AFRL-AFOSR-VA-TR-2020-0063

Light-Mass-Atom Semiconductor Materials and Devices

Huili 'Grace' Xing
CORNELL UNIVERSITY

04/24/2020
Final Report

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Huili 'Grace' Xing, Debdeep Jena

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14. ABSTRACT
In the three years of this project, the principal investigators explored four wide- and ultrawide-bandgap semiconductors (AlN, ScAlN, BN,and Ga2O3.), their properties, and potential applications.
The research team published 27 journal papers and 11 conference papers.

15. SUBJECT TERMS
extreme bandgap, AlBN, MOCVD, heterostructure, BGaN, phonon, acousto-electronic

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Grace Huili Xing and Debdeep Jena

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5e. TASK NUMBER

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Ithaca NY 14850-2820

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Arlington VA 22203-1768

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
In the three years of this project, the principal investigators (PIs) have explored four wide- and ultrawide-bandgap semiconductors and their applications: AlN, ScAlN, BN, and Ga_2O_3.

The PIs and their students published 27 journal papers and 11 conference papers. The report briefly summarizes some of the achievements. For more details, please refer to the full list of publications in the end of the report.

15. SUBJECT TERMS

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a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Kenneth C. Goretta
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Final Report on ” Light-Mass-Atom Semiconductor Materials and Devices” (AFOSR#FA9550-17-1-0048)

PIs: Grace Huili Xing & Debdeep Jena
Cornell University
Prepared on April 21, 2020
Performance Period: Dec. 15, 2016 – Dec. 14, 2019

I. MAJOR RESEARCH ACTIVITIES.

In the 3 years of this project, the PIs have explored 4 wide bandgap semiconductors and their applications: AlN, ScAlN, BN and Ga_2O_3.

The PIs and their students published 27 journal papers and 11 conference papers in venues including Science, IEDM etc. Below we briefly summarize some of the achievements. For more details, please refer to the full list of publications in the end of the report.

AlN/GaN/AlN heterostructures: polarization-induced holes for the first time, fundamental understanding of hole mobility and how to improve it, p-channel FETs with record performance and QW n-channel HEMTs.

1. Free holes should be present at the lower GaN/AlN interface due to polarization alone. To this end, we have aimed to achieve 2D hole gas without any intentional doping. 2DHG has been consistently achieved in over 20 1x1 cm^2 growths and more than one 2” wafer in ***completely un-doped heterostructures***, which indicates the compensating point defect levels in our heterostructures are unprecedentedly low! This result appeared in **Science 2019 (Reet Chaudhuri et al.)**.

2. How to engineer hole mobility in GaN to be >100 cm^2/Vs at room temperature from 10-20 cm^2/Vs? This is another exciting topic we have explored. We have discovered by properly straining a GaN channel with polarization-induced holes (therefore they are largely free from impurity scattering), it is possible to reduce the hole effective mass along the current flowing direction by 5X; as a result, it is feasible to improve the hole mobility to be >100 cm^2/Vs (**APL 2019, Sam J. Bader et al; PRL, Ponce et al; PRB, Ponce et al)**!

3. We have developed p-channel FETs based on our high-quality 2DHG in GaN/AlN. P-channel FETs are highly sought since p-FETs enable complementary operation together with n-channel FETs thus much reduced power consumption. We have experimentally achieved ***new record-setting p-channel FETs*** achieving simultaneously an on-current > 100 mA/mm and an on/off ratio >100, which will be presented in **IEEE IEDM 2019 (Sam J. Bader et al), including** highlights: 1) our p++InGaN contacts reliably produce Rc~5-10 ohm-mm, 2) our gate-recessed p-FETs, and 3) our p-FETs deliver >100 mA/um at RT and ~300 mA/um at 77 K.

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4. For QW HEMTs, we demonstrated their advantages – high breakdown field thus voltage, showing the highest Johnson figure-of-merit among all GaN HEMT variations. The results are detailed in an **IEEE EDL 2019 by Austin Hickman et al**.

ScN and AlScN: new nitrides with enhanced properties or completely new properties are one of our strong interests.

