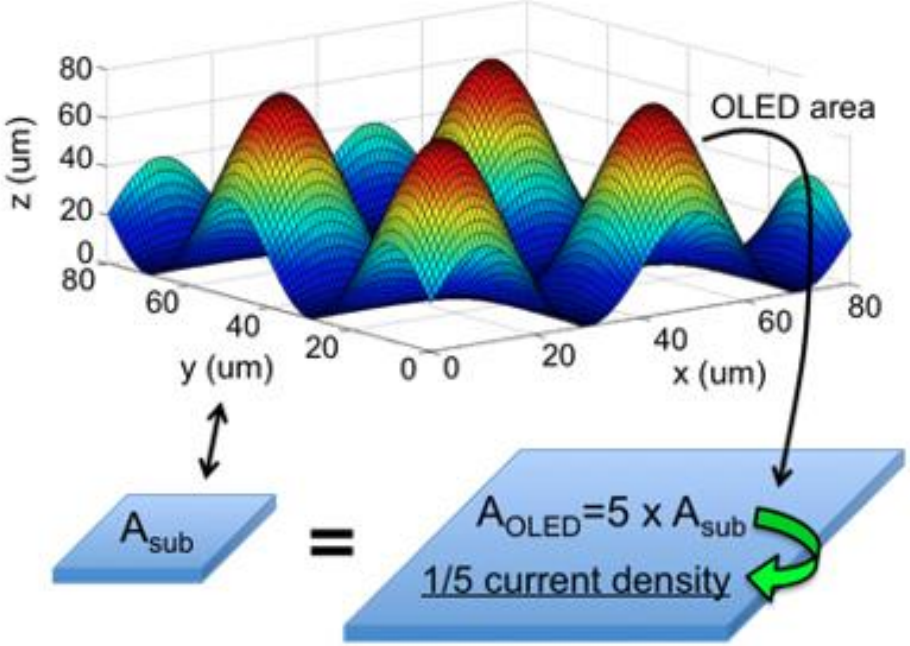
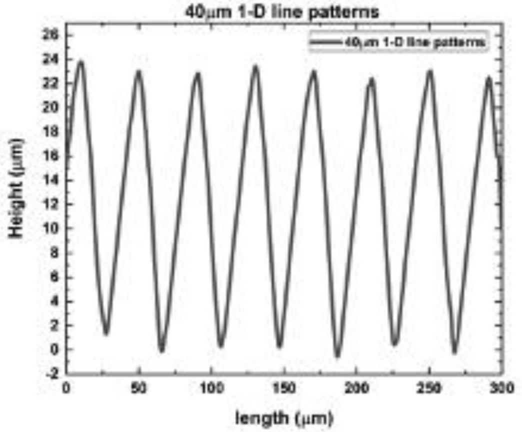
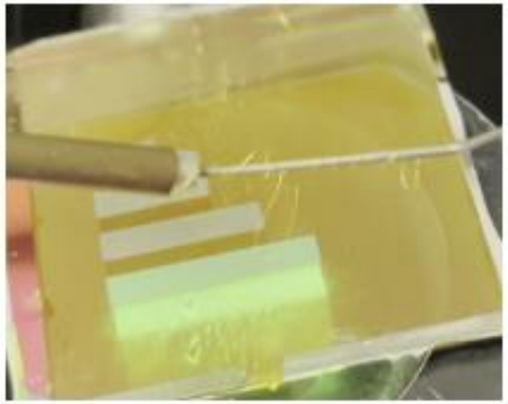
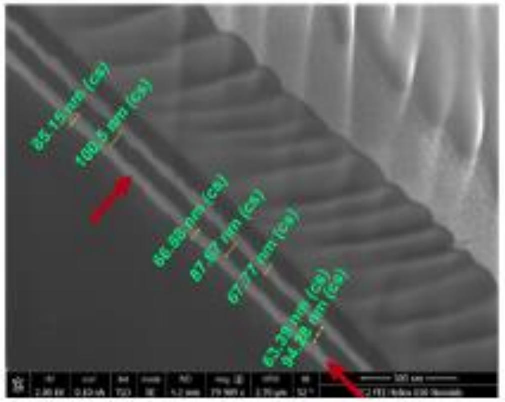
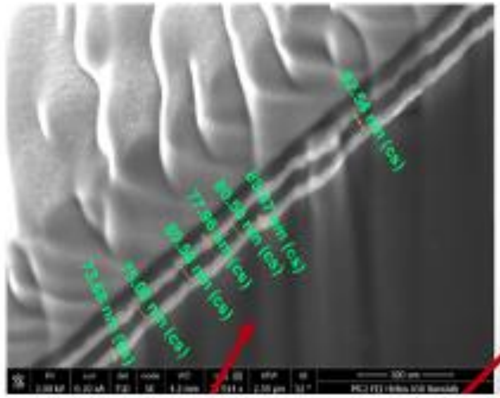
High Aspect Ratio OLEDs

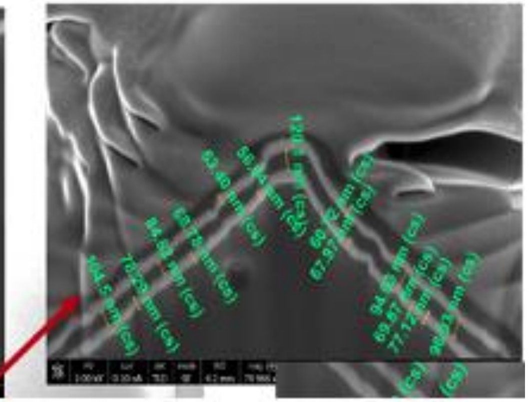












Penn State University, University of Michigan, OLEDWorks, LLC
Chris Giebink, Professor
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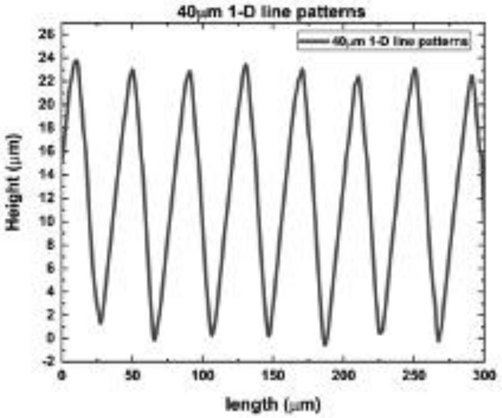
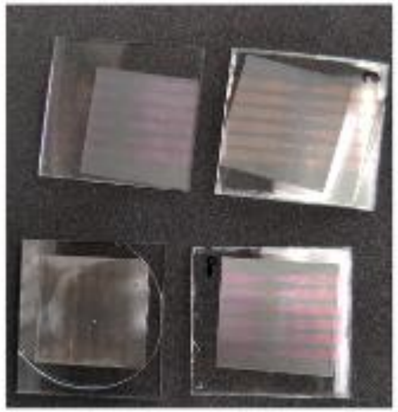
DE-EE0009694

Project Summary

Objective and outcome

Goal is to realize OLEDs on substrates with high aspect ratio surface texture to increase the OLED active area per unit panel area. If successful, this will enable the same panel brightness to be achieved at lower OLED current density, thereby increasing lifetime by at least the area enhancement factor (β), while also boosting internal quantum efficiency and reducing drive voltage.





Team and Partners

Penn State (PSU): creation of high aspect ratio substrates, vacuum deposition of prototypes

Univ. of Michigan (UM): vacuum and organic vapor phase deposition on high aspect substrates

OLEDWorks: Deposit stacked OLEDs and test scalability on manufacturing pilot line

Stats

Performance Period: 10/2021 – 9/2024

DOE budget: $1.35M, Cost Share: $0.34M

Milestone 1: Demo single stack OLED w/ β>1.5

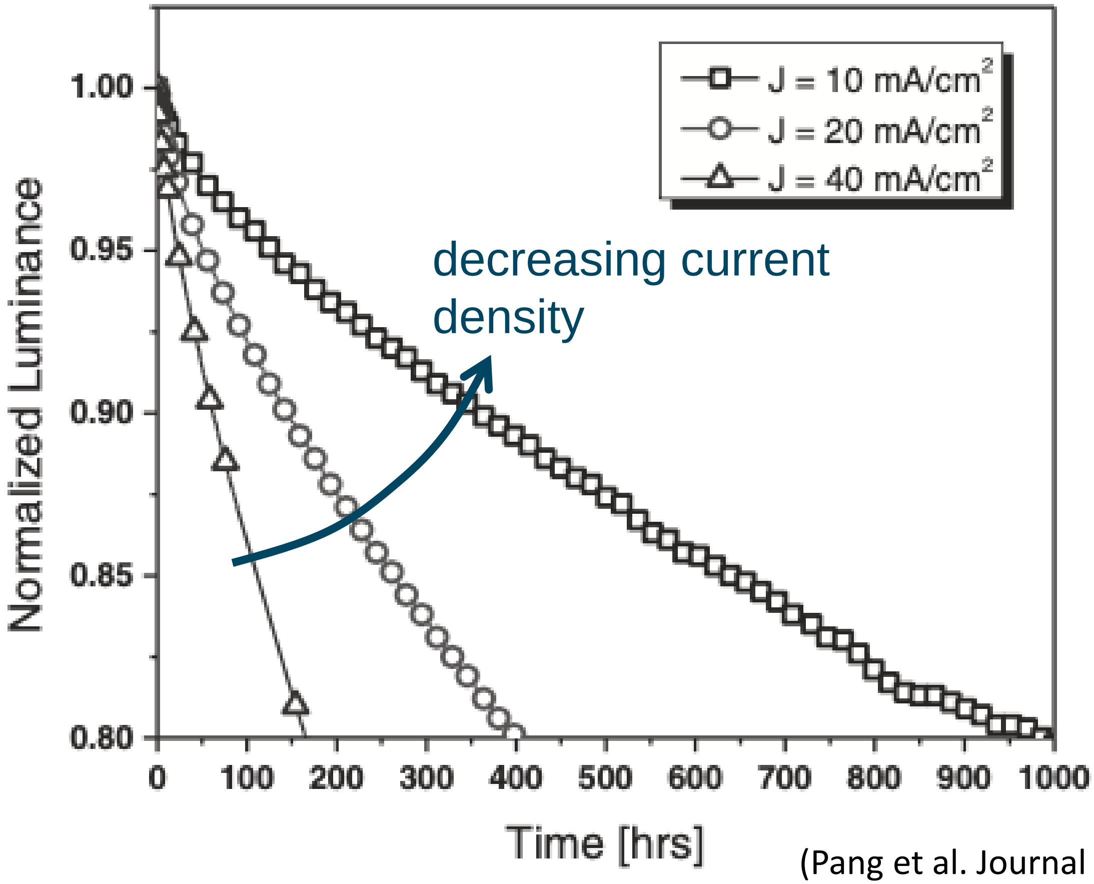
Milestone 2: Validate β-lifetime scaling

