

The Graduate School of Science's 16<sup>th</sup> Monthly Seminar

**Title: Atomic-Scale Structural Characterization and Manipulation of Black Phosphorus**



Dr. Yangjin Lee

Visiting Post-doc Scholar and Post-doctoral  
Research Fellow, Department of Physics,  
University of California, Berkeley, USA and  
Yonsei University, Korea, respectively.  
See his publications: <https://bit.ly/2WPvQ9V>

**Speaker: Dr. Yangjin Lee**  
Moderator: Dr. Chan Oeurn Chey

**Friday, 27 August 2021, 9:00 AM-10:00 AM** via Zoom

Scan the QR code or go to: <https://bit.ly/3f5E2ZG>  
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### Talk Summary:

Title: Atomic-Scale Structural Characterization and Manipulation of Black Phosphorus

Black phosphorus (BP), a two-dimensional (2D) layered mono-elemental material, has interesting anisotropy electronic, optical, mechanical, and thermal properties originating from its puckered honeycomb structure. Atomic-scale structural analysis including stacking, defects, and edge structures in BP is essential to fully understand its electronics and optical properties. In this talk, I will discuss atomic-scale characterization and manipulation of BP. Various transmission electron microscopy (TEM) techniques are employed to study BP at atomic-scales. TEM sample fabrication method that minimizes surface degradation of BP is developed. Atomic-resolution TEM imaging and electron diffraction analysis are utilized to analyze BP's structure. Moreover, the modification of BP structure using e-beam, including controlled layer-by-layer etching of BP, the construction of BP nanoribbons, the formation of various BP edge structures, and, is investigated.

## Personal Information

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### Name

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### Affiliation

Korea: Department of Physics, Yonsei University

USA: Department of Physics, UC Berkeley

### Current position

Korea: Postdoctoral research fellow

USA: Visiting postdoc scholar

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## Education & Research Experience

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Jun. 2021 – present	Visiting Postdoc Scholar, Department of Physics, UC Berkeley, USA Advisor: Prof. Alex Zettl
Mar. 2021 – present	Postdoctoral research fellow, Department of Physics, Yonsei University, Korea Advisor: Prof. Kwanpyo Kim
Mar. 2018 – Feb. 2021	Ph.D. Department of Physics, Yonsei University, Korea Advisor: Prof. Kwanpyo Kim
Mar. 2015 – Feb. 2018	Ph.D. course, Department of Physics, Ulsan National Institute of Science and Technology(UNIST), Korea Advisor: Prof. Kwanpyo Kim (Transfer to Yonsei University)
Mar. 2013 – Feb. 2015	M.S. Materials Science and Engineering, Jeonbuk National University, Korea Academy-Research Cooperation Program, Institute of Advanced Composite Materials, Korea Institute of Science and Technology (KIST) Advisor: Prof. Byung Soo Lee and Ph.D. Jun Yeon Hwang (KIST)
Mar. 2007 – Feb. 2013	B.S. Electronic Materials Engineering, Jeonbuk National University, Korea

## Awards and Honors

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Mar. 2021 – Feb. 2026	Sejong Science Fellowship, NRF of Korea
Nov. 2020	Presentation Award, 2020 Korea Physics Society Fall Meeting
Jun. 2020	Grand Prize, Graduate School of Yonsei University Paper Award Spring 2020, Yonsei University

Jun. 2020 – Feb. 2021	Research Subsidies for Ph.D. Candidates, NRF of Korea
Dec. 2019	Poster Presentation Award, ICAMD 2019, The 11 <sup>th</sup> International Conference on Advanced Materials and Devices
Apr. 2019	Presentation Award, 2019 Korea Physics Society Spring Meeting
Nov. 2018	Presentation Award, 2018 5 <sup>th</sup> SGPF Annual Conference
Oct. 2018	Presentation Award, 2018 Korea Physics Society Fall Meeting
Jun. 2018	Poster Presentation Award, 2018 Korean Society of Microscopy Spring Meeting
Apr. 2018	Poster Presentation Award, 2018 Korea Physics Society Spring Meeting
Feb. 2018	Honor Prize, 24 <sup>th</sup> Samsung Human tech, SAMSUNG Electronics Co.
Oct. 2017	Poster Presentation Award, 2017 Korea Physics Society Fall Meeting
Apr. 2017	Presentation Award, 2017 Korea Physics Society Spring Meeting
Oct. 2016	Presentation Award, 2016 Korea Physics Society Fall Meeting
Apr. 2016	Presentation Award, 2016 Korea Physics Society Spring Meeting
Mar. 2015 – Feb. 2018	Global Ph.D. Fellowship, NRF of Korea
Oct. 2014	Excellent Analysis Support Award, Korea Institution of Science and Technology in Jeonbuk (KIST JB)
Mar. 2013 – Feb. 2015	Graduate School Research Scholarship, Jeonbuk National University

