Office of Naval Research (ONR)

Final Research Performance Progress Report

Jon A. Schuller

University of California at Santa Barbara

Accomplishments

1. Major goals and objectives of the project

The central objective of this project is to develop the fundamental understanding and technical expertise needed to produce efficient light-emitting metasurfaces with novel functionality. The work is divided into four thematic areas:
1) Design, Growth and Fabrication: Goals of this theme are focused around designing, fabricating, and demonstrating metasurfaces that efficiently couple light into desired metasurface-modified channels.
2) Measurement: The primary goal of measurement efforts is accounting for **ALL** the light emitted by luminescent metasurfaces. We aim to develop new measurement capabilities to quantify quantum efficiencies, and the fraction of light directed into metasurface-coupled modes versus other modes of the system.
3) Theory: The overarching goal of theory efforts is to develop new simulation techniques that accurately predict/reproduce experimental results, and in doing so establish simple heuristics that provide intuitive understanding and prediction of the impact of e.g. emitter placement, orientation, inter-pillar coupling, etc.
4) Materials: The primary materials goals are understanding: a) how nanofabrication affects internal quantum efficiencies by modifying radiative lifetimes and transition matrix elements.

2. Accomplishments Towards Project Goals

Accomplishments are divided into the four thematic areas described above
1) We developed and calibrated new fabrication process for producing luminescent GaN metasurfaces and fabricated a variety of different metasurfaces:

- We started with 1D linear phase-gradient “beam-deflecting” metasurfaces based on nanopillar arrays (Fig. 1a). These metasurfaces exhibit excellent unidirectional transmission properties (Fig. 1b), highlighting their potential as passive metasurfaces operating throughout the visible frequency regime, up to the UV bandgap of GaN. Most significantly, these metasurfaces exhibit unidirectional photoluminescence (Fig. 1c), particularly for p-polarized light. Results from beam-deflecting metasurfaces were compared to results from fabricated uniform arrays of nanopillars with similar sizes. Results were published in Nature Photonics
- Adapting design heuristics from 1D beam-deflecting metasurfaces, we designed, fabricated, and demonstrated 2D luminescent metasurface lenses and axicons. Ultimately, we showed successful focusing and beaming of spontaneous emission from the lenses and axicons respectively. Results were published in Nature Communications.

