Direct synthesis of two-dimensional MoS$_2$ on $p$-type Si and application to solar hydrogen production

Amirhossein Hasani$^1$, Quyet Van Le$^2$, Mahider Tekalgne$^1$, Min-Ju Choi$^3$, Tae Hyung Lee$^3$, Ho Won Jang$^2$ and Soo Young Kim$^4$

Abstract
Transition metal dichalcogenides (TMDs) are promising two-dimensional (2D) materials, and MoS$_2$ has been specifically utilized in electronic devices and integrated circuits. However, the direct synthesis of MoS$_2$ on traditional semiconductors, such as silicon, remains challenging due to the hydrophobic surface of nonoxide wafers (e.g., Si, GaAs, and InP). Herein, a novel, facile, reliable, and one-step method for the direct synthesis of single-crystal MoS$_2$ on a $p$-Si wafer via hybrid thermolysis is proposed. To demonstrate the applicability of the proposed method, a MoS$_2$/$p$-Si heterojunction was fabricated and used for solar-driven hydrogen production. The as-fabricated $n$-MoS$_2$/$p$-Si heterojunction exhibited a benchmark current density of $-13.5 \pm 1$ mA/cm$^2$ at 0 V and an onset potential of $+0.02$ V. This method reliably and efficiently produced high-quality MoS$_2$ crystals on a wafer scale and is sufficiently simple to overcome the challenges associated with previous approaches. The method developed herein represents a tremendous advancement in the fabrication of 2D electronic devices.

Introduction
The discovery of low-dimensional materials represents a key point in the progress of electronic device development$^{1-4}$. Emerging transition metal dichalcogenides (TMDs) have revolutionized two-dimensional (2D) semiconductor-based electronics due to their unique optical, electronic, and mechanical properties. TMDs have great potential to be utilized in various applications, including solar cells, light-emitting diodes (LEDs), gas sensors, photocatalysis systems, and photodetectors$^{5-9}$. Recently, TMDs such as MoS$_2$, WS$_2$, MoSe$_2$, and WSe$_2$ have been introduced for use in different applications$^{10-13}$. Among these TMDs, the n-type semiconductor MoS$_2$ has been most extensively studied owing to its remarkably tunable optoelectronic and photochemical properties with a direct band gap of 1.8 eV, making it a promising low-dimensional material for future optoelectronic devices$^{3,14}$. For over a decade, a variety of synthesis methods for MoS$_2$ have been proposed using chemical vapor deposition (CVD), hydrothermal, sputtering, epitaxial growth, and thermolysis methods$^{15-19}$. However, the fabrication of large-scale, uniform, and high-quality crystalline MoS$_2$ remains challenging.

The elementary building blocks of p–n junctions are vital for semiconductor electronic devices such as integrated circuits, photodetectors, solar cells, LEDs, diodes, and transistors$^{20-24}$. Recently, the integration of low-dimensional TMD materials with single-crystal traditional semiconductors (e.g., Si, GaAs, and InP) has significantly impacted the development of functional electronic...
devices, including field effect transistors (FETs), diodes, photodetectors, and photoelectrochemical cells. However, poor-quality TMD-based heterojunctions and difficulty in large-scale fabrication restrict commercial applications. For example, so-called native oxides form easily on the Si wafer surface, resulting in poor contact with MoS₂ and deteriorated device performance. Therefore, the large-scale synthesis of superpristine MoS₂ on Si wafers has yet to be achieved.

Generally, two procedures are used for the fabrication of p–n heterojunctions in 2D TMD materials and Si: (1) synthesis of TMDs on SiO₂ and subsequent transfer to arbitrary substrates such as Si, GaAs, and InP wafers and (2) direct synthesis of TMDs on an arbitrary substrate. To the best of our knowledge, extensive research on the transfer process has been performed. For example, Kwon et al. fabricated a p–n heterojunction using n-MoS₂ and p-Si for use in photoelectrochemical hydrogen production. The fabrication process involved wet transferring, where MoS₂ was initially grown on SiO₂/Si and subsequently transferred to p-Si using a supporting layer and removal process. Despite the efficient performance obtained, the fabrication of p–n heterojunctions is not easily reproducible because the transfer process is challenging and time-consuming for n-MoS₂/p-Si heterojunctions. On the other hand, the only method for the direct synthesis of TMDs on Si is the sputtering method. Hao et al. fabricated MoS₂/Si p–n junctions using the DC magnetron technique for use in photovoltaic cells. However, the sputtering method for the direct synthesis of MoS₂ on p-Si results in poor MoS₂ crystallinity, and the formation of the MoS₂ film on p-Si is not easily controlled. Therefore, significant demand exists for the development of a reliable method for 2D p–n junction fabrication. The proposed method should be a wafer-scale, simple, fast (no transfer step), reproducible method that produces highly crystalline TMD films.