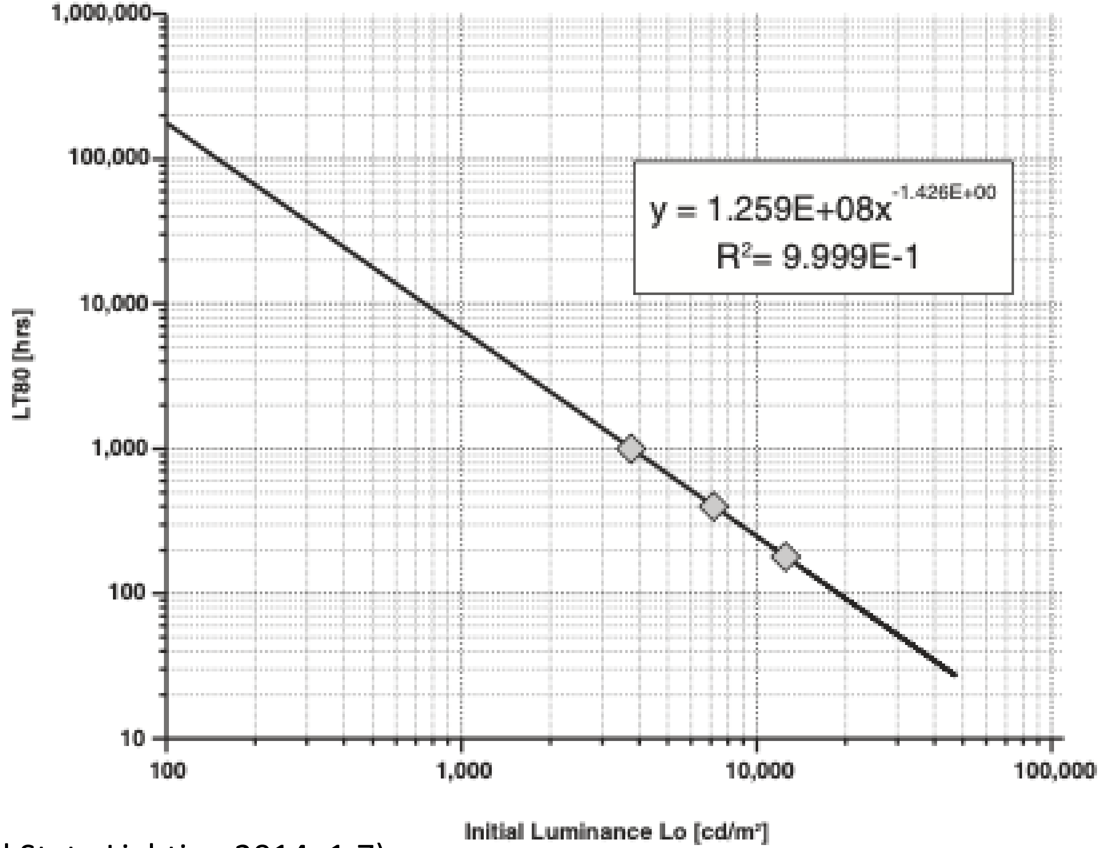
Milestone 3: Demo stacked white OLEDs with 2x lifetime of SOTA planar controls

Problem

Reliability of OLED lighting must improve for widespread adoption (DOE MYPP 2019)

→ Intrinsic OLED degradation scales inversely with current density





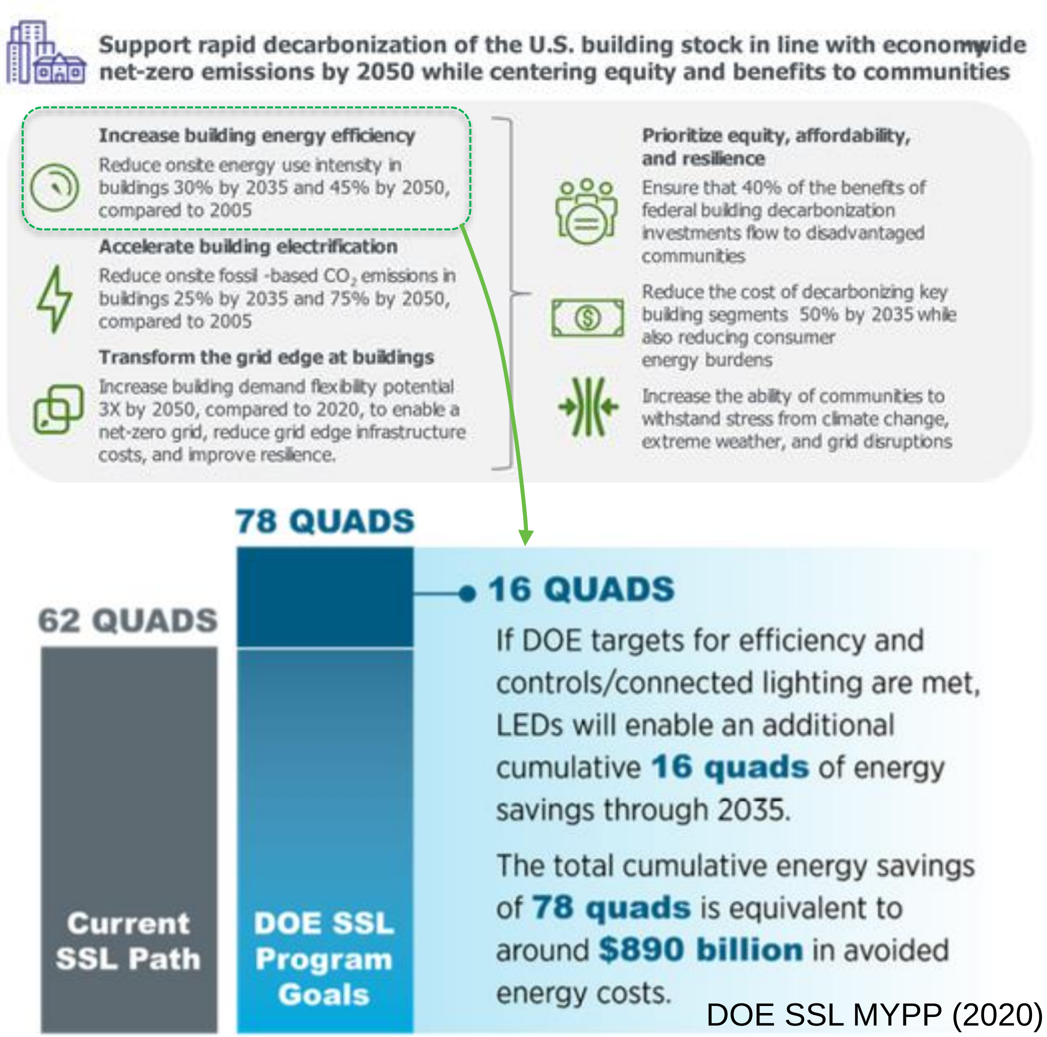
(Pang et al. Journal of Solid State Lighting 2014, 1:7)

Alignment and Impact

Goal of this project is to double OLED lifetime and increase efficiency *without* increasing cost.

If successful, this would:

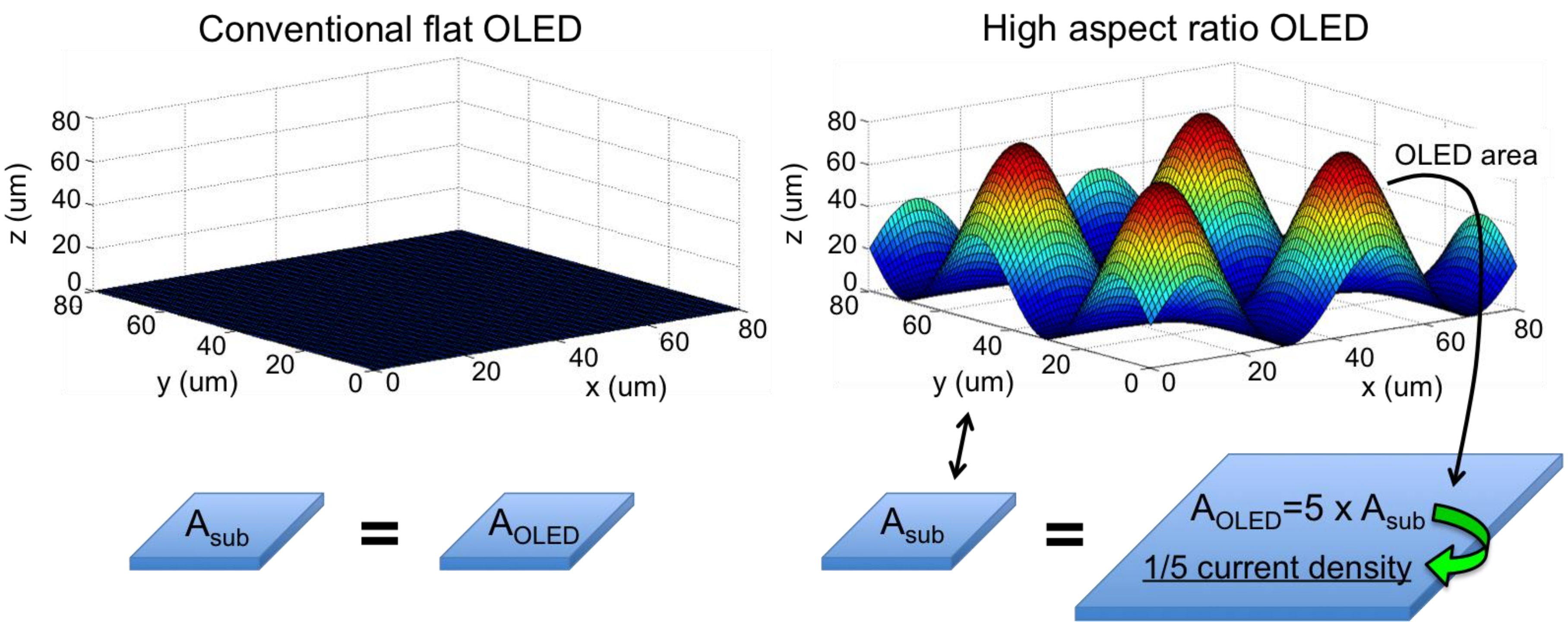
- Improve efficiency (lm/W)
- Decrease panel cost ($/klm)
- Reduce warranty costs
- Improve OLED perception within lighting market
- Improve competitiveness with manufacturers in Asia
- Fewer dead panels → lower OLED lifecycle cost



DOE SSL MYPP (2020)

The High Aspect Ratio Approach

- Create more OLED active area per unit panel area by moving to 3D
- Same *total* panel current, but reduced *local* current density
- Efficiency and lifetime both ∝ 1/J



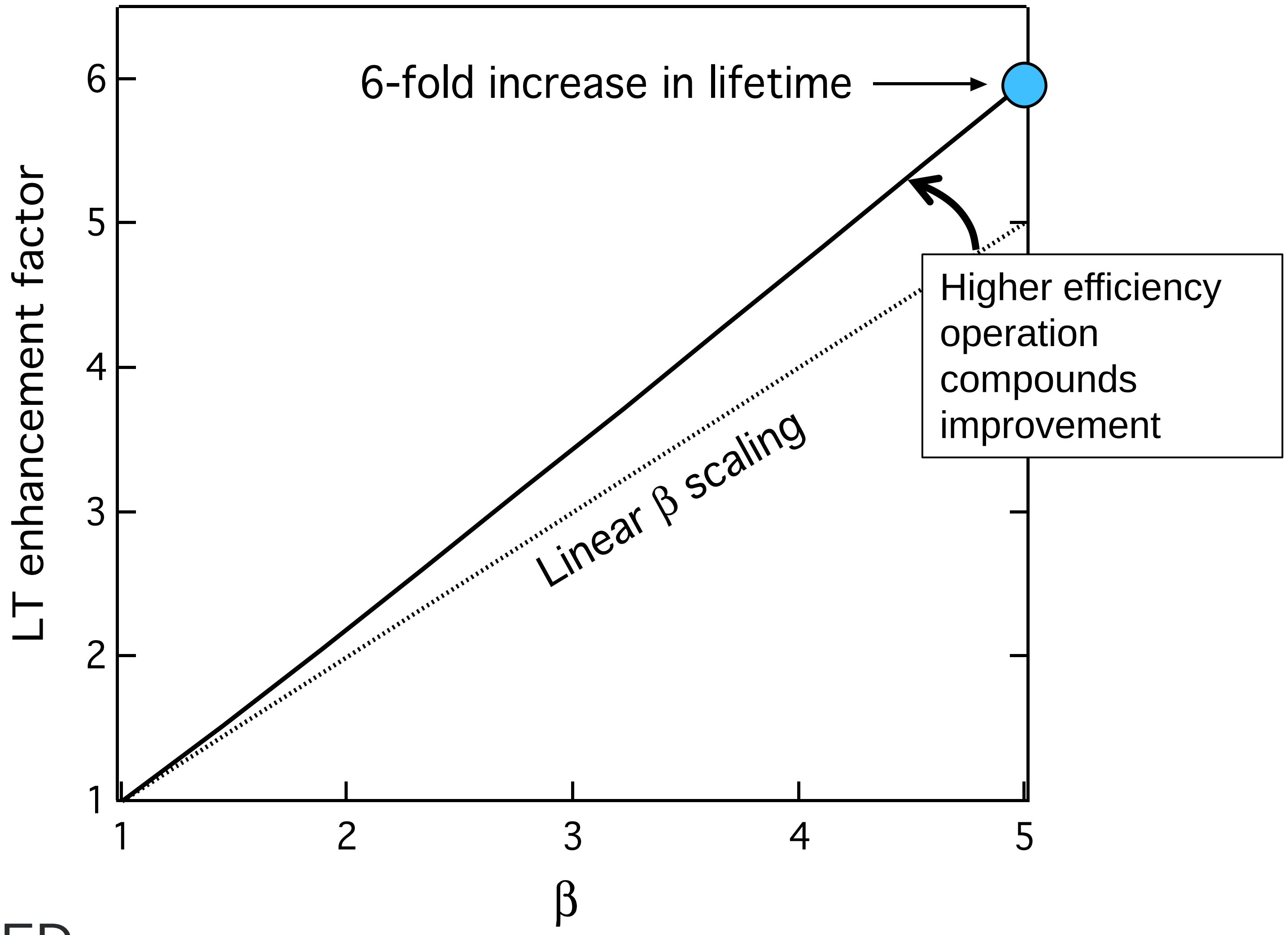
- Current industry strategy: Stacked OLEDs
  → Effectively does the same thing, but has a practical upper limit of ~6 stacks
  → High aspect ratio could extend with little added cost

Potential benefits: Lifetime

- Superlinear increase in lifetime with area enhancement factor, β.
  - Current density $J \propto 1/\beta$
  - Lifetime $LT \propto (1/J)^{\gamma}$

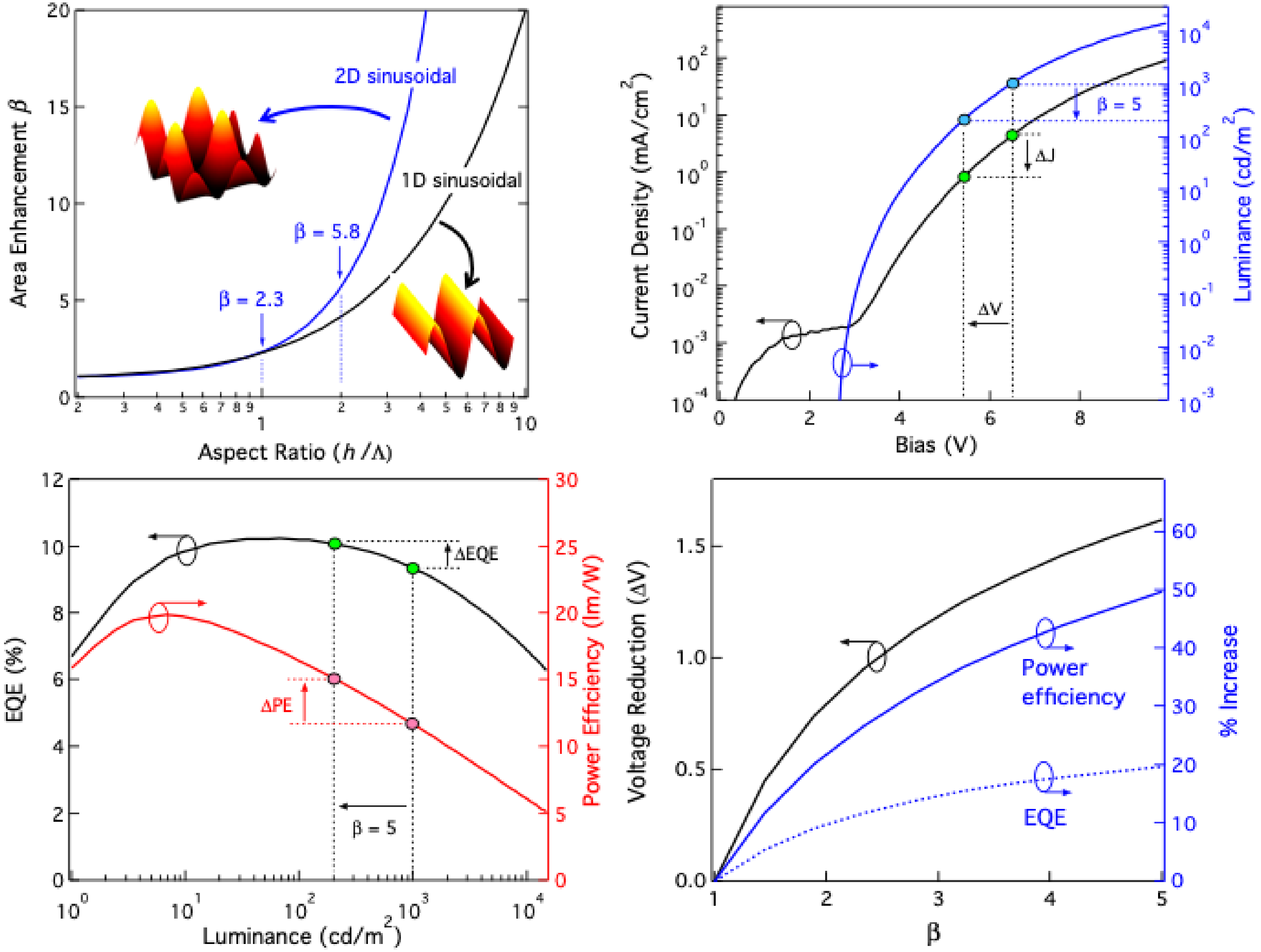
  → $LT \propto (\beta)^{\gamma}$

- Compounding factors:
  - Higher efficiency → lower current
  - Distributed heat load → cooler OLED