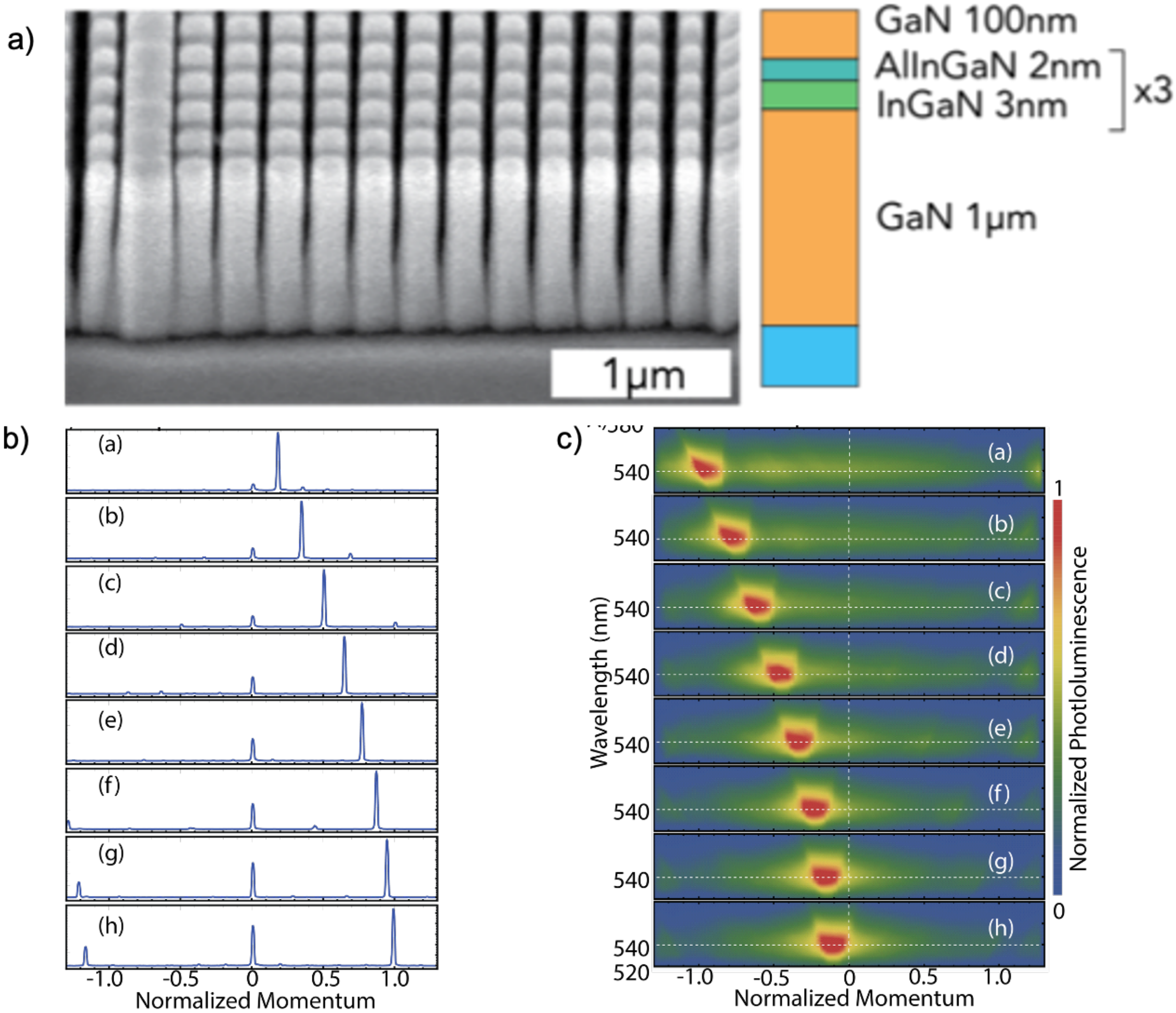

Figure 1. Example experimental results demonstrating metasurface-mediated photoluminescence (PL). a) SEM of a 1D phase-gradient "beam-deflecting" metasurface, along with schematic illustrating the buried quantum well emitters. b) The metasurface exhibits high-efficiency unidirectional transmission lobes under 540nm illumination. Each panel represents a different metasurface, with steeper phase gradients as the panels descent. c) The metasurface exhibits complementary unidirectional 540nm PL lobes, although in this case the lobe represents emission at the critical angle being redirected towards normal exitence.

- A hole-array metasurface platform for electroluminescent (EL) devices was designed, fabricated, and tested. Unfortunately, e-beam results were inconsistent, precluding reliable fabrication. Furthermore, transmission results showed poor beam-deflecting efficiencies, and did not agree well with the high efficiencies predicted by simulation. As a result, we changed tactics and are investigating new approaches for designing and fabricating EL metasurface devices. One such approach that we investigated, but moved on from due to poor performance, was based on planarization and etch-back of 2D metasurface arrays.

- We developed new fabrication recipes for depositing ITO current spreading layers that achieve ~5 times smoother films than the current approach used in the UCSB Nanofab cleanroom.