Herein, we report a novel method for the direct synthesis of 2D layered MoS₂ on a p-Si substrate, representing a tremendous advancement in the fabrication of 2D electronic devices, overcoming the challenges of previously reported techniques. We demonstrate an approach for the direct synthesis of wafer-scale MoS₂ on p-Si using thermolysis to achieve perfect crystals. This method can be more broadly applied to other TMDs and single-crystal wafers. In addition, to show the applicability of the developed method, the as-fabricated n-MoS₂/p-Si heterojunction was used for photoelectrochemical hydrogen production. Because of the direct formation of superpristine MoS₂ on p-Si and the high-quality p–n heterojunctions formed, the as-prepared photocathode exhibited efficient performance with a high current density of −13.5 ± 1 mA/cm² at 0 V and an onset potential of +0.02 V. The direct fabrication of p–n heterojunctions prepared using the proposed method offers a facile, reliable, time-saving fabrication process representing a remarkable development for the production of high-quality semiconductor electronic devices.

**Direct synthesis of MoS₂ on p-Si**

Thermolysis of ammonium tetrathiomolybdate ((NH₄)₂MoS₄) was used to form the MoS₂ thin film. Preparation of large-scale and high-quality MoS₂ by thermolysis is an efficient and facile approach that is well documented in the literature. Liu et al. synthesized MoS₂ using thermal decomposition of an (NH₄)₂MoS₄ layer in the presence of sulfur. Similarly, Kwon et al. used the same process to fabricate high-quality MoS₂. To date, the decomposition of the (NH₄)₂MoS₄ layer at high temperatures to form MoS₂ thin films has mostly involved the use of a SiO₂/Si substrate. In this study, the (NH₄)₂MoS₄ precursor was coated on a SiO₂/Si substrate and subsequently annealed in the presence of sulfur to form MoS₂/SiO₂/Si. Coating of the (NH₄)₂MoS₂ precursor on a substrate with a hydrophobic surface, such as p-Si, is impossible so we used a hybrid method to directly synthesize MoS₂ on the p-Si substrate. As shown schematically in Fig. 1a, MoO₃ with different thicknesses (5, 10, 15, and 20 nm) was deposited onto the p-Si substrate via evaporation to increase the hydrophilicity of the Si substrate. The (NH₄)₂MoS₂ solution was then coated onto MoO₃/p-Si via spin coating. Finally, the (NH₄)₂MoS₄/MoS₂ was converted to MoS₂/p-Si at 500 °C under H₂ and N₂ gas flow via thermolysis (Fig. 1b). Finally, the temperature was raised to 900 °C to transform the MoS₂ layer to a MoS₂ thin film and fabricate the MoS₂/p-Si heterojunctions. It is clear from Fig. 1c that the contact angle of (NH₄)₂MoS₄ with p-Si is quite high (55.5°), suggesting a poorly hydrophilic surface and the impossibility of coating the (NH₄)₂MoS₄ solution on p-Si (Fig. 1c, left). On the other hand, the p-Si surface could be converted to a super-hydrophilic surface after MoO₃ deposition, allowing the (NH₄)₂MoS₄ precursor to be easily coated on the substrate (Fig. 1c, right). To show the successful coating of the (NH₄)₂MoS₄ precursor on p-Si, a video was recorded before and after MoO₃ deposition (Video S1, S2). Figure 1d shows the wafers of the directly fabricated MoS₂/p-Si heterojunction, highlighting the efficiency and ease of the proposed method. Using this method, the large-scale fabrication of 2D-based semiconductor devices and integrated circuits could be achieved.

**Results and discussion**

The uniformity of 2D-TMD materials is an important parameter that directly affects device performance. Methods such as sputtering, epitaxial growth, and thermolysis have been proposed for the fabrication of large-
scale and uniform MoS$_2$. Dumcenco et al. demonstrated the growth of monolayer MoS$_2$ via epitaxial growth\textsuperscript{36}. However, randomly triangular-shaped MoS$_2$ with uncontrollable orientation limited the reliability of their process and prevented commercialization.