1. As Sc-based alloys with AlN and GaN (such as ferroelectric ScAlN) are beginning to be explored by epitaxy, it is essential that the epitaxial growth of the limiting binary ScN thin films and their physical properties are understood. The binary compound scandium nitride (ScN) is part of the family of the transition metal nitride semiconductors, with desirable physical properties such as high hardness, mechanical strength and high temperature stability. Its equilibrium phase has a face-centered cubic (FCC) rock salt (NaCl) structure with a lattice constant of 4.505 A. The (111) lattice constant of cubic ScN is nearly lattice-matched (only ~0.1% difference) to the c-plane lattice constant of wurtize GaN. Our initial study of MBE ScN is reported in an **Casamento et al. APL 2019**. ScN epitaxially grows on hexagonal substrates but maintains its cubic crystalline structure: the 6-fold symmetry revealed in the pole figure is due to twinning of cubic grains not hexagonal ScN! It is also discovered the ScN thin film is degenerately doped, which is most likely similar to InN: in early days the oxygen level is >>10^{19} cm^{-3}.
2. Oxygen incorporation has been identified as a key obstacle in AlScN since O induces shallow trap states in AlScN thus reducing its dielectric strength. This study has been reported by us in **Casamento et al. PSSb 2020**.

BN: both cubic BN and hexagonal BN are intriguing materials, being the counterpart of diamond.

We have grown successfully hBN on sapphire and SiC after overcoming significant learning curves associated with the high temperature Boron effusion cell as well as the ebeam sources in our 1800 °C MBE system. We have not confirmed growth of cBN since a cubic substrate that can sustain high growth temperature is needed. For this reason, diamond substrates are needed. We characterizing the hBN films grown in our lab in collaboration with a few other groups in terms of TEM, XPS, absorption, single photon emitters, PL etc. These results are subsequently published in **Physical Review Materials 2019 by Ryan Page** et al. Highlight results include that at a substrate holder temperature <1600 °C, the resultant MBE hBN is polycrystalline; when grown at a substrate holder temperature >1700 °C – a desorption dominated region, smooth and rotationally aligned hBN on sapphire is confirmed. In fact, a thin layer of AlN forms below hBN as a result of nitridization of the sapphire substrate.

Ga_2O_3 devices: Ga_2O_3 is another wide bandgap semiconductor that can potentially rival GaN, AlN, cBN in terms of high-power applications.

Our team is one of the few that started investigation of Ga_2O_3 for device applications (nanomembrane FETs in DRC-2013 & APL-2014, electron transport in APL-2016, vertical

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SBDs in DRC-2016, thermal transport in APL-2016). In 2017, we investigated dry etching behavior of Ga_2O_3 (**JJAP 2017**), demonstrated the first vertical MISFETs (**DRC-2017**), and MBE growth of Ge-doped Ga_2O_3 and $AlGaO/Ga_2O_3$ heterostructures (WOX-2018). In 2018, >1 kV E-mode transistors and JBSDs are routinely achieved in our lab (**EDL 2018, APL 2018 by Zongyang Hu et al on transistors; APL 2018 and IEDM 2018 by Wenshen Li et al on trench SBDs**). We have also explored carrier dynamics in Ga_2O_3 in collaboration with Prof. Farhan Rana (**APL 2018**). This year we reported a peculiar dependence of fin-orientation in trench SBDs (**APEX 2019**), thermal stability of Ni/Ga_2O_3 Schottky barrier (**DRC 2019**), record-setting Ga_2O_3 trench SBDs with a BV^2/Ron figure-of-merit of 0.78 GW/cm^2 (**DRC 2019**), another new record of 0.95 GW/cm^2 among all Ga_2O_3 power devices (**EDL 2019**), and finally Wenshen Li will deliver his **2nd IEDM paper in 2019** prior to graduation with Ph.D. reporting new record of Ga_2O_3 vertical fin transistors.

II PUBLICATION LIST TO DATE: 27 JOURNAL PAPERS AND 11 CONFERENCE PROCEEDING PAPERS

(J: journal; CP: conference proceeding)

Publication list in 2020:

[J-27] *YongJin Cho*, Celesta S. Chang, *KevinLee, Mingli Gong, Kazuki Nomoto*, Masato Toita, Leo J. Schowalter, David A. Muller, Debdeep Jena, and **Huili Grace Xing**
AlN homoepitaxy by molecular beam epitaxy using Al-assisted desorption of surface native oxides
Appl. Phys. Lett., (2020)
Editor's Pick

[J-26] Lei Li, Kazuki Nomoto, Ming Pan, Austin Hickman, Kevin Lee, Jeffery Miller, Zongyang Hu, Wenshen Li, Samuel James Bader, Soo Min Lee, James C.M. Hwang, Debdeep Jena, and Huili Grace Xing
T-gate InAlN/GaN HEMTs on silicon with fT/fmax of 250/204 GHz
IEEE Electron Dev. Lett., (2020) 10.1109/LED.2020.2984727