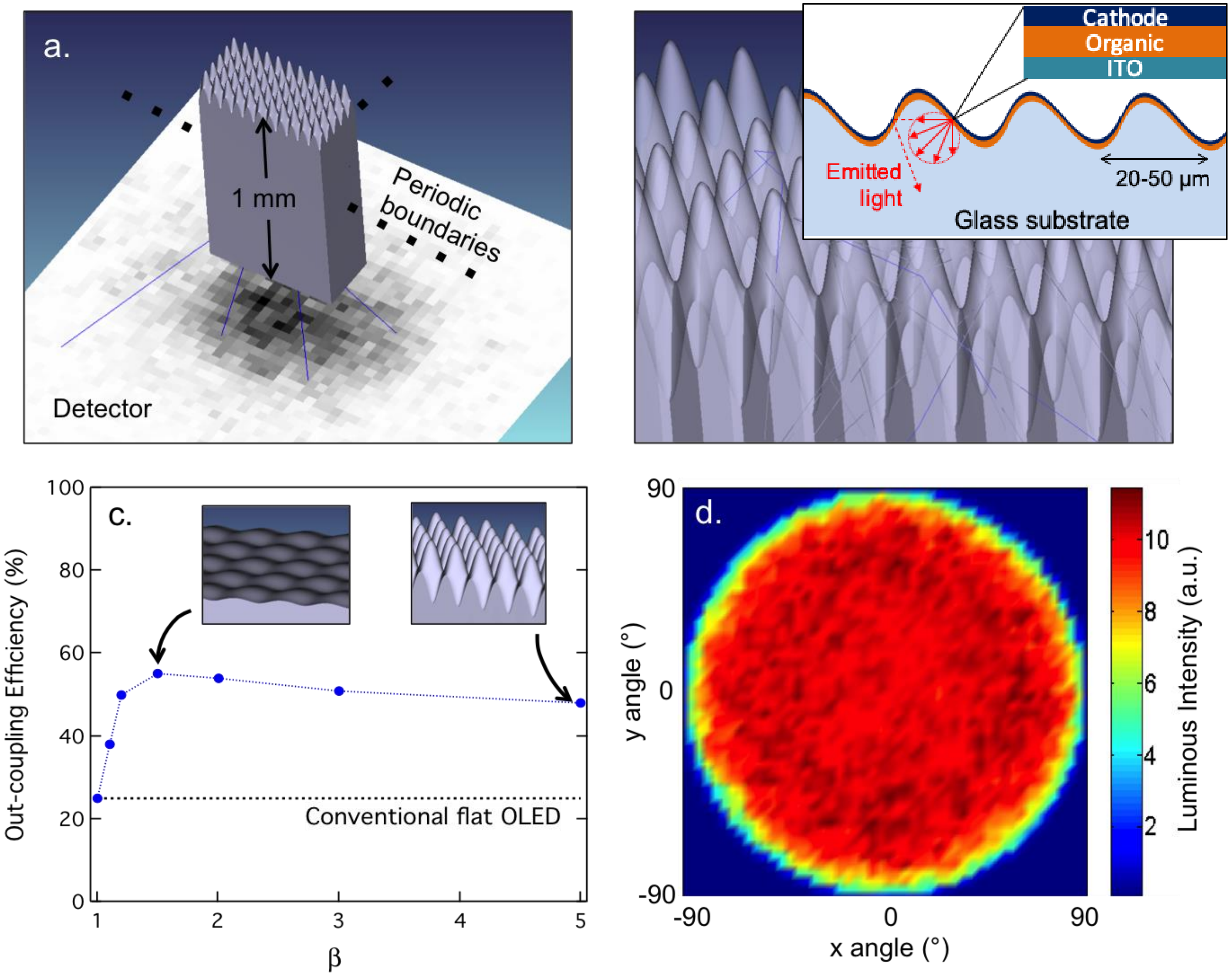
Potential benefits: Efficiency

- For a 2x area enhancement at 1000 cd/m^2:
  - 10% reduction in drive voltage
  - 10% increase in internal quantum efficiency
  - 25% increase in power efficiency



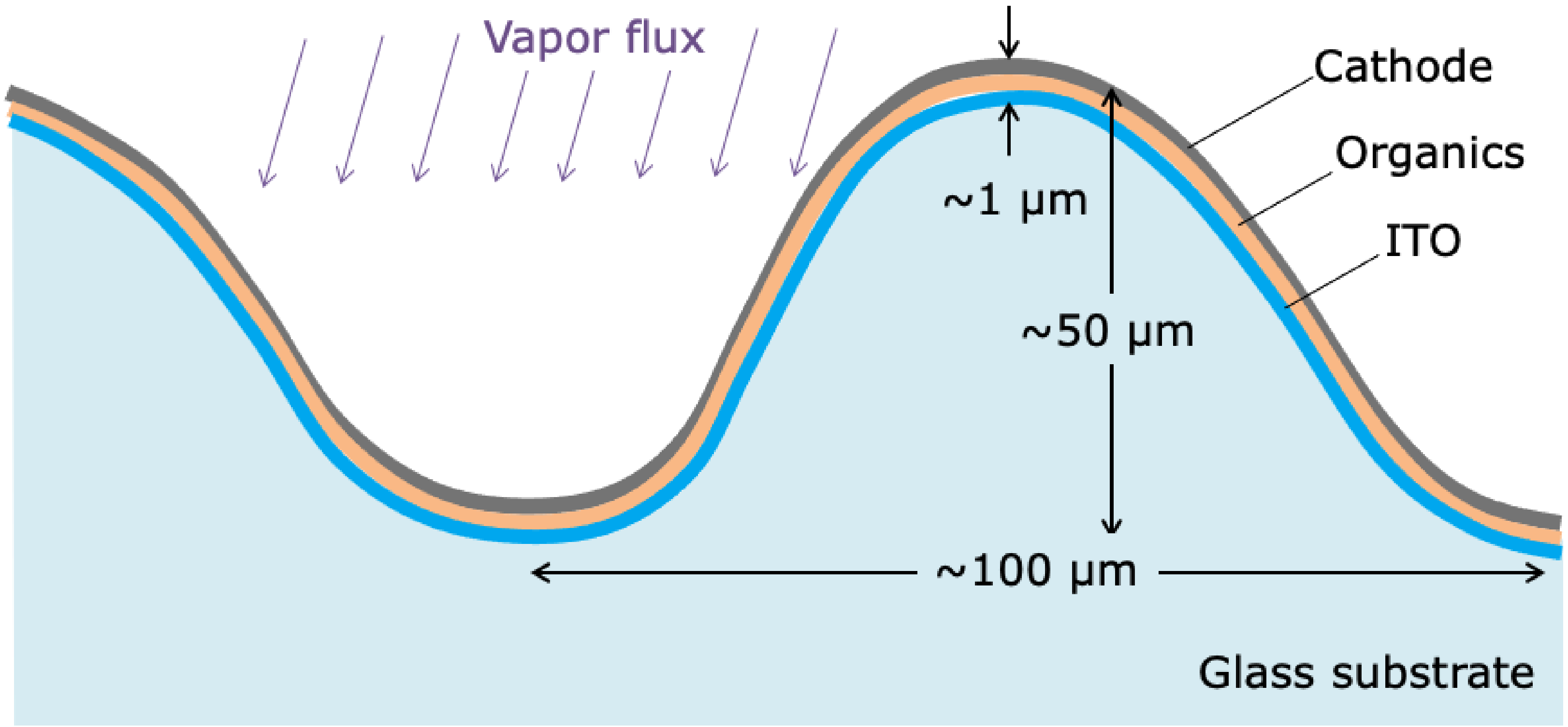
Potential benefits: Light outcoupling

- OLED texture scatters out trapped light
  - Ray tracing predicts 2x increase in outcoupling for β>1.5
  - Light extraction comparable to microlens arrays
  - Lambertian white output maintained



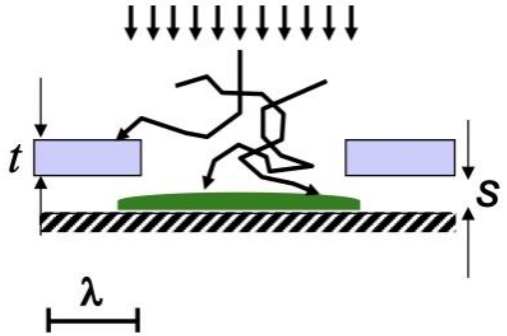
The challenge

- Need to make OLEDs on high AR that are equivalent to planar:
  - Uniform layer thickness. No shunts or hot spots
  - Compatible with high-throughput deposition
  - High AR substrates must be scalable, economical, reliable



How we will do it

- Project plan:
  1. Fabricate textured substrates with conformal anode
  2. Model organic deposition uniformity
  3. VTE proof-of-concept at PSU & UM; SOTA at OW
  4. Progress systematically: β=1.3 → β=1.5 → β=2



