021**, *33*, 2102091. [CrossRef]
- Novoselov, K.S.; Mishchenko, A.; Carvalho, A.; Castro Neto, A.H. 2D materials and van der Waals heterostructures. *Science* 2016, 353, aac9439. [CrossRef]
- Liu, Y.; Weiss, N.O.; Duan, X.; Cheng, H.-C.; Huang, Y.; Duan, X. Van der Waals heterostructures and devices. *Nat. Rev. Mater.* 2016, 1, 16042. [CrossRef]
- Jariwala, D.; Marks, T.J.; Hersam, M.C. Mixed-dimensional van der Waals heterostructures. *Nat. Mater.* 2017, 16, 170–181. [CrossRef]

- Pak, S.; Lim, J.; Hong, J.; Cha, S. Enhanced Hydrogen Evolution Reaction in Surface Functionalized MoS₂ Monolayers. *Catalysts* 2021, 11, 70. [CrossRef]
- 10. Liu, Y.; Guo, J.; Zhu, E.B.; Liao, L.; Lee, S.J.; Ding, M.N.; Shakir, I.; Gambin, V.; Huang, Y.; Duan, X.F. Approaching the Schottky-Mott limit in van der Waals metal-semiconductor junctions. *Nature* **2018**, *557*, 696–700. [CrossRef]
- Wang, Y.; Kim, J.C.; Wu, R.J.; Martinez, J.; Song, X.J.; Yang, J.; Zhao, F.; Mkhoyan, K.A.; Jeong, H.Y.; Chhowalla, M. Van der Waals contacts between three-dimensional metals and two-dimensional semiconductors. *Nature* 2019, 568, 70–74. [CrossRef] [PubMed]
- 12. Shen, P.C.; Su, C.; Lin, Y.X.; Chou, A.S.; Cheng, C.C.; Park, J.H.; Chiu, M.H.; Lu, A.Y.; Tang, H.L.; Tavakoli, M.M.; et al. Ultralow contact resistance between semimetal and monolayer semiconductors. *Nature* 2021, 593, 211–217. [CrossRef] [PubMed]
- 13. Lee, J.; Pak, S.; Lee, Y.-W.; Cho, Y.; Hong, J.; Giraud, P.; Shin, H.S.; Morris, S.M.; Sohn, J.I.; Cha, S.; et al. Monolayer optical memory cells based on artificial trap-mediated charge storage and release. *Nat. Commun.* **2017**, *8*, 14734. [CrossRef] [PubMed]
- Jung, S.W.; Pak, S.; Lee, S.; Reimers, S.; Mukherjee, S.; Dudin, P.; Kim, T.K.; Cattelan, M.; Fox, N.; Dhesi, S.S.; et al. Spectral functions of CVD grown MoS₂ monolayers after chemical transfer onto Au surface. *Appl. Surf. Sci.* 2020, 532, 147390. [CrossRef]
 Lin J. K.; Cattelan, M.; Fox, N.; Dhesi, S.S.; et al. Spectral functions of CVD grown MoS₂ monolayers after chemical transfer onto Au surface. *Appl. Surf. Sci.* 2020, 532, 147390. [CrossRef]
- 15. Liu, H.; Liu, Y.; Zhu, D. Chemical doping of graphene. J. Mater. Chem. 2010, 21, 3335–3345. [CrossRef]
- Mouri, S.; Miyauchi, Y.; Matsuda, K. Tunable Photoluminescence of Monolayer MoS₂ via Chemical Doping. *Nano Lett.* 2013, 13, 5944–5948. [CrossRef]
- 17. Yang, L.; Majumdar, K.; Liu, H.; Du, Y.; Wu, H.; Hatzistergos, M.; Hung, P.Y.; Tieckelmann, R.; Tsai, W.; Hobbs, C.; et al. Chloride molecular doping technique on 2D materials: WS₂ and MoS₂. *Nano Lett.* **2014**, *14*, 6275–6280. [CrossRef]
- 18. Tarasov, A.; Zhang, S.; Tsai, M.-Y.Y.; Campbell, P.M.; Graham, S.; Barlow, S.; Marder, S.R.; Vogel, E.M. Controlled doping of large-area trilayer MoS₂ with molecular reductants and oxidants. *Adv. Mater.* **2015**, *27*, 1175–1181. [CrossRef]
- 19. Cho, Y.; Pak, S.; Li, B.; Hou, B.; Cha, S. Enhanced Direct White Light Emission Efficiency in Quantum Dot Light—Emitting Diodes via Embedded Ferroelectric Islands Structure. *Adv. Funct. Mater.* **2021**, *31*, 2104239. [CrossRef]
- 20. Kiriya, D.; Tosun, M.; Zhao, P.; Kang, J.S.; Javey, A. Air-stable surface charge transfer doping of MoS₂ by benzyl viologen. *J. Am. Chem. Soc.* **2014**, *136*, 7853–7856. [CrossRef]
- Andleeb, S.; Singh, A.; Eom, J. Chemical doping of MoS₂ multilayer by p-toluene sulfonic acid. *Sci. Technol. Adv. Mater.* 2015, 16, 035009. [CrossRef] [PubMed]
- Sim, D.M.; Kim, M.; Yim, S.; Choi, M.J.; Choi, J.; Yoo, S.; Jung, Y.S. Controlled Doping of Vacancy-Containing Few-Layer MoS₂ via Highly Stable Thiol-Based Molecular Chemisorption. ACS Nano 2015, 9, 12115–12123. [CrossRef] [PubMed]
- Qi, L.; Wang, Y.; Shen, L.; Wu, Y. Chemisorption-induced n-doping of MoS₂ by oxygen. *Appl. Phys. Lett.* 2016, 108, 063103. [CrossRef]
- Kim, T.; Pak, S.; Lim, J.; Hwang, J.S.; Park, K.-H.; Kim, B.-S.; Cha, S. Electromagnetic Interference Shielding with 2D Copper Sulfide. ACS Appl. Mater. Interfaces 2022, 14, 13499–13506. [CrossRef]
- Zhang, X.K.; Liao, Q.L.; Liu, S.; Kang, Z.; Zhang, Z.; Du, J.L.; Li, F.; Zhang, S.H.; Xiao, J.K.; Liu, B.S.; et al. Poly(4-styrenesulfonate)induced sulfur vacancy self-healing strategy for monolayer MoS₂ homojunction photodiode. *Nat. Commun.* 2017, *8*, 15881. [CrossRef]
- Kufer, D.; Konstantatos, G. Highly Sensitive, Encapsulated MoS₂ Photodetector with Gate Controllable Gain and Speed. *Nano* Lett. 2015, 15, 7307–7313. [CrossRef]
- Lee, J.; Pak, S.; Giraud, P.; Lee, Y.W.; Cho, Y.; Hong, J.; Jang, A.R.; Chung, H.S.; Hong, W.K.; Jeong, H.; et al. Thermodynamically Stable Synthesis of Large-Scale and Highly Crystalline Transition Metal Dichalcogenide Monolayers and their Unipolar n–n Heterojunction Devices. *Adv. Mater.* 2017, 29, 1702206. [CrossRef]
- 28. Lee, J.; Pak, S.; Lee, Y.W.; Park, Y.; Jang, A.R.; Hong, J.; Cho, Y.; Hou, B.; Lee, S.; Jeong, H.Y.; et al. Direct Epitaxial Synthesis of Selective Two-Dimensional Lateral Heterostructures. *ACS Nano* **2019**, *13*, 13047–13055. [CrossRef]
- 29. Rybin, M.G.; Islamova, V.R.; Obraztsova, E.A.; Obraztsova, E.D. Modification of graphene electronic properties via controllable gas-phase doping with copper chlroide. *Appl. Phys. Lett.* **2018**, *112*, 033107. [CrossRef]
- 30. Mansour, A.E.; Kirmani, A.R.; Barlow, S.; Marder, S.R.; Amassian, A. Hybrid Doping of Few-Layer Graphene via a Combination of Intercalation and Surface Doping. *ACS Appl. Mater. Interfaces* **2017**, *9*, 20020–20028. [CrossRef]
- Kwon, K.C.; Choi, K.S.; Kim, S.Y. Increased Work Function in Few-Layer Graphene Sheets via Metal Chloride Doping. *Adv. Funct. Mater.* 2012, 22, 4724–4731. [CrossRef]
- 32. Chakraborty, B.; Bera, A.; Muthu, D.V.S.; Bhowmick, S.; Waghmare, U.V.; Sood, A.K. Symmetry-dependent phonon renormalization in monolayer MoS₂ transistor. *Phys. Rev. B* **2012**, *85*, 161403. [CrossRef]
- Mak, K.F.; He, K.; Lee, C.; Lee, G.H.; Hone, J.; Heinz, T.F.; Shan, J. Tightly bound trions in monolayer MoS₂. *Nat. Mater.* 2013, 12, 207–211. [CrossRef] [PubMed]
- 34. Akgul, F.; Akgul, G.; Yildirim, N.; Unalan, H.; Turan, R. Influence of thermal annealing on microstructural, morphological, optical properties and surface electronic structure of copper oxide thin films. *Mater. Chem. Phys.* **2014**, *147*, 987–995. [CrossRef]
- 35. Gan, Z.H.; Yu, G.Q.; Tay, B.K.; Tan, C.M.; Zhao, Z.W.; Fu, Y.Q. Preparation and characterization of copper oxide thin films deposited by filtered cathodic vacuum arc. J. Phys. D Appl. Phys. 2004, 37, 81–85. [CrossRef]
- Krumpolec, R.; Homola, T.; Cameron, D.; Humlíček, J.; Caha, O.; Kuldová, K.; Zazpe, R.; Přikryl, J.; Macak, J. Structural and Optical Properties of Luminescent Copper(I) Chloride Thin Films Deposited by Sequentially Pulsed Chemical Vapour Deposition. *Coatings* 2018, *8*, 369. [CrossRef]