## Activities

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Jan. 2016 – Nov. 2019	Organizing Committee, Korea Global Ph.D Fellowship
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## Training

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Jul. 2019	JEOL ARM-200F TEM Training course, JEOL, Japan
Jul. 2014	TEM workshop, Korean Society of Microscopy, Korea
Jun. 2014	Advanced SEM training course, FEI company, Netherlands
Jul. 2013	PLS- 2 summer school & tutorials, Pohang Accelerator Laboratory, Korea
May. 2013	Cryo in the sun Ultramicrotomy course, RMC product, U.S.A.

## Research Skills

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- Material characterization using various tools:  
Transmission electron microscopy (TEM), Cs-corrected TEM/STEM, energy-filtered TEM (EF-TEM), In-situ TEM, energy dispersive X-ray spectroscopy (EDX), electron energy loss spectroscopy (EELS), scanning electron microscopy (SEM), electron back scattered diffraction (EBSD), focused ion beam (FIB), ultra-microtome, X-ray diffractometry, synchrotron X-ray imaging, Raman spectroscopy.
- Operation trained TEM list (Since 2013)  
Tecnai F20 (FEI), Monochromated Image Cs-corrected Titan (FEI, Titan G2),  
Double Image/Probe Cs-corrected ARM (JEOL, ARM200F)
- Synthesis of two-dimensional material using chemical vapor deposition (CVD).
- TEM sample fabrication using various techniques (FIB, microtome, etc.).
- Fabrication of two-dimensional (2D) material-based van der Waals hetrostructures.
- General deposition techniques: thermal evaporation, e-beam evaporation.

## Publications

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### First-authored publications

- [1] **Y. Lee**, H. Kim, T. K. Yun, J. C. Kim, S. Lee, S. J. Yang, M. Jang, D. Kim, H. Ryu, G.-H. Lee, S. Im, J. Cheon, H. Y. Jeong, H. J. Choi, and K. Kim, Single-Crystalline Metallic Films Induced by van der Waals Epitaxy on Black Phosphorus, *Chem. Mater.*, 33, 3593-3601 (2021).
- [2] **Y. Lee**, S. Lee, J.-Y. Yoon, J. Cheon, H. Y. Jeong, and K. Kim, Fabrication and Imaging of Monolayer Phosphorene with Preferred Edge Configurations via Graphene-Assisted Layer-by-Layer Thinning, *Nano Lett.*, 20, 559-566 (2020).
- [3] **Y. Lee**, J. Koo, S. Lee, J.-Y. Yoon, K. Kim, M. Jang, J. Jang, J. Choe, B.-W. Li, C. T. Le, F. Ullah, Y. S. Kim, J. Y. Hwang, W. C. Lee, R. S. Ruoff, H. Cheong, J. Cheon, H. Lee, and Kwanpyo Kim, Universal Oriented van der Waals Epitaxy of 1D Cyanide Chains on Hexagonal 2D Crystals, *Adv. Sci.*, 1900757 (2020).
- [4] J. Jang<sup>‡</sup>, **Y. Lee**<sup>‡</sup>, J.-Y. Yoon, H. H. Yoon, J. Koo, J. Choe, S. Jeon, J. Sung, J. Park, W. C. Lee, H. Lee, H. Y. Jeong, K. Park, and K. Kim, One-Dimensional Assembly on Two-Dimensions: AuCN Nanowire Epitaxy on Graphene for Hybrid Phototransistors, *Nano Lett.*, 18, 6214 (2018). († Equal contribution)
- [5] **Y. Lee**, J.-Y. Yoon, D. Scullion, J. Jang, E. J. G. Santos, H. Y. Jeong, and K. Kim, Atomic-scale imaging of few-layer black phosphorus and its reconstructed edge, *J. Phys. D: Appl. Phys.*, 50, 084003 (2017).