OLEDWorks production line in Aachen

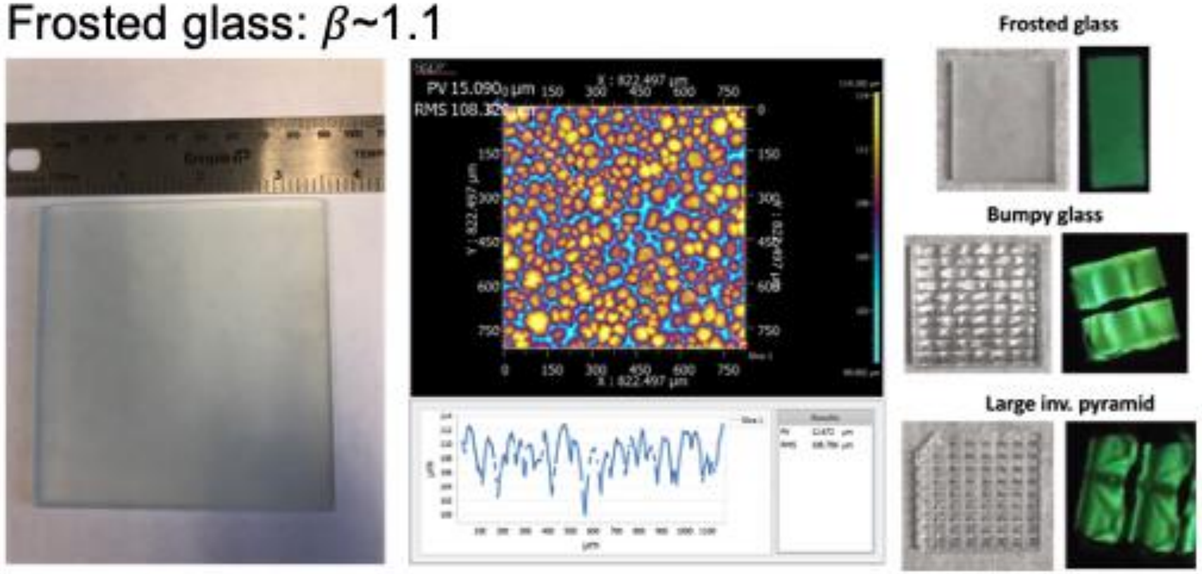
- What if things go wrong?
  - Have OVPD for risk mitigation
  - Not *if* successful, but by *how much*

- What will be demonstrated in the end?
  - β=2 stacked WOLED with >2x lifetime, equal or better efficacy than planar SOTA
  - Pilot line demonstration at OLEDWorks' Rochester facility → transition technology