[J-25] Reet Chaudhuri, Samuel James Bader, Zhen Chen, David A. Muller, Huili Grace Xing and Debdeep Jena
Molecular beam epitaxy growth of large-area GaN/AlN 2D hole gas heterostructures
Physica Status Solidi B, **257**, 1900567 (2020) https://doi.org/10.1002/pssb.201900567

[J-24] Joseph Casamento, Huili Grace Xing and Debdeep Jena
Oxygen incorporation in the MBE growth of $Sc_xGa_{1-x}N$ *and* $Sc_xAl_{1-x}N$
Physica Status Solidi B, 1900612 (2020) https://doi.org/10.1002/pssb.201900612

[J-23] Wenshen Li, Kazuki Nomoto, Zongyang Hu, Debdeep Jena, and Huil Grace Xing
Field-plated Ga2O3 trench Schottky barrier diodes with a figure-of-merit of up to 0.95 GW/cm2
IEEE Electron Dev. Lett., **41**(1) 107 (2020) **DOI:** 10.1109/LED.2019.2953559

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Publication list in 2019:

[J-22] Samuel Ponce, Debdeep Jena, and Feliciano Giustino
Hole mobility of strained GaN from first principles
Phys. Rev. B 100, 085204/1–16 (2019). http://dx.doi.org/10.1103/PhysRevB.100.085204
Editor's suggestion

[J-21] Yongjin Cho, Yuxing Ren, Huili Grace Xing and Debdeep Jena
High-mobility two-dimensional electron gas at (Al,Ga)GaN/GaN heterostructures grown on GaN bulk wafers and GaN template substrates
Appl. Phys. Express 12, 121003 (2019) https://doi.org/10.7567/1882-0786/ab512c

[J-20] Joseph Casamento, John Wright, Reet Chaudhuri, Huili Grace Xing, and Debdeep Jena
Molecular beam epitaxy growth of scandium nitride on hexagonal SiC, GaN, and AlN
Appl. Phys. Lett. 115, 172101 (2019); doi: 10.1063/1.5121329

[J-19] Reet Chaudhuri, Samuel James Bader, Zhen Chen, David A. Muller, Huili Grace Xing and Debdeep Jena
A Polarization-induced 2D hole gas in undoped gallium nitride quantum wells
Science, **365**, 6460 pp. 1454-1457. (2019). DOI: 10.1126/science.aau8623.
Cornell News Release
http://news.cornell.edu/stories/2019/09/discovery-gallium-nitride-key-enabler-energy-efficient-electronics

[J-18] Samuel Ponce, Debdeep Jena, and Feliciano Giustino
Route to high hole mobility in GaN via reversal of crystal-field splitting
Physical Review Letters 123, 096602 (2019) DOI: 10.1103/PhysRevLett.123.096602
Editor's suggestion

[J-17] Austin Hickman, Reet Chaudhuri, Samuel James Bader, Kazuki Nomoto, Kevin Lee, Huili Grace Xing, and Debdeep Jena
High breakdown voltage in strained AlN/GaN/AlN quantum well HEMTs
IEEE Electron Dev. Lett. 40(8), 1293 (2019) 10.1109/LED.2019.2923085
Featured by Semiconductor Today
http://www.semiconductor-today.com/news_items/2019/jul/cornell-110719.shtml

[J-16] Samuel James Bader, Reet Chaudhuri, Martin Schubert, Han Wui Then, Huili Grace Xing and Debdeep Jena
Wurtzite phonons and the mobility of a GaN/AlN 2D hole gas
Appl. Phys. Lett., 114, 253501 (2019) DOI: 10.1063/1.5099957
Editor's Pick

[J-15] Debdeep Jena, Ryan Page, Joseph Casamento, Phillip Dang, Jashan Singhal, Zexuan Zhang, John Wright, Guru Khalsa, Yongjin Cho, and Huili Grace Xing

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The new nitrides: layered, ferroelectric, magnetic, metallic and superconducting nitrides to boost the GaN photonics and electronics eco-system
J. J. of Applied Physics **58**, SC0801, (2019) https://doi.org/10.7567/1347-4065/ab147b
Open Access

[J-14] Wenshen Li, Kazuki Nomoto, Zongyang Hu, Debdeep Jena, Huili Grace Xing
Fin-channel orientation dependence in kV-class Ga_2O_3 trench Schottky barrier diodes
Appl. Phys. Express, 12, 061007 (2019) https://doi.org/10.7567/1882-0786/ab206c
Featured as Spotlights