### Co-authored publications

- [1] J.-Y. Lee, J. Kim, Y. Jung, J. C. Shin, **Y. Lee**, K. Kim, N. Kim, A. van der Zande, J. Son, and G.-H. Lee, Evolution of defect formation in atomic precision etching of monolayer MoS<sub>2</sub>, *Commun. Mater.*, Accepted.
- [2] S. Lee, J.-E. Jung, H. Kim, **Y. Lee**, J. Park, J. Jang, S. Yoon, A. Gohsh, M. Kim, J. Kim, W. Na, J. Kim, H. J. Choi, H. Cheong, and K. Kim,  $\gamma$ -GeSe: a new hexagonal polymorph from group IV–VI monochalcogenides, *Nano Lett.*, 21, 4305-4313 (2021).
- [3] X. Du, **Y. Lee**, Y. Zhang, T. Yu, K. Kim, and N. Liu, Electronically Weak Coupled Bilayer MoS<sub>2</sub> at Various Twist Angles via Folding, *ACS Appl. Mater. Interfaces*, 13, 22819-22827 (2021).
- [4] H. Cho, D. Kang, **Y. Lee**, H. Bae, S. Hong, Y. Cho, K. Kim, Y. Yi, J. H. Park, and S. Im, Dramatic reduction of contact resistance via ultrathin LiF in two-dimensional MoS<sub>2</sub> field effect transistors, *Nano Lett.*, 21, 3503-3510 (2021).
- [5] L. J. Widiapradja, T. Nam, Y. Jeong, H.-J. Jin, **Y. Lee**, K. Kim, S. Lee, H. Kim, H. Bae, and S. Im, 2D MoS<sub>2</sub> Charge Injection Memory Transistors Utilizing Hetero-Stack SiO<sub>2</sub>/HfO<sub>2</sub> Dielectrics and Oxide Interface Traps, *Adv. Elect. Mater.*, 2100074 (2021).
- [6] K.-T. Kim, H.-J. Jin, W. Choi, Y. Jeong, H. G. Shin, Y. Lee, K. Kim, and S. Im, High Performance  $\beta$ -Ga<sub>2</sub>O<sub>3</sub> Schottky Barrier Transistors with Large Work Function TMD Gate of NbS<sub>2</sub> and TaS<sub>2</sub>, *Adv. Funct. Mater.*, 2010303 (2021).
- [7] M. Jang, H. Bae, **Y. Lee**, W. Na, B. Yu, S. Choi, H. Cheong, H. Lee, and K. Kim, Unidirectional Alignment of AgCN Microwires on Distorted Transition Metal Dichalcogenide Crystals, *ACS Appl. Mater. Interfaces*, 13, 8727-8735 (2021).
- [8] M. Moschetta, J.-Y. Lee, J. Rodrigues, A. Podesta, O. Varvicchio, J. Son, **Y. Lee**, K. Kim, G.-H. Lee, F. Benfenati, M. Bramini, and A. Capasso, Hydrogenated Graphene Improves Neuronal Network Maturation and Excitatory Transmission, *Adv. Bio.*, 2000177 (2021).
- [9] D. Rossi, X. Liu, **Y. Lee**, M. Khurana, J. Puthenpurayil, K. Kim, A. V. Akimov, J. Cheon, and D. H. Son, Intense Dark Exciton Emission from Strongly Quantum Confined CsPbBr<sub>3</sub> Nanocrystals, *Nano Lett.*, 20, 7321-7326 (2020).
- [10] Y.-J. Kim, **Y. Lee**, K. Kim, and O.-H. K, Light-Induced Anisotropic Morphological Dynamics of Black Phosphorus Membranes Visualized by Dark-Field Ultrafast Electron Microscopy, *ACS Nano*, 14, 11383-11393 (2020).