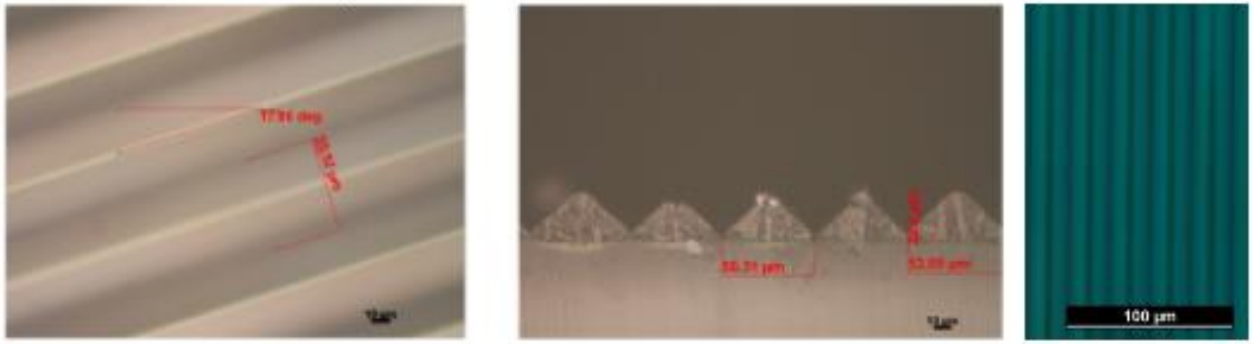
Progress: Textured substrates

Off-the-shelf solutions

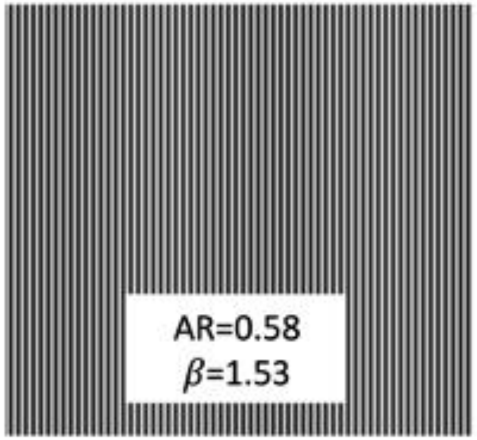
Frosted glass: β~1.1

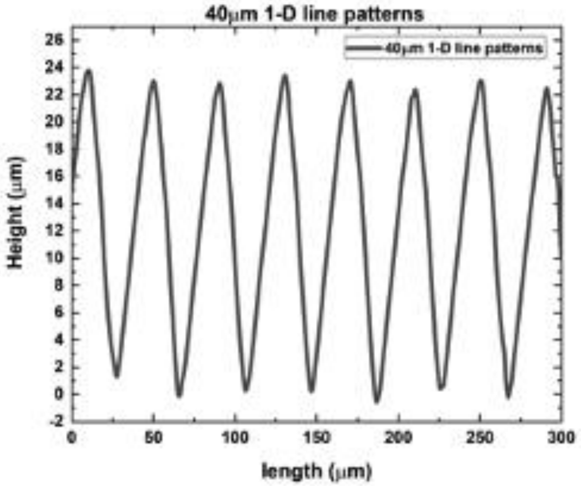


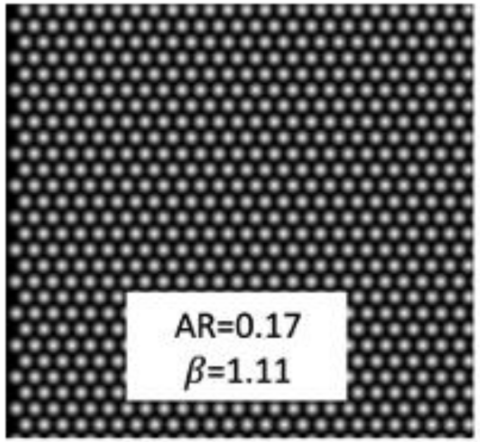
Embossed film: β~1.5

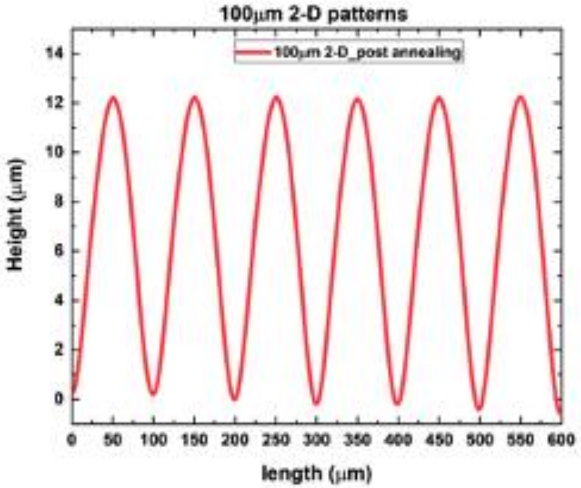


Gray-scale litho + replication



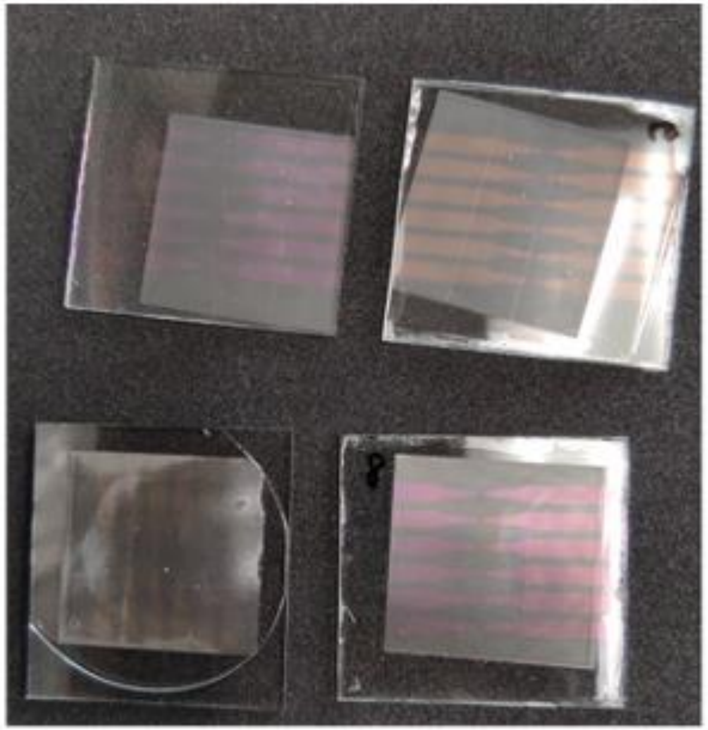






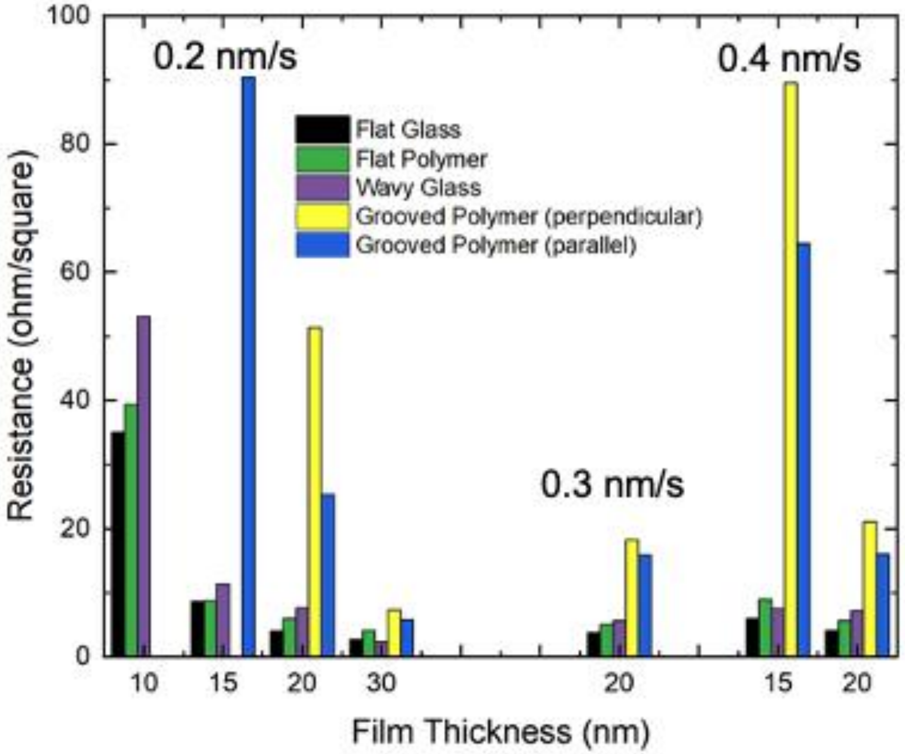
Progress: Conformal anodes

Replicate textures on glass



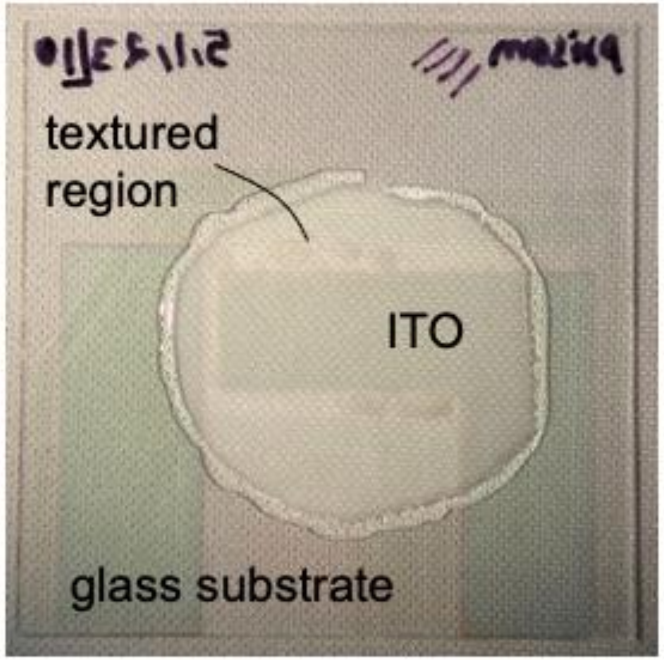
High temperature, UV-curable adhesive on glass

Metal anode for top emission



30 nm planetary Au enables <10 Ω/sq on β=1.5

ITO anode for bottom emission

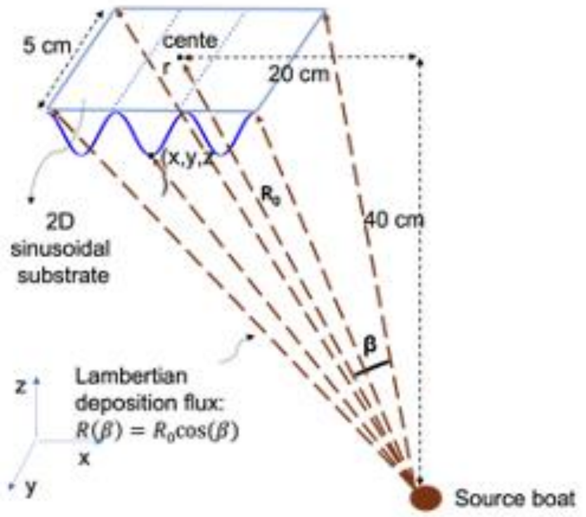


100 nm sputtered ITO gives ~130 Ω/sq on β=1.5

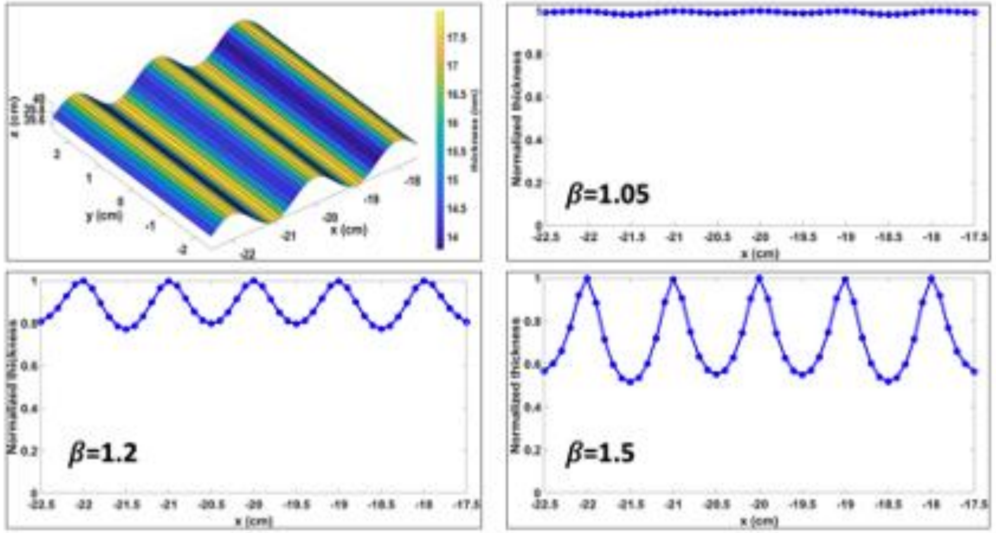
Ultimate goal is to realize textures directly in glass