2) We developed and used a variety of new measurement capabilities:

- We calibrated our homebuilt momentum-resolved spectrometer to enable measurements of 1D beam-steering metasurface quantum efficiencies. We reported between 100-190 fold enhancements of the PL external quantum efficiency (EQE) for emission into air (i.e., NA $\leq$ 1.0) across the range of fabricated metasurfaces. These enhancements are ~ 5-fold larger than uniform arrays of equivalent sized pillars—phasing with metasurface concepts provides superior photon extraction than equivalent periodic structures. We also adapted a collaborator's integrating sphere apparatus to enable EQE measurements of metasurfaces (Figure 2a), which have smaller areas than the system is designed to measure. These Integrating sphere measurements reveal ~ 7-fold enhancements of the EQE over the total 4π emission solid angle. These results were reported in Nature Photonics.
- We adapted our momentum-resolved reflectometry apparatus to measure the dispersion relations of Tamm plasmon modes supported by the interface between a GaN distributed Bragg reflector (DBR) and a metal layer (Figure 2c). These results were published in Optics Express.
- We modified our home-built momentum resolved measurement system to enable transmission experiments where we illuminate metasurfaces with rings in momentum space (Figure 2b) and measure the distribution of transmitted photon momenta (see section 3). This new capability was essential for understanding and comparing transmission and photoluminescence results in various 2D metasurface structures
- We also adapted the system—originally designed purely for Fourier imaging—to allow real space imaging as well. These changes were essential for characterizing the 2D luminescent metasurface lenses and explaining the observed behavior.

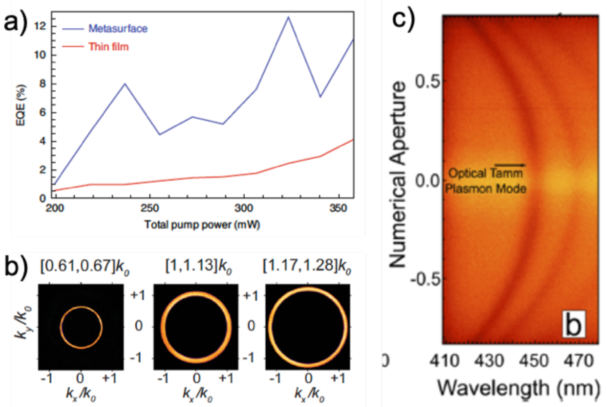

Figure 2. Examples of newly developed measurement capabilities. a) Adapting integrating sphere measurements for small area metasurfaces reveals a 7-10 fold enhancement of external quantum efficiency (EQE) relative to unpatterned thin films. c) Momentum-resolved reflection measurements reveal Tamm plasmons at the interface of a metal and GaN-based distributed Bragg Reflector (DBR)

3) We made considerable progress in our ability to describe the performance of our light-emitting metasurfaces via both analytical and numerical calculations.

- We started with analytical reciprocity-based LDOS calculations of emission patterns from 1D beam-deflecting metasurfaces. This "toy-model" does a good job predicting the location of unidirectional emission lobes, but did not have strong quantitative prediction powers nor could it explain e.g. the strong polarization dependence observed in experiments. This work was reported in our Nature Photonics publication. These discrepancies were resolved in later numerical simulation work described below.

- We adapted our LDOS model that was specific for 1D phase-gradients to describe photoluminescence from 2D phase-gradient metasurface axicons (Figure 3a). These simulations used input experimental parameters from experiments described above in section 2) and were reported in our Nature Communications publication.
- We completed first successful numerical simulations of 1D beam-deflecting metasurfaces. These simulations used a numerical reciprocity-based approach that is otherwise conceptually to our analytical LDOS models. These simulations showed excellent agreement with experimental results, validating their use for future design work (Figure 3c).