- [11] T. Kim, D. Kang, **Y. Lee**, S. Hong, H. G. Shin, H. Bae, Y. Yi, K. Kim, and S. Im, Two Dimensional TMD Channel Transistors with ZnO Nanowire Gate for Extended Nonvolatile Memory Applications, *Adv. Funct. Mater.*, 2004140 (2020).
- [12] T. Sriv, T. M. H. Nguyen, **Y. Lee**, S. Y. Lim, V. Q. Nguen, K. Kim, S. Cho, and H. Cheong, Optical phonons of  $\text{SnSe}_{(1-x)}\text{S}_x$  layered semiconductor alloys, *Sci. Rep.*, 10, 11761 (2020).
- [13] S. Choi, N. N. Nguyen, **Y. Lee**, S.-J. Yang, K. Kim, K. Cho, and C.-J. Kim, Nanoscale Molecular Building Blocks for Layer-by-Layer Assembly, *Adv. Mater. Inter.*, 7, 2000522 (2020).
- [14] S. J. Yang, K.-T. Park, J. Im, S. Hong, **Y. Lee**, B.-W. Min, K. Kim, and S. Im, Ultrafast 27GHz cutoff frequency in semitransparent vertical  $\text{WSe}_2$  Schottky diodes with extremely low contact resistance, *Nature Commun.*, 11, 1574 (2020).
- [15] H.-J. Jin, J. Kim, Y. Kim, S. Yoon, **Y. Lee**, K. Kim, and W. Jo, Photo-response in 2D metal chalcogenide-ferroelectric oxide heterostructure controlled by spontaneous polarization, *J. Mater. Chem. C*, 8, 3724 (2020).
- [16] A. D. Nguyen, T. K. Nguyen, C. T. Le, S. Kim, F. Ullah, **Y. Lee**, S. Lee, K. Kim, D. Lee, S. Park, J.-S. Bae, J. I. Jang, and Y. S. Kim, Nitrogen Plasma Treated Continuous Monolayer  $\text{MoS}_2$  for Improving Hydrogen Evolution Reaction, *ACS Omega*, 4, 21509 (2019).
- [17] J. Choe, **Y. Lee**, J. Park, Y. Kim, C. Kim, and K. Kim, Direct imaging of structural disordering and heterogeneous dynamics of fullerene molecular liquid, *Nature Commun.*, 10, 4395 (2019).
- [18] J. K. Won, C. Hwang, K. Ahn, S.-Y. Choi, Y. Lee, J. Kim, **Yangjin Lee**, S. K. Park, I. Chung, C. Kim, K. Kim, S. H. Ahn, M. Lee, and M.-G. Kim, Controlled synthesis of  $\text{SnS}_x\text{Se}_{2-x}$  nanoplate alloys via synergetic control of reactant activity and surface defect passivation control with surfactant and co-surfactant mixture, *J. Solid State Chem.*, 278, 120887 (2019).
- [19] S. J. Yang, **Y. Lee**, J. H. Kim, H. J. Kim, B. K. Choi, H. Y. Jeong, K. Kim, J. S. Choi, and Y. J. Chang, Single-step synthesis of wrinkled  $\text{MoSe}_2$  thin films, *Curr. Appl. Phys.*, 19, 273 (2019).
- [20] J. Yang, K. Kim, **Y. Lee**, K. Kim, W. C. Lee, and J. Park, Self-organized growth and self-assembly of nanostructures on 2D materials, *FlatChem*, 5, 50 (2017).
- [21] F. Ullah, Y. Sim, C. T. Le, M. J. Seong, J. I. Jang, S. H. Rhim, B. C. Tran Khac, K. H. Chung, K. Park, **Y. Lee**, K. Kim, H. Y. Jeong, and Y. S. Kim, Growth and Simultaneous Valleys Manipulation of Two-Dimensional  $\text{MoSe}_2$ - $\text{WSe}_2$  Lateral Heterostructure, *ACS Nano*, 11, 8822 (2017).
- [22] J. W. F. To, J. W. D. Ng, S. Siahrostami, A. L. Koh, **Y. Lee**, Z. H. Chen, K. D. Fong, S. C. Chen, J. J. He, W. G. Bae, J. Wilcox, H. Y. Jeong, K. Kim, F. Studt, J. K. Nørskov, T. F. Jaramillo, and Z. N. Bao, High-performance oxygen reduction and evolution carbon catalysis: From mechanistic studies to device integration, *Nano Res.*, 10, 1163 (2017).
- [23] J. Kim, K. Lim, **Y. Lee**, J. Kim, K. Kim, J. Park, K. Kim, and W. C. Lee, Precise Identification of Graphene's Crystal Structures by Removable Nanowire Epitaxy, *J. Phys. Chem. Lett.*, 8, 1302 (2017).
- [24] J. Choe, **Y. Lee**, L. Fang, G. D. Lee, Z. Bao, and K. Kim, Direct imaging of rotating molecules anchored on graphene, *Nanoscale*, 8, 13174 (2016).
- [25] B. S. Lee, **Y. Lee**, J. Y. Hwang, and Y. C. Choi, Structural properties of reduced graphene oxides prepared using various reducing agents, *Carbon Lett.*, 16, 255 (2015).
- [26] M. S. Kim, D. H. Lee, C. H. Kim, **Y. J. Lee**, J. Y. Hwang, C.-M. Yang, Y. A. Kim, and K. S. Yang, Shell-core structured carbon fibers via melt spinning of petroleum- and wood-processing waste blends, *Carbon*, 85, 194 (2015).
- [27] C. H. Kim, M. S. Kim, Y. A. Kim, K. S. Yang, S. J. Baek, Y.-J. Lee, C.-M. Yang, **Y. Lee**, and J. Y. Hwang, Electro-conductively deposited carbon fibers for power controllable heating elements, *RSC Adv.*, 5, 26998 (2015).