Atomic force microscopy (AFM) was used to examine the topological properties and thickness of the MoS$_2$ thin films. The inset of Fig. 2a shows the morphology of the as-obtained thickness (11 nm) of the 10 nm MoO$_3$ deposited on p-Si, which is attributed to the incorporation of (NH$_4$)$_2$MoS$_4$ and MoO$_3$ layers to form the MoS$_2$ thin film. The roughness of MoS$_2$ was 2.4 Å for the 10 nm MoO$_3$ deposited on p-Si (Fig. 2a), which is one of the smallest reported values to the best of our knowledge\textsuperscript{27,37}. These results confirm that the MoS$_2$ thin film on p-Si obtained using this method is superpristine and ultraclean, resulting in high-quality p–n heterojunctions and enhanced device performance. Furthermore, AFM was performed to evaluate the roughness and thickness under various conditions (Fig. S1) and confirmed the controllability of the developed method. The results demonstrate that the MoS$_2$ thickness can be easily controlled by the deposition of MoO$_3$, obtaining MoS$_2$ thicknesses of approximately 8.5, 11, 16.8, and 25.2 nm for the 5, 10, 15, and 20 nm MoO$_3$ depositions on p-Si, respectively (Fig. 2b). In addition, the lowest roughness of 2.4 Å was obtained for the 11 nm MoS$_2$ film, which would likely provide the best device performance. From the AFM results, the film roughness can be optimized by adjusting the MoO$_3$ thickness on p-Si. Field-emission scanning electron microscopy (FE-SEM) was used to examine the morphology of the MoS$_2$ thin film on the p-Si substrate (Fig. 2c). From the FE-SEM images of the as-synthesized MoS$_2$ films, the films were uniform and continuous over the entire surface of the p-Si substrate. Moreover, Fig. S2a–d shows the as-synthesized MoS$_2$ on p-Si with different

![Fig. 1](image_url)
MoO$_3$ thicknesses (5, 10, 15, and 20 nm). Figure 2d shows the Raman spectra of the MoS$_2$ thin films with different thicknesses. Two vibrational modes ($A_{1g}$ and $E_{1g}$) were observed and attributed to the out-of-plane and in-plane stretching, respectively$^{38}$. The distance between $A_{1g}$ and $E_{1g}$ increased with an increase in the thickness of the MoS$_2$ film, which was attributed to the tightening of the $A_{1g}$ mode and moderation of the $E_{1g}$ mode$^{27}$. To confirm the formation of the MoS$_2$ thin film and the impossibility of MoS$_2$/MoO$_3$, Raman analysis was utilized for the as-synthesized MoS$_2$ thin film and as-deposited MoO$_3$ layer (see Fig. S3). Two dominant peaks ($A_{1g}$ and $E_{1g}$) are located at 383 and 404 cm$^{-1}$ in the as-prepared MoS$_2$, while two dominant peaks are located at 820 and 997 cm$^{-1}$ in MoO$_3$. Therefore, the possibility of the existence of MoO$_3$ in the as-direct synthesized MoS$_2$ can be excluded.

X-ray diffraction (XRD) measurements were used to confirm the ultrahigh purity of the 2H-MoS$_2$ single crystal on p-Si (Fig. 3a). The corresponding peaks were sharp and located at 14.5 and 63.8°, arising from the (002) and (008) planes, respectively. Patil et al. evaluated the crystal structure of bulk MoS$_2$ and thin film MoS$_2$$^{15}$. The bulk MoS$_2$ showed various peaks, whereas the as-prepared MoS$_2$ showed only a (002) peak, and the other peaks were diminished, suggesting a highly pristine MoS$_2$ single-crystal layer. High-resolution transmission electron microscopy (HR-TEM) was used to confirm the quality of the MoS$_2$ crystal, and the result is shown in the inset of Fig. 3a. The 2H-phase of MoS$_2$ was observed mainly with
[002] and [008] orientations (inset of Fig. 3a), which was completely confirmed by the XRD results. From the XRD data, three sharp domain peaks were observed and were ascribed to the highly crystalline MoS2 film on p-Si. X-ray photoelectron spectroscopy (XPS) was used to determine the elemental composition, and the atomic ratios of the samples are shown in Fig. 3b. The XPS spectra are shown in Fig. 3b, confirming the presence of Mo and S and successful formation of the MoS2 film. In addition, the ratio of Mo to S was 31:69, which approximately agrees with the MoS2 structure (inset of Fig. 3b). The high-resolution XPS peaks of S 2p and Mo 3d are shown in Fig. 3c. To study the effects of the (NH4)2MoS4 precursor on the formation of single-crystal MoS2 on p-Si, XPS was performed on the MoS2 prepared with and without the (NH4)2MoS4 layer. The (NH4)2MoS4 precursor assists in the formation of MoS2 and likely acts as a protective layer to prevent evaporation of the MoO3 layer during thermolysis. In previous studies, this phenomenon has been attributed to the higher O-S bonding energy compared to that of the Si-S bond. However, we believe that the poor hydrophilicity of the Si wafer is the main reason underlying the impossibility of direct growth of MoS2 crystals on nonoxide wafers. The UV-vis normalized absorbance of the different thicknesses of the as-transferred MoS2 thin films on glass are shown in Fig. 3d. The optical band gaps were evaluated via prolonging the line of the initial absorbance peak and increased from 1.39 to 1.65 eV as the layer thickness decreased from 25.2 to 8.5 nm. Additionally, the as-transferred MoS2 layers with different thicknesses on glass are shown in the inset of Fig. 3d. The films uniformly covered the glass substrate, and the film color changed from transparent to dark brown with an increase in
thickness from 8.5 to 25.2 nm. These results confirmed that the optical and electronic properties can be easily tuned via the proposed method, which is more reliable and reproducible than previously developed methods.\(^\text{29,31}\)