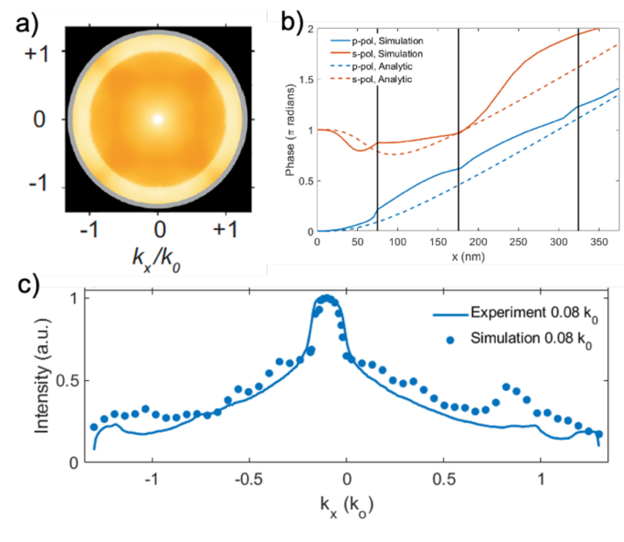

Figure 3. Examples of newly developed theory capabilities. a) Analytical calculation of expected PL radiation patterns from a 2D metasurface axicon. b) Analytical calculation and simulation of interpillar coupling phase, showing the different coupling phase for s- and p-polarized geometries. c) Reciprocity based numerical simulation of metasurface mediated PL shows good agreement with experiments.

- Using different, dipole-based simulations we showed that relative orientation-dependent phase shifts between driving dipoles and induced dipoles (Figure 3b) explains why we only see directed light emission for one polarization (p-pol).
- We used simulation results to perform a first optimization study of 1D beam-deflecting metasurface, resulting in ~ 2 fold enhancements of metasurface directivities while also, developing new insight into how to direct more of the PL into desired metasurface-mediated channels
- Using our newfound simulation capabilities, we demonstrated a new metasurface designs for producing directed PL into air (previous results were all for emission into the substrate), and for producing directed s-polarized PL (as opposed to p-pol).
- Results for the previous 4 bullet points were summarized in a journal manuscript that is currently under review.
- We completed our first successful simulation of focused Pl from a metasurface lens, and established constraints on what lenses we can accurately simulate given computational constraints.

4) Coupled with theme 2 we showed that metasurface fabrication significantly enhances IQE through reduction in the quantum confined stark effect. Also:

- We completed preliminary studies of lasing in quantum well metasurfaces using pumped sources (collaboration with Sandia labs), observing no evidence of a transition to lasing, even as pump powers reach the material's damage threshold.
- We reconfigured our fabrication recipes to accommodate our collaborators' changes in the Quantum Well growth recipes and geometries.

What opportunities for training and professional development did the project provide?

This primarily supported two graduate students, Ryan DeCrescent and Larry Heki. Both students learned and developed new experimental and theoretical techniques and expertise. Graduate students Sepanta Assadi and Zihad Asad also contributed to the project. Additionally, postdoctoral scientist Dr. Yahya Mohtashami is the lead experimentalist on this project. This program supports his myriad efforts, but not his salary/benefits.

How were the results disseminated to communities of interest?

Results from this project were published in Nature Photonics, Optics Express, and Nature Communcations. PI Jon Schuller spoke about this work at the following conferences, workshops, and universities: Frontiers in Optics, North Carolina State Materials Science and Engineering Seminar, International Conference on Materials for Advanced Technologies, Columbia University, Raytheon Vision Systems, IEEE RAPID, International Conference on Advanced Materials and Devices, UCSB Graduate Physics Seminar, SPIE Photonics West (2021 and 2022), SPIE Optics and Photonics, DOE LED R&D Workshop, IEEE COMCAS Meeting. Group member Ryan DeCrescent reported results at the 2020 CLEO conference. Group member Yahya Mohtashami reported results at the 2020 and 2021 CLEO conferences, 2021 International Congress on Artificial Materials for Novel Wave Phenomena, and UCSB Nitrides Seminar.

Products

Journal Publications

1. Iyer, P.P., DeCrescent, R.A., Mohtashami, Y., Lheureux, G., Butakov, N.A., Alhassan, A., Weisbuch, C., Nakamura, S., DenBaars, S.P. and Schuller, J., 2020. Unidirectional luminescence from InGaN/GaN quantum-well metasurfaces. *Nature Photonics*, *14*(9), pp.543-548.
2. Mohtashami, Y., DeCrescent, R.A., Heki, L.K., Iyer, P.P., Butakov, N.A., Wong, M.S., Alhassan, A., Mitchell, W.J., Nakamura, S., DenBaars, S.P. and Schuller, J., 2021. Light-emitting metalenses and meta-axicons for focusing and beaming of spontaneous emission. *Nature communications*, *12*(1), pp.1-7.
3. Lheureux, G., Monavarian, M., Anderson, R., DeCrescent, R.A., Bellessa, J., Symonds, C., Schuller, J.A., Speck, J.S., Nakamura, S. and DenBaars, S.P., 2020. Tamm plasmons in metal/nanoporous GaN distributed Bragg reflector cavities for active and passive optoelectronics. *Optics Express*, *28*(12), pp.17934-17943.