[J-13] Samuel James Bader, Reet Chaudhuri, Martin Schubert, Han Wui Then, Huili Grace Xing and Debdeep Jena
Wurtzite phonons and the mobility of a GaN/AlN 2D hole gas
Appl. Phys. Lett., 114, 253501 (2019) DOI: 10.1063/1.5099957
Editor's Pick

[J-12] Ryan Lowry Page, Yongjin Cho, Joseph Casamento, Huili Grace Xing, and Debdeep Jena.
Rotationally aligned hexagonal boron nitride on sapphire by high-temperature molecular beam epitaxy
Physical Review Materials 3, 064001 (2019) DOI: 10.1103/PhysRevMaterials.3.064001
Editor's Suggestion

[J-11] Shyam Bharadwaj, S.M. Islam, Kazuki Nomoto, Vladimir Protasenko, Alex Chaney, Huili Grace Xing and Debdeep Jena
Bandgap narrowing and Mott transition in Si-doped $Al_{0.7}GaN$
Appl. Phys. Lett., **114**, 113501 (2019); https://doi.org/10.1063/1.5086052

[CP-11] S. J. Bader, R. Chaudhuri, A. Hickman, K. Nomoto, S. Bharadwaj, H. W. Then, H. G. Xing and D. Jena
GaN/AlN Schottky-gate p-channel HFETs with InGaN contacts and 100 mA/mm on-current
IEEE International Electron Device Meeting (IEDM) 2019.

[CP-10] Wenshen Li, K. Nomoto, Z. Hu, T. Nakamura, D. Jena and H. G. Xing
Single and multi-fin normally-off Ga2O3 vertical transistors with a breakdown voltage over 2.6 kV
IEEE International Electron Device Meeting (IEDM) 2019.

[CP-9] Wenshen Li, Kazuki Nomoto, Zongyang Hu, Debdeep Jena and Huili Grace Xing
Field-plated Ga_2O_3 trench Schottky barrier diodes with a record high figure-of-merit of 0.78 GW/cm^2
IEEE Device Research Conference (DRC), Ann Arbor, 2019

[CP-8] Wenshen Li, Kazuki Nomoto, Zongyang Hu, Debdeep Jena and Huili Grace Xing
Barrier Height Stability and Reverse Leakage Mechanisms in Ni/Ga_2O_3 (001) Schottky Barrier Diodes

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DRC, June 2019

[CP-7] Kevin Lee, Shyam Bharadwaj, Vladimir Protasenko, Huili Grace Xing and Debdeep Jena
Efficient InGaN p-contacts for deep-UV light emitting diodes
IEEE Device Research Conference (DRC), Ann Arbor, 2019
Best Poster Award

[CP-6] Zongyang Hu, Kazuki Nomoto, Wenshen Li, Riena Jinno, Tohru Nakamura, Debdeep Jena and Huili Grace Xing
1.6 kV vertical Ga_2O_3 FinFETs with source-connected field plates and normally-off operation
IEEE International Symposium on Power Semiconductors and Devices (ISPSD), Shanghai 2019

[CP-5] Samuel Bader, Austin Hickman, Reet Chaudhuri, Kazuki Nomoto, Han Wui Then, Huili Xing and Debdeep Jena
GaN-on-AlN as a superior platform for integrated wide-bandgap electronics
GOMAC, March 2019

Publication list in 2018:

[J-10] Okan Koksal, Nicholas Tanen, Debdeep Jena, Huili Grace Xing and Farhan Rana
Measurement of ultrafast dynamics of photoexcited carriers in beta-Ga2O3 by two-color optical pump-probe spectroscopy
Applied Physics Letters **113**, 252102 (2018). doi: 10.1063/1.5058164
Featured by AIP Scilight https://aip.scitation.org/doi/10.1063/1.5085722

[J-9] Wenshen Li, Zongyang Hu, Kazuki Nomoto, Zexuan Zhang, Jui-Yuan Hsu, Thieu Quang Tu, Kohei Sasaki, Akito Kuramata, Debdeep Jena, Huili Grace Xing
1230 V beta-Ga2O3 trench Schottky barrier diodes with an ultra-low leakage current of <1 uA/cm2
Appl. Phys. Lett. **113**, 202101 (2018); https://doi.org/10.1063/1.5052368
Editor's Pick
Featured by Semiconductor Today
http://www.semiconductor-today.com/news_items/2018/dec/cornell_051218.shtml