The crystalline structure of the vertical cross-section of the MoS\(_2\) film was examined by TEM (see Fig. 4). TEM with energy-dispersive X-ray spectroscopy (TEM-EDS) mapping of the as-direct synthesized MoS\(_2\) thin film showed Mo and S constituting the MoS\(_2\) crystalline structure were uniformly distributed throughout the film. However, there was some O due to air oxidation of the film. Therefore, the results confirm the formation of MoS\(_2\)/p-Si, and the possibility of MoS\(_2\)/MoO\(_3\)/p-Si is excluded.

To confirm the applicability of this method, a MoS\(_2\)/p-Si photocathode was fabricated, and it is clear that the most difficult and time-consuming step (the transfer process) was removed to improve upon previously reported methods.\(^\text{27,29,31}\). The as-fabricated photocathode was used as a working electrode in a three-electrode electrochemical cell filled with 0.5 M sulfuric acid as an electrolyte and was placed under simulated solar irradiation (100 mW/cm\(^2\)). Figure 5a shows the photocurrent onset potential (RHE) vs. current density of the sample under different conditions, confirming the successful fabrication of a MoS\(_2\)/p-Si heterojunction that showed p–n junction behavior. The dark current is shown as the violet–color line. The cost-effective fabrication procedure of bare p-Si, as well as its suitable band gap and crystallinity, are particularly suited for solar hydrogen production.\(^\text{27,40}\)

However, to absorb H\(_2\) onto the p-Si surface, a very large voltage must be applied. Therefore, the integration of a catalyst, such as 2D-TMDs, with p-Si must be performed to achieve efficient hydrogen production performance. MoS\(_2\) (11 nm)/p-Si showed the highest performance with a current density benchmark of \(-13.5 \pm 1\) mA/cm\(^2\) at 0 V and an onset potential of \(+0.02\) V, which is significantly improved over that of bare p-Si (0.2 mA/cm\(^2\) at 0 V and an onset potential of \(-0.38\) V). To investigate the mechanism and catalytic activity of the MoS\(_2\) layers, current density-potential polarization curves were translated to the logarithmic value of the current density as a function of the overpotential (Fig. 5b). From the photoelectrochemical (PEC) measurement results, the MoS\(_2\) (11 nm)/p-Si sample is expected to exhibit the highest catalytic activity. MoS\(_2\) (11 nm)/p-Si exhibited the lowest Tafel slope of 65 mV/dec, which corresponds to the Volmer–Heyrovsky electrochemical mechanism\(^\text{31}\). These results show that the optimization of the MoS\(_2\) layer thickness is essential for achieving the highest performance of the resulting devices. Since the proposed fabrication method is a controllable process, the resulting MoS\(_2\) thin film can be easily optimized. Electrochemical impedance spectroscopy (EIS) is another method that can be used to evaluate photocatalytic activity. The small circle in the EIS Nyquist plot represents the figure of merit for the HER activity, as shown in Fig. 5c. From these EIS results, the smallest circle was obtained for the MoS\(_2\) (11 nm)/p-Si sample, as expected. The fastest movement of electrons between the electrolyte and working electrode was obtained using the optimized MoS\(_2\) (11 nm)/p-Si photocathode. The inset of Fig. 5c shows the Randles equivalent circuit including the active electrolyte resistance (R\(_s\)), charge-transfer resistance (R\(_ct\)), and capacitor. The value of R\(_ct\) was determined to be 66.5 Ω for the optimized MoS\(_2\) (11 nm)/p-Si photocathode, agreeing with the current density results. Because the MoS\(_2\) thin film is relatively transparent, the incident solar light passed through the film and was absorbed by p-Si, generating hole-electron pairs and current induction via electrons moving to the MoS\(_2\) thin film and electrolyte. The stability of the as-optimized MoS\(_2\) (11 nm)/p-Si photocathode was assessed for 20 cycles to clarify the durability of the device for the photoelectrochemical HER (see Fig. 5d). We found a negligible current density shift after 20 cycles (ΔJ = ± 1 mA/cm\(^2\)), which confirmed the excellent stability of the as-fabricated MoS\(_2\) (11 nm)/p-Si photocathode for solar hydrogen production. For the optimized MoS\(_2\)/p-Si photocathode, the current density was stable after 40 h without notable degradation, indicating that the synthesized MoS\(_2\) thin film acts as not only a catalyst for hydrogen production but also an excellent passivation layer that prevents the p-Si photocathode from experiencing severe photocorrosion (see Fig. S4). Therefore, the optimized device prepared by the direct synthesis process...
can be applied for long-term HER activity in acidic solutions under solar illumination. Ultraviolet photoelectron spectroscopy (UPS) measurements were performed to obtain the band diagram and energy levels, and the energy diagram of the optimized MoS2/p-Si heterojunction is shown in Fig. 5e. From the UPS results, the work functions were determined to be 4.67 and 4.48 eV for the optimized MoS2/p-Si and p-Si, respectively. From Fig. 5e, it is clear that for the optimized MoS2, the Fermi level was located at 0.23 eV less than the conduction band (E_c), demonstrating n-type semiconductor behavior. The junction between the n- and p-type semiconductors resulted in band bending and Fermi level equalization. Therefore, the photogenerated carriers (electrons) were easily transferred from p-Si to the n-MoS2 layer. In addition, the proximity of the E_c in MoS2 to the hydrogen reduction potential (E_H^+/H2 = 4.53 eV) facilitated electron transfer from MoS2 to the electrolyte without any significant obstacles.

The results show that the proposed method can provide a reliable and facile procedure for the fabrication of 2D material-based p–n junctions, which can be applied in an efficient manner. Table S1 indicates a comparison between the device performance of the as-direct synthesized MoS2/p-Si photocathode with that of previously reported similar structures, current densities at 0 V vs. RHE and overpotentials for our MoS2/p-Si photocathode and other photocathodes based on 2D material /p-Si.

Conclusions
In conclusion, we developed a controllable method for the direct synthesis of MoS2 on p-Si. Thermolysis is an efficient method for synthesizing MoS2, but a superhydrophilic surface is required for the deposition of the (NH4)2MoS4 precursor onto a nonoxide substrate. Therefore, we added an additional preliminary step (MoO3 deposition) to convert the p-Si wafer from a poorly hydrophilic to a superhydrophilic surface for the precursor coating. The as-fabricated MoO3/(NH4)2MoS4/p-Si was successfully converted to MoS2/p-Si via thermolysis. In addition, the MoS2/p-Si heterojunction was used for solar hydrogen production to confirm the
applicability of the proposed method. The significant advantages of this controllable wafer-scale production process for the reproducible generation of highly crystalline products have the potential to revolutionize the 2D electronic industry in the near future.

**Experimental section**

**Materials**

All three chemicals used for the three-step cleaning process had purities exceeding 99.99% and were purchased from Sigma Aldrich Company. Hydrofluoric acid (HF, 10 vol%), MoO₃ powder (99.97% trace metals basis), ammonium tetrathiomolybdate (99.97% trace metals basis) and sulfur powder (99.98% purity) were purchased from Sigma Aldrich Company. Commercially available p-Si wafer, where p-Si specified with (100) orientation and p-type boron dopant, was used.