Conference Proceedings

4. Mohtashami, Y., DeCrescent, R.A., Iyer, P.P., Butakov, N.A., Mitchell, W.J., Alhassan, A., Nakamura, S., DenBaars, S.P. and Schuller, J.A., 2020, May. Light-Emitting Metasurfaces: A

Metalens Approach for Focusing Spontaneous Emission. In *CLEO: QELS_Fundamental Science* (pp. FTu4Q-4). Optical Society of America.

5. DeCrescent, R.A., Iyer, P.P., Mohtashami, Y., Lheureux, G., Butakov, N.A., Alhassan, A., Weisbuch, C., Nakamura, S., DenBaars, S.P. and Schuller, J.A., 2020, May. Unidirectional Luminescence from InGaN/GaN Quantum-Well Metasurfaces. In *CLEO: QELS_Fundamental Science* (pp. FTu4Q-6). Optical Society of America.

6. Mohtashami, Y., Heki, L.K., Alhassan, A., Nakamura, S., DenBaars, S.P. and Schuller, J.A., 2021, May. Controlling Spontaneous Emission with Nanohole-Based Phased-Array Metasurfaces. In *2021 Conference on Lasers and Electro-Optics (CLEO)* (pp. 1-2). IEEE.

Mohtashami, Y., DeCrescent, R., Heki, L., Iyer, P., Butakov, N., Wong, M., Alhassan, A., Mitchell, W., Nakamura, S., DenBaars, S. and Schuller, J., 2021, September. Luminescent Metalenses for Focusing Spontaneous Emission. In *2021 Fifteenth International Congress on Artificial Materials for Novel Wave Phenomena (Metamaterials)* (pp. 281-283). IEEE.

REPORT DOCUMENTATION PAGE

1. REPORT DATE 20220414	**2. REPORT TYPE** Final Performance Report	**3. DATES COVERED** **START DATE** 20190101	 **END DATE** 20211231

4. TITLE AND SUBTITLE
Light Emitting GaN Quantum Well Metasurfaces

5a. CONTRACT NUMBER	**5b. GRANT NUMBER** N00014-19-1-2004	**5c. PROGRAM ELEMENT NUMBER**
5d. PROJECT NUMBER	**5e. TASK NUMBER**	**5f. WORK UNIT NUMBER**

6. AUTHOR(S)
Schuller, Jon A.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of California, Santa Barbara Office of Research, 3227 Cheadle Hall Santa Barbara, CA 93106-2050	**8. PERFORMING ORGANIZATION REPORT NUMBER**

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research 875 N. Randolph Street, Suite 1425 Arlington, VA 2223-1995	**10. SPONSOR/MONITOR'S ACRONYM(S)**	**11. SPONSOR/MONITOR'S REPORT NUMBER(S)**

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for Public Release; Distribution is Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The central objective of this project is to develop the fundamental understanding and technical expertise needed to produce efficient light-emitting metasurfaces with novel functionality. Progress in the project is summarized and divided into four technical areas: 1) Design, growth and fabrication, 2) measurement, 3) theory, and 4) materials.

15. SUBJECT TERMS
metasurface, GaN, quantum well, light emission

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**
a. REPORT U	**b. ABSTRACT** U	**C. THIS PAGE** U	UU	7

19a. NAME OF RESPONSIBLE PERSON Schuller, Jon A.	**19b. PHONE NUMBER** *(Include area code)* 805-893-4295