[J-8] Samuel James Bader, Reet Chaudhuri, Kazuki Nomoto, Austin Hickman, Zhen Chen, Han-Hui Then, David A. Muller, Huili Grace Xing and Debdeep Jena
Gate-recessed E-mode p-channel HFET with high on-current based on GaN/AlN 2D hole gas
IEEE Electron Device Letters, **39**(12), 1848 (2018) dot:10.1109/LED.2018.2874190
Featured by Semiconductor Today
http://www.semiconductor-today.com/news_items/2018/dec/cornell_311218.shtml

[J-7] Zongyang Hu, Kazuki Nomoto, Wenshen Li, Zexuan Zhang, Nicholas Tanen, Kohei Sasaki, Akito Kurmata, Tohru Nakamura, Debdeep Jena and Huili Grace Xing
Breakdown mechanism in 1 kA/cm^2 and 960 V E-mode Ga_2O_3 vertical transistors
Appl. Phys. Lett. **113**, 122103 (2018) doi: 10.1063/1.5038105

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Editor's Pick
Featured by Semiconductor Today

[J-6] Hugo O. Condori Quispe, Ashish Chanana, Jimy Encomendero, Mingda Zhu, Nicole Trometer, Ajay Nahata, Debdeep Jena, Huili Grace Xing and Berardi Sensale-Rodriguez
Comparison of unite cell coupling for grating-gate and high electron mobility transistor array THz resonant absorbers
J. of Appl. Phys. **124**, 093101 (2018) doi: 10.1063/1.5032102
Editor's Pick
Cover Image of JAP

[J-5] Wenshen Li, Kazuki Nomoto, Kevin Lee, S.M. Islam, Zongyang Hu, Mingda Zhu, Xiang Gao, Andy Xie, Manyam Pilla, Debdeep Jena, Huili Grace Xing
Activation of buried p-GaN in MOCVD regrown vertical structures
Appl. Phys. Lett. **113**, 062105 (2018) DOI: 10.1063/1.5041879
Featured by Semiconductor Today
http://www.semiconductor-today.com/news_items/2018/sep/cornell_060918.shtml

[J-4] Zongyang Hu, Kazuki Nomoto, Wenshen Li, Nicholas Tanen, Kohei Sasaki, Akito Kurmata, Tohru Nakamura, Debdeep Jena and Huili Grace Xing
Enhancement-mode Ga_2O_3 vertical transistors with breakdown voltage >1 kV.
IEEE Electron Dev. Lett., (2018). DOI: 10.1109/LED.2018.2830184
Featured by Semiconductor Today
http://www.semiconductor-today.com/news_items/2018/may/cornell_160518.shtml
News Release at Cornell
http://news.cornell.edu/stories/2018/06/vertical-gallium-oxide-transistor-high-power-efficiency

[CP-4] Wenshen Li, Kazuki Nomoto, Zongyang Hu, Riena Jinno, Zexuan Zhang, Thieu Quang Tu, Kohei Sasaki, Akito Kuramata, Debdeep Jena and Huili Grace Xing
2.44 kV Ga_2O_3 vertical trench Schottky barrier diodes with very low reverse leakage current
IEEE International Electron Device Meeting (IEDM) 2018. Paper 8.5, pp.193-196
DOI: 10.1109/IEDM.2018.8614693

[CP-3] Wenshen Li, Kazuki Nomoto, Zongyang Hu, Nicholas Tanen, Kohei Sasaki, Akito Kuramata, Debdeep Jena and Huili Grace Xing
1.5 kV vertical Ga_2O_3 trench-MIS Schottky Barrier Diodes
IEEE Device Research Conference, University of California, Santa Barbara, June 2018.
DOI: 10.1109/DRC.2018.8442245

[CP-2] Wenshen Li, Mingda Zhu, Kazuki Nomoto, Zongyang Hu, Xiang Gao, Manyam Pilla, Debdeep Jena and Huili Grace Xing
Enhancement of punch-through voltage in GaN with buried p-type layer utilizing polarization-induced doping
IEEE 30th International Symposium on Power Semiconductor Devices and ICs
Chicago, May 2018. DOI: 10.1109/ISPSD.2018.8393644

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Publication list in 2017:

[J-1] Meng Qi, Guowang Li, Satyaki Ganguly, Pei Zhao, Xiaodong Yan, Jai Verma, Bo Song, Mingda Zhu, Kazuki Nomoto, Huili Grace Xing and Debdeep Jena.
Strained GaN quantum-well FETs on single crystal bulk AlN substrates
Appl Phys. Lett., 110, 063501 (2017). doi:10.1063/1.4975702.
Featured by Semiconductor-Today

[J-2] H. Condori Quispe, S.M. Islam, S. Bader, A. Chanana, K. Lee, R. Chaudhuri, A. Nahata, H. G. Xing, D. Jena and B. Sensale-Rodriguez.
Terahertz spectroscopy of an electron-hole bilayer system in AlN/GaN/AlN quantum wells.
Appl. Phys. Lett. 111, 073102 (2017), doi: 10.1063/1.4996925

[J-3] Liheng Zhang, Amit Verma, Huili Grace Xing and Debdeep Jena.
ICP-RIE etch of single crystal β-Ga_2O_3
J. J. Appl. Phys. 56, 030304 (2017). https://doi.org/10.7567/JJAP.56.030304

[CP-1] Zongyang Hu, Kazuki Nomoto, Wenshen Li, Liheng Jerry Zhang, Jae-Ho Shin, Nicholas Tanen, Tohru Nakamura, Debdeep Jena and Huili Grace Xing.
Vertical fin Ga_2O_3 field-effect transistors with on/off ratio >10^9.
IEEE Device Research Conference, June 2017.

IIII AWARDS AND HONORS

in 2019

- APS fellow, Huili Grace Xing
- Best Student Paper Award of IWGO 2019, Riena Jinno
- Best Poster Award at DRC 2019, Kevin Lee
- Cornell Commercialization Fellowship, Austin Hickman
- NSF Graduate Research Fellowship, Jonathan McCandless
- Cornell MSE TA Award of 2019: Ryan Page
- Cornell ECE Best Poster Award of 2019: Shuyao Chen

in 2018

- Chair professorship at Cornell: Huili Grace Xing, and Debdeep Jena
- NIST Uncertainty Analysis Award at the 2018 Electronic Materials Conference, Jimy Encomendero
- IWN 2018 Student Award at the International Workshop on Nitrides, Kevin Lee
- Best Paper Award Honorable Mention at the Compound Semiconductor Week (CSW) 2018, Wenshen Li
- Best Paper Award at the Compound Semiconductor Week (CSW) 2018, Shyam Bharadwaj
- Second place of Best Posters at CCMR Symposium 2018, Kevin Lee

in 2017

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- Shyam Bharadwaj: Best Student Paper Award at DRC 2017
- Nicholas Tanen: Kionix Fellowship awarded by Cornell
- Kevin Lee: Young Scientist Award at IWUVMD 2017
- Debdeep Jena: APS fellow

IV STUDENTS GRADUATED

- Current students involved in the project:
  - Reet Chaudhuri
  - Sam J. Bader, to graduate with PhD in summer 2020
  - Austin Hickman
  - Joseph Casamento
  - Wenshen Li, to graduate with PhD in summer 2020
  - Ryan Page
- Ph.D students:
  - None graduated yet under this project
- M.S students:
  - Anni Wu, MSE'2019;
  - Jui-Yuan (Steven) Hsu, MSE'2019;
  - Ren Zhong, MSE'2019;
  - Vasanth Balakrishman, MSE'2019 (now with ASML)
- M. Eng students:
  - Shuyao Chen, ECE'2019 (now with Intel)
- Undergraduate students:
  - Vineeta Muthuraj, MSE'19 (now PhD student at UCSB)
  - Joshua Lederman, APE'19 (now PhD student at Princeton)

V COLLABORATIONS WITHIN THE PROGRAM

in Year 3 (2019)

- Shin Mou, Kelson Chabak, Adam Neal, Amber Reed and John Cetnar at AFRL
- Darrell Schlom on BaSnO3, resulted in one publication in APLm

in Year 2 (2018)

- Berardi Sensale, University of Utah, collaboration resulted in one publication in APL (J-6)
- Gregg Jessen, Shin Mou, Kelson Chabak, Amber Reed and John Cetnar at AFRL
- Darrell Schlom on BaSnO3

in Year 1 (2017)

- Berardi Sensale, University of Utah, collaboration resulted in one publication in APL (J-1 in the list above)
- Gregg Jessen, AFRL, collaborations on Ga2O3 have been started
- Shin Mou and Kent Averitt, AFRL, conversations were had; still in the process to identify a collaboration project.

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