Progress: Modeling and metrology

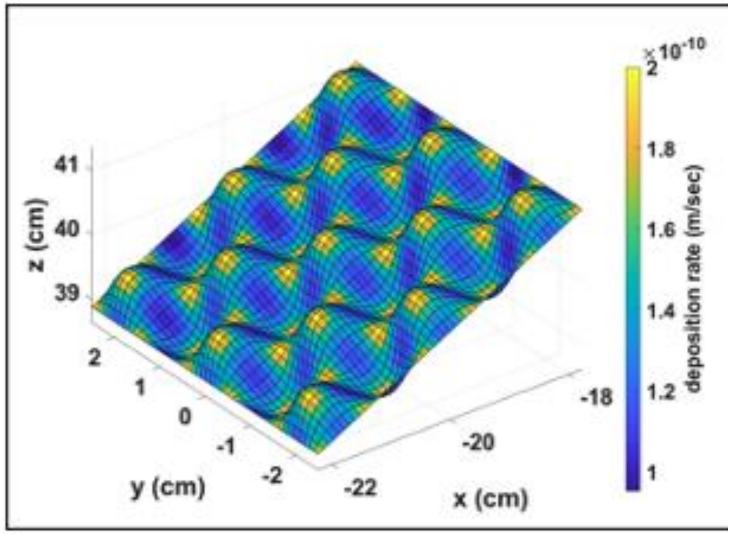
Numerical model



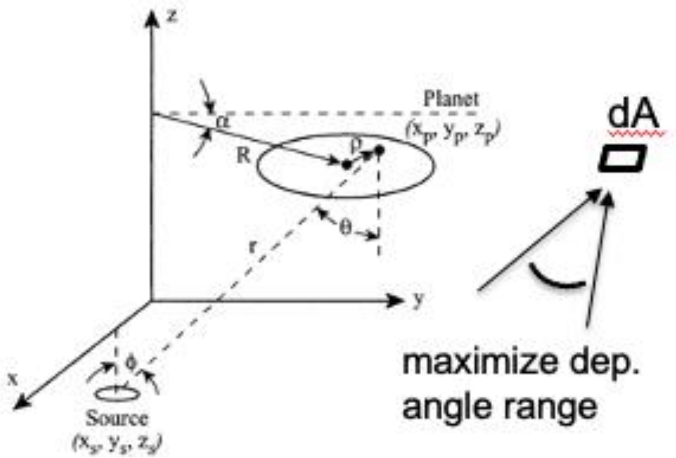
1D sine, simple rotation

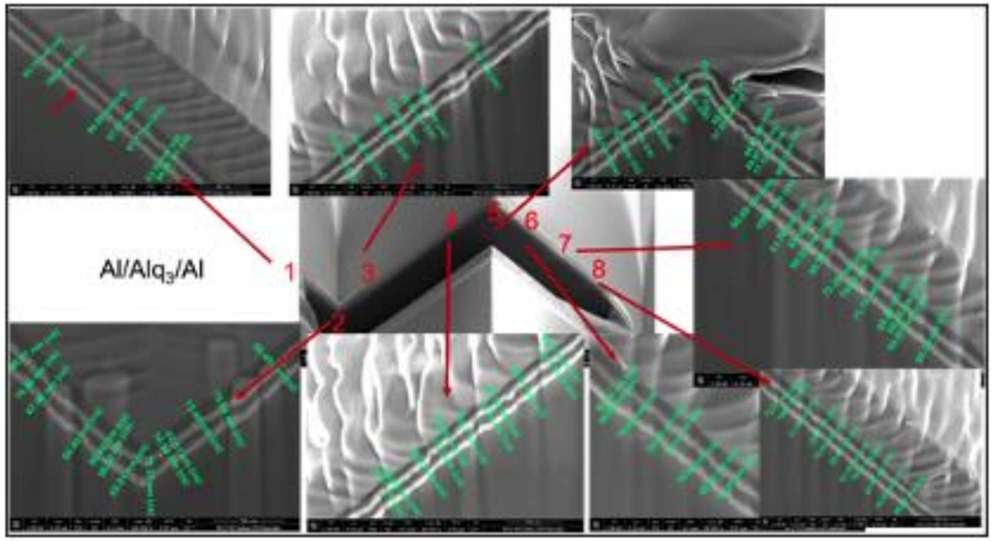


2D sine, simple rotation

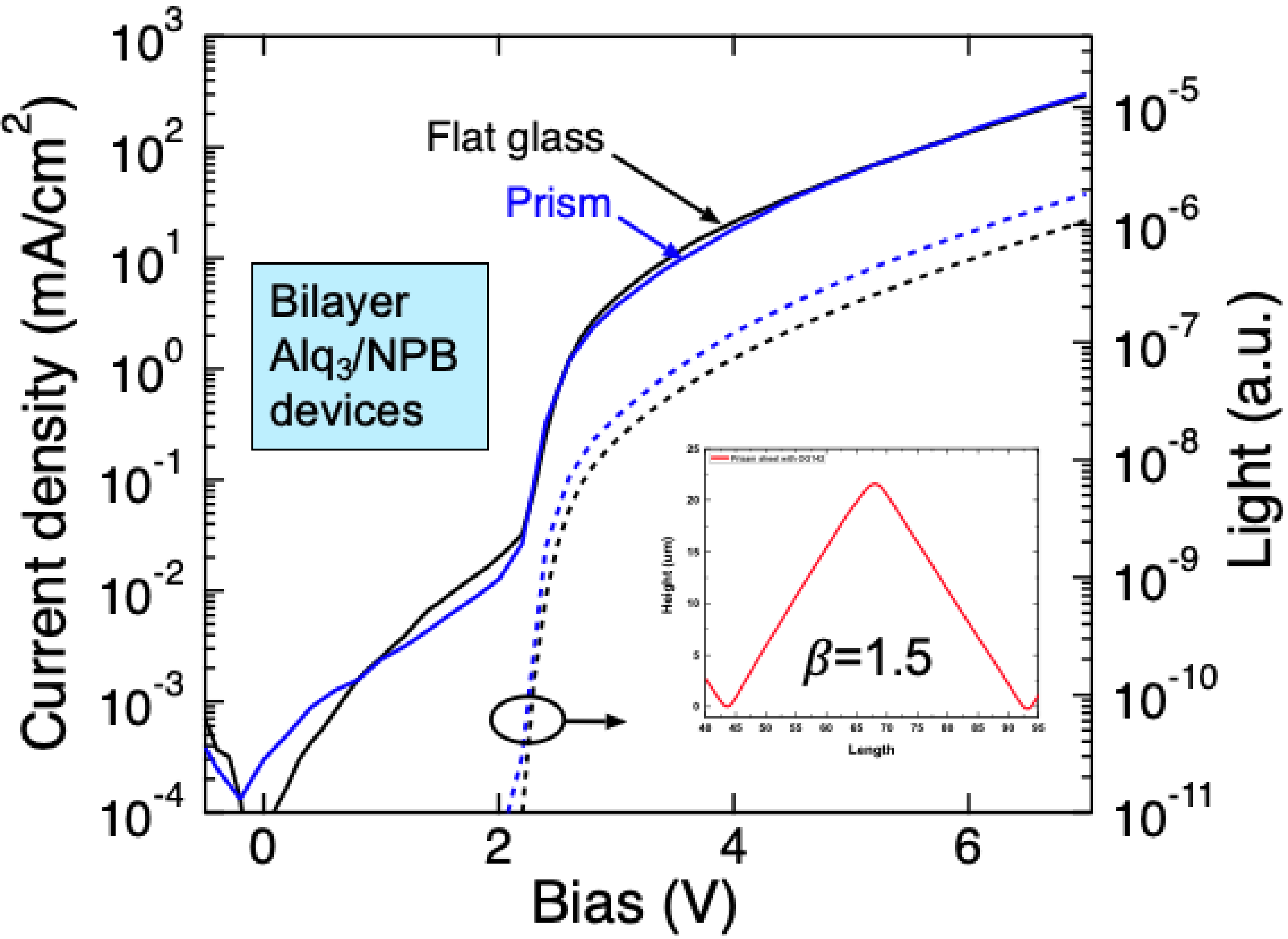


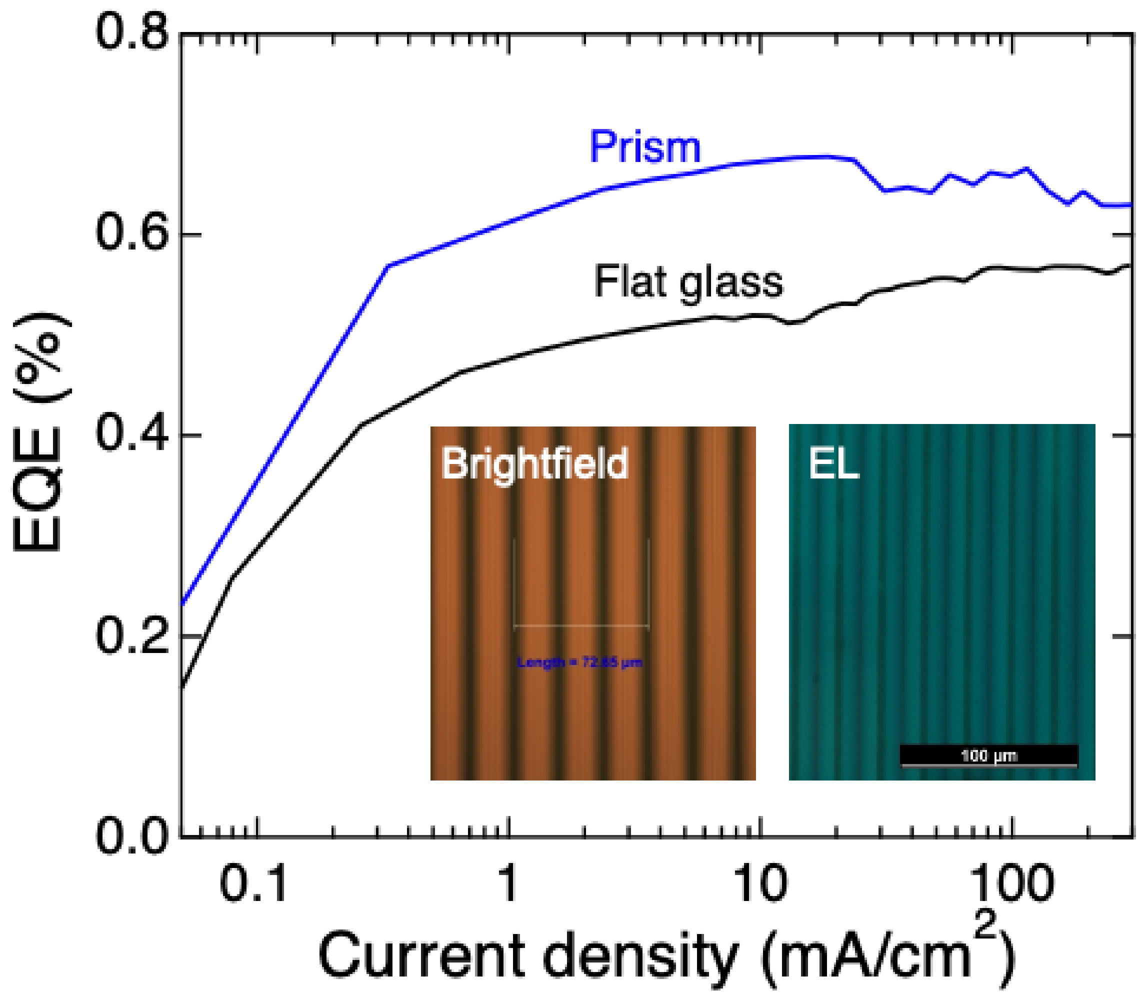
Planetary deposition:





Progress: High aspect OLED demonstration and performance

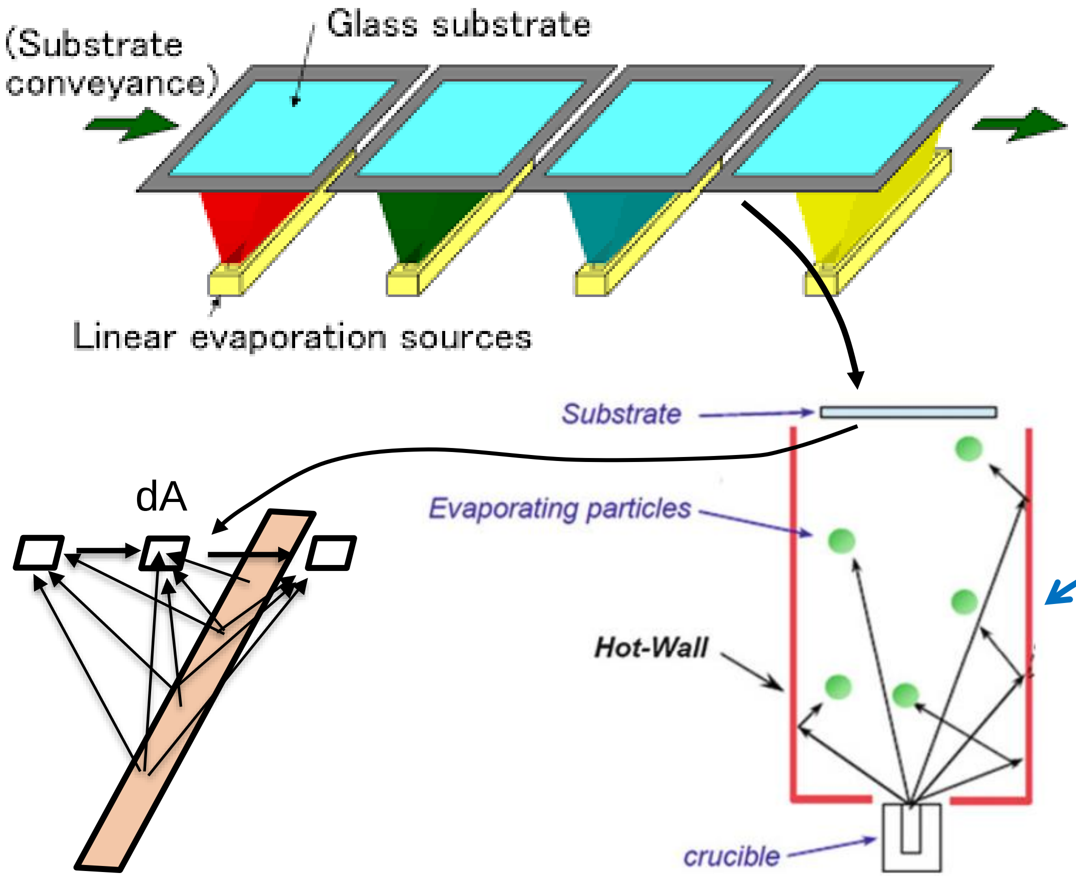


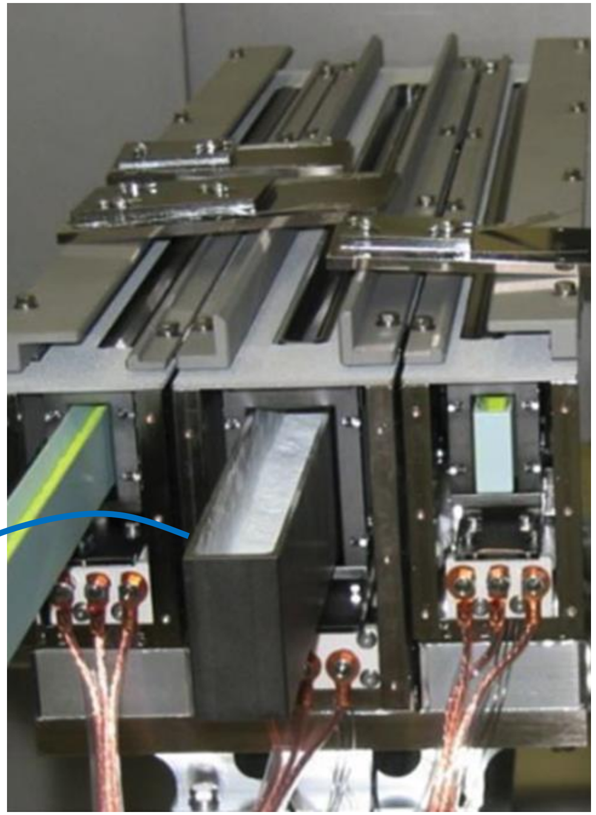


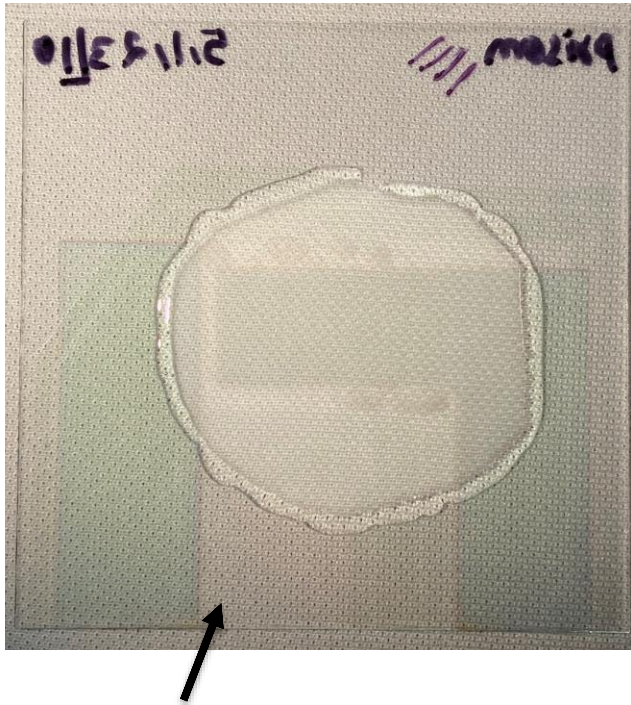
Proof-of-concept: β=1.5 OLEDs can perform better than controls. Next step: Lifetime

What's next? Pilot in-line deposition + SOTA devices

Modeling predicts best uniformity for in-line deposition → Test on OW pilot line







ITO-coated high aspect ratio OW substrate ready for deposition

First in-line depositions planned for April >> Compare uniformity >> SOTA devices

Thank You

Penn State University, University of Michigan, OLEDWorks LLC
Chris Giebink, Professor
ncg2@psu.edu
DE-EE0009694

REFERENCE SLIDES

Project Execution

	FY2022				FY2023				FY2024			
Planned budget	485K				558K				651K			
Spent budget	413K											
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Past Work												
Q1 Milestone: Demo β>1.5 substrate												
Q2 Milestone: Demo β>1.5 conformal anode coating												
Q3 Milestone: Demo electroluminescence uniformity												
Q4 Milestone: Demo β>1.5 OLED												
Q1 Milestone: Demo β>2 substrate												
Current/Future Work												
Q3 Milestone: Validate β-lifetime scaling relationship												
Q4 Milestone: Demo β>1.5 multi-stack white OLED												
Q2 Milestone: Demo SOTA white OLED w/ higher efficiency												
Q2 Milestone: Demo SOTA white OLED with 2x lifetime												
Q3 Milestone: Demo pilot line high-β OLED fabrication												
Q4 Milestone: Technoecon. analysis of high-β OLED prod.												

- Go/no-go #1: Demo β>1.5 OLED with performance exceeding planar control
- Go/no-go #2: Validate β-lifetime scaling relationship for blue phosphorescent OLEDs
- Received an extension of Budget Period 1 due to delays in getting project partner sub-contracts in place, which caused slipped Q4 & Q1 milestone completion

Team

- <u>Project partners</u>:

  - **University of Michigan** (Max Shtein)
    Role: Development of planetary deposition, Organic vapor phase deposition to maximize OLED uniformity.

  - **OLEDWorks** (Marina Kondakova)
    Role: ITO deposition, Multi-stack OLED deposition, Test scalability on manufacturing pilot line.

EERE/BTO goals

The nation's ambitious climate mitigation goals

Greenhouse gas emissions reductions

50-52% reduction by 2030 vs. 2005 levels

Net-zero emissions economy by 2050

Power system decarbonization

100% carbon pollution-free electricity by 2035

Energy justice

40% of benefits from federal climate and clean energy investments flow to disadvantaged communities

EERE/BTO's vision for a net-zero U.S. building sector by 2050

2023 BTO Peer Review - Presentation Instructions

(Not a template slide – for informational purposes only)

- Please work with your respective BTO TM in the development of your slides. We strongly encourage you to have TMs review your slide deck **PRIOR** to the submission deadline.

- **Presentation Submission Requirements:**
  - MS PowerPoint format
  - Size Limit: 15 MB (prefer smaller file)
  - Due Date for initial draft for manager review: Thursday, March 23, 2023
  - Submit via email to [BTOPeerReview@ee.doe.gov]
  - Name your electronic MS PowerPoint presentation file as follows (use the first 4 letters of your title): [Title_Organization_LastName.ppt]

- **NOTE:** We will send your presentations to reviewers prior to the meeting. To provide adequate time for the reviewers, you **MUST** submit your presentation by **COB on Thursday, March 23, 2023**.
- You may NOT provide a different presentation to the event. Reviewers will see the same presentation at the peer review event that they review off-line in advance.

2023 BTO Peer Review - Presentation Instructions

(Not a template slide – for informational purposes only)

- **All** red text on the slides should be deleted (when it is instructional) or replaced with information (when it is placeholder text).
- **Do not** include any proprietary, copyrighted, or confidential information. Do not mark any slide with "Official Use Only" or any similar restriction used by your organization.
- **Do not** incorporate animation or special effects. All presentations will be saved as PDF files for presentation and for posting on the web. Animations critical to describing the project may be presented as separate files, however they must be approved by the Program and presented within your allotted time.
- The 2023 BTO Review is reviewing active projects. Emphasis should be on the activities and progress since the last peer review. For newer projects, focus on activities and progress since project start (**be sure to clearly identify yourself as a new project**). However, presenters may include past progress to put current activities/progress into context. Presenters should also describe future activities/milestones that will bring the project to successful outcomes and conclusions.
- Use of graphics / photos is encouraged. Please be mindful of size of embedded graphics, font size of all text (≥18 recommended), and visibility of presentation materials to attendees sitting in presentation rooms.

2023 BTO Peer Review - Presentation Instructions

(Not a template slide – for informational purposes only)

- **The narrative will be structured to follow the four "Heilmeier Questions":**
    i. What problem are you solving?
    ii. What will be the impact of solving this problem? Why is it worth solving?
    iii. What (if any) is the current approach to solving this problem?
    iv. What is new and promising about the approach taken in this project?

- **The project will be scored on the following evaluation criteria (see additional guidance on slides 7-9):**
    – Alignment and Impact (20%): How will the outcomes of the project contribute to BTO's goals? How do you define success?
    – Approach (40%): What is novel about this project? How are you planning to accomplish your goals? How will you commercialize, transform the market, address a barrier, and/or engage stakeholders?
    – Progress and Future Work (40%): What are your major accomplishments to date? Have you encountered obstacles? What lessons have you learned? What are your plans for the rest of the project and beyond?

- **NOTE: You should allocate your slides and presentation time according to the scoring and weights noted above. Presenters will be held to their allotted time. If your time differs than the examples below, its usually a 2:1 ratio of presentation to Q&A.**

TOTAL TIME	Presentation	Q&A	# of Slides
30 minutes	20 minutes	10 minutes	No more than 15

* Title, Project Summary, and REFERENCE SLIDES (i.e., first 2 slides and last 3 slides) do not count towards slide count as these should be quick. The information on the project summary will be addressed in later slides, but there is value to providing them as snapshots up front.