R2R Manufacturing of WOLED Lighting

-Methods-Results-Costs-

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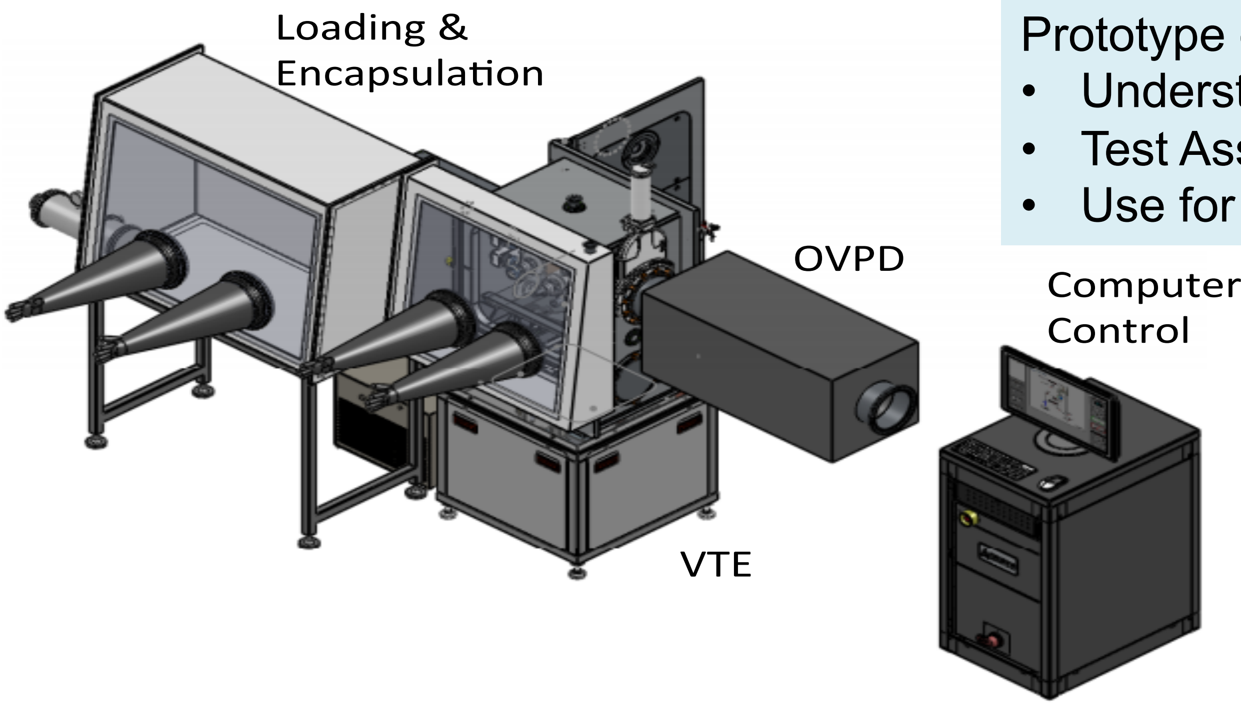
OPTOELECTRONIC COMPONENTS & MATERIALS

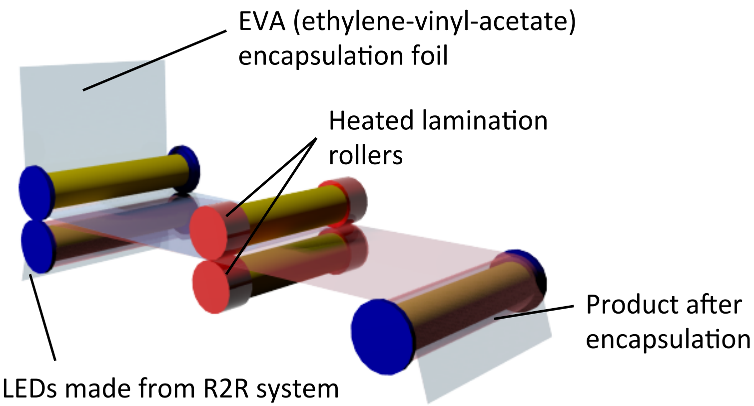
Lab System Overview

Prototype device fabrication system
- Understand limitations
- Test Assumptions
- Use for cost basis in scale-up



- Combination of VTE and OVPD growth
- In-situ mask patterning, registration to <0.1 mm
- 10 materials sources (metals and organics)

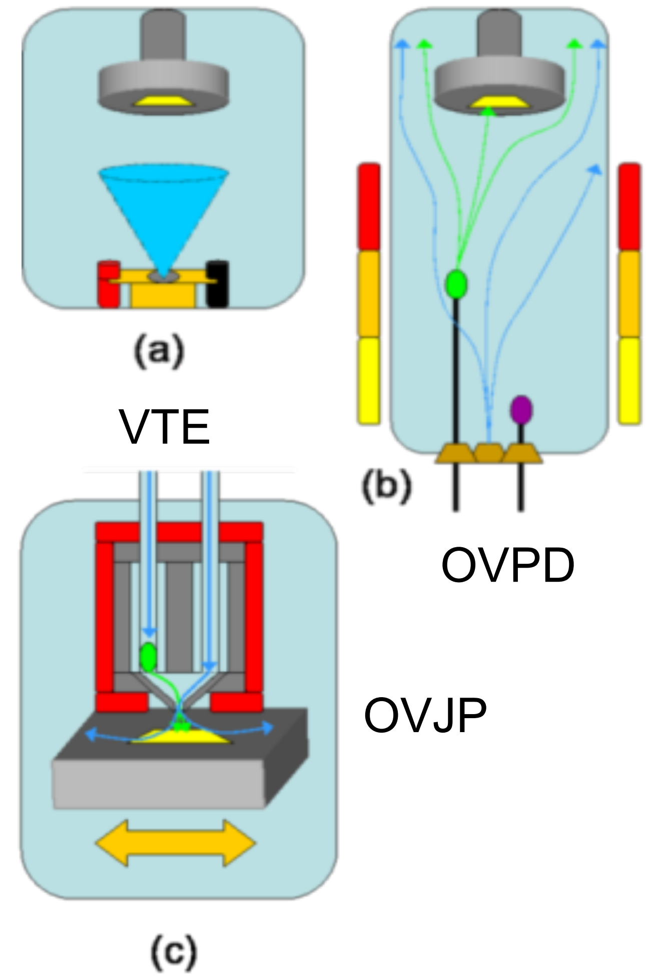
Future encapsulation



OLED Deposition Processes

	Vapor (PVD)	Condensed Phase
Examples	VTE OVPD OVJP	Inkjet Nozzle Printing LITI µ-contact printing
Materials	Small molecules	Small molecules or polymers
Multilayer Structures	Molecularly sharp interfaces	Less thickness ctrl. May damage heterojunctions & complicate doping.
Co-deposition	Even Mixing Amorphous film	
Patterning	Thin Metal Mask Direct Print	Direct Print
Atmosphere	Vacuum	Inert Gas
Media	None	Solvent or xfer film
Use	Commercial & Research	Research