- [28] H. Jeong, H. J. Kim, **Y. J. Lee**, J. Y. Hwang, O.-K. Park, J.-H. Wee, C.-M. Yang, B.-C. Ku, and J. K. Lee, Amino acids derived nitrogen-doped carbon materials for electrochemical capacitive energy storage, *Mater. Lett.*, 145, 273 (2015).
- [29] K.-H. Lee, J.-H. Lee, H.-D. Kang, C.-Y. Han, S. M. Bae, **Y. Lee**, J. Y. Hwang, and H. Yang, Highly fluorescence-stable blue CdZnS/ZnS quantum dots against degradable environmental conditions, *J. Alloys Compd.*, 610, 511 (2014).
- [30] J.-H. Kim, K.-H. Lee, D.-Y. Jo, **Y. Lee**, J. Y. Hwang, and H. Yang, Cu–In–Ga–S quantum dot composition-dependent device performance of electrically driven light-emitting diodes, *Appl. Phys. Lett.*, 105, 133104 (2014).

## International Conferences

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### Oral Presentations

- [1] **Y. Lee**, J. Koo, J.-Y. Yoon, K. Kim, J. Choe, J. Jang, J. Y. Hwang, H. Y. Jeong, Y. S. Kim, H. Cheong, R. S. Ruoff, H. Lee, and K. Kim, Universal Oriental Epitaxy of AgCN Microwires on Various Hexagonal Two-Dimensional Crystals, *2018 International Nanophotonics and Nanoenergy Conference*, Seoul, Korea (2018.08).

### Poster Presentations

- [1] **Y. Lee**, H. Kim, T. K. Yun, J. C. Kim, S. Lee, S. J. Yang, M. Jang, D. Kim, H. Ryu, G.-H. Lee, S. Im, H. Y. Jeong, H. J. Choi, and K. Kim, Epitaxial Growth Single-Crystalline Metal Films on Black Phosphorus, *ENGE 2020, The 6th International Conference on Electronic Materials and Nanotechnology for Green Environment*, Online (2020. 11)
- [2] **Y. Lee**, S. Lee, J.-Y. Yoon, J. Cheon, H. Y. Jeong, and K. Kim, TEM Imaging of Edges and Point Defects in Monolayer Phosphorene, *2020 Microscopy & Microanalysis Virtual Meeting*, Online (2020. 08)
- [3] **Y. Lee**, S. Lee, J.-Y. Yoon, J. Cheon, H. Y. Jeong, and K. Kim, Fabrication and Imaging of Monolayer Phosphorene with Preferred Edge Configurations via Graphene-Assisted Layer-by-Layer Thinning, *ICAMD 2019, The 11th International Conference on Advanced Materials and Devices*, Jeju, Korea (2019. 12).
- [4] **Y. Lee**, J.-Y. Yoon, H. Y. Jeong, and K. Kim, Atomic Resolution Imaging of Single-Layer Phosphorene and Its Crystalline Edge Configurations, *2019 Microscopy & Microanalysis Spring Meeting*, Portland, U.S.A. (2019. 08).
- [5] **Y. Lee**, J. Koo, J.-Y. Yoon, K. Kim, J. Choe, J. Jang, J. Y. Hwang, H. Y. Jeong, Y. S. Kim, H. Cheong, R. S. Ruoff, H. Lee, and K. Kim, Oriental Epitaxy of AgCN Microwires on Various Hexagonal Two-Dimensional Crystals, *2017 Materials Research Society Fall Meeting*, Boston, U.S.A. (2017.11).
- [6] **Y. Lee**, J.-Y. Yoon, H. Y. Jeong, and K. Kim, TEM study of few-layer black phosphorus nanostructure, *7th International Conference on Recent Progress in Graphene Research*, Victoria, Australia (2015.10).
- [7] **Y. Lee**, H. Y. Jeong, and K. Kim, Investigation of atomic structures of few-layer black phosphorous using TEM, *Nano Korea 2015 Symposium*, Seoul, Korea (2015.07).