**Methods**

**Fabrication of the MoS₂/p-Si heterojunction**

First, p-Si wafers were cleaned ultrasonically using a conventional three-step process, followed by immersion in acetone, isopropyl, and deionized water. Next, the p-Si wafers were immersed in 10% hydrofluoric acid (HF, 10 vol%) to remove the native oxide. Subsequently, different thicknesses (5, 10, 15, and 20 nm) of MoO₃ were deposited onto p-Si using thermal evaporation. Next, a 10 mM solution of ammonium tetrathiomolybdate (NH₄)₂MoS₄ dissolved in glycol ethylene was spin coated onto the MoO₃/p-Si wafers at 4000 rpm for 60 s. Afterward, the samples were placed on a hot plate at 50 °C for 15 min to remove any remaining solvent. Subsequently, the MoO₃/p-Si wafers were placed in a CVD chamber to initiate thermolysis, and N₂ (200 cm³/min) and H₂ (40 cm³/min) gases were flowed in the chamber. Initially, the temperature was raised to 500 °C and was maintained for 30 min. The chamber pressure was maintained under the same N₂/H₂ gas flow at 1.2 Torr. Afterward, the chamber temperature was increased to 900 °C and maintained for 1 h. Finally, sulfurization was initiated using 0.5 g of sulfur powder (Sigma-Aldrich, 99.5% purity) in another heating zone at 350 °C for 1 h. Figure 1 schematically illustrates the preparation process.

**Fabrication of the MoS₂/p-Si photocathode**

To achieve better contact, the backs of the MoS₂/p-Si samples were scratched using a blade, and an InGa alloy (Sigma-Aldrich, 99% purity) was subsequently coated on the scratched samples. Next, a copper wire was connected to the back of the MoS₂/p-Si samples using silver paste and dried on a hot plate at 50 °C for 1 h. Finally, epoxy resin was used to passivate the sample for subsequent PEC measurements. Figure S5 schematically shows the fabrication process.

**Characterization**

X-ray photoelectron spectroscopy (XPS) was performed using a K-alpha plus (ThermoFisher Scientific, USA) instrument under a vacuum of 1 × 10⁻⁷ mbar using Mg Kα radiation (1250 eV) and a constant pass energy of 50 eV. The crystal structures of the thin film samples were determined by X-ray diffraction (XRD) analysis (New DB-Advance, Bruker-AXS, Germany) with a Cu Kα target at 0.1542 nm. Raman spectra (LabRAM HR, Horiba Jobin Yvon, Japan) were obtained at an excitation wavelength of 515 nm. The field-emission scanning electron microscopy (FE-SEM, Zeiss 300 VP) images were obtained at an acceleration voltage of 50 kV. Transmission electron microscopy (TEM) was performed using a JEOL-2100F (Japan) instrument. Atomic force microscopy (AFM, XE-100/PSIA) was used to evaluate the roughness and thickness of the prepared thin films. The transmittance spectra of the thin films were examined by a UV-vis spectrophotometer (V-670).

**Photoelectrochemical measurements**

Electrochemical measurements were performed in 0.5 M H₂SO₄ using a three-electrode quartz electrochemical cell connected to a potentiostat (Ivium 5612, Netherlands). An Oriel 150 W solar simulator was used and calibrated to an output of 100 mW/cm² under AM 1.5 G 100 mW/cm² illumination. A scan rate of 10 mV/s was used for the 15 linear sweeps. EIS was conducted by applying a constant potential of ~0.65 V relative to the open circuit potential with a sweeping frequency ranging from 250 kHz to 0.1 Hz with a 10 mV AC dither.

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**Author details**

1School of Chemical Engineering and Materials Science, Integrative Research Center for Two-Dimensional Functional Materials, Institute of Interdisciplinary Convergence Research, Chung-Ang University, 84 Heukseok-ro, Dongjak-gu, Seoul 06974, Republic of Korea. 2Institute of Research and Development, Duy Tan University, Da Nang 550000, Vietnam. 3Department of Materials Science and Engineering, Research Institute of Advanced Materials, Seoul National University, Seoul, Republic of Korea. 4Department of Materials Science and Engineering, Korea University, 145, Anam-ro Seongbuk-gu, Seoul 02841, Republic of Korea

**Author contributions**

A.H. and Q.V.L. contributed equally to this work. A.H. and Q.V.L. performed the synthesis of the materials and most of the characterization. A.H. and M.T. performed the device characterization. M.J.C. and T.H.L. analyzed the characterization of the materials. H.W.J. and S.Y.K. supervised the experiments and contributed to the manuscript preparation. H.W.J. and S.Y.K. initiated and directed the research. S.Y.K. conceived the idea and designed the experiments. All authors were involved in writing the manuscript.

**Conflict of interest**

The authors declare that they have no conflict of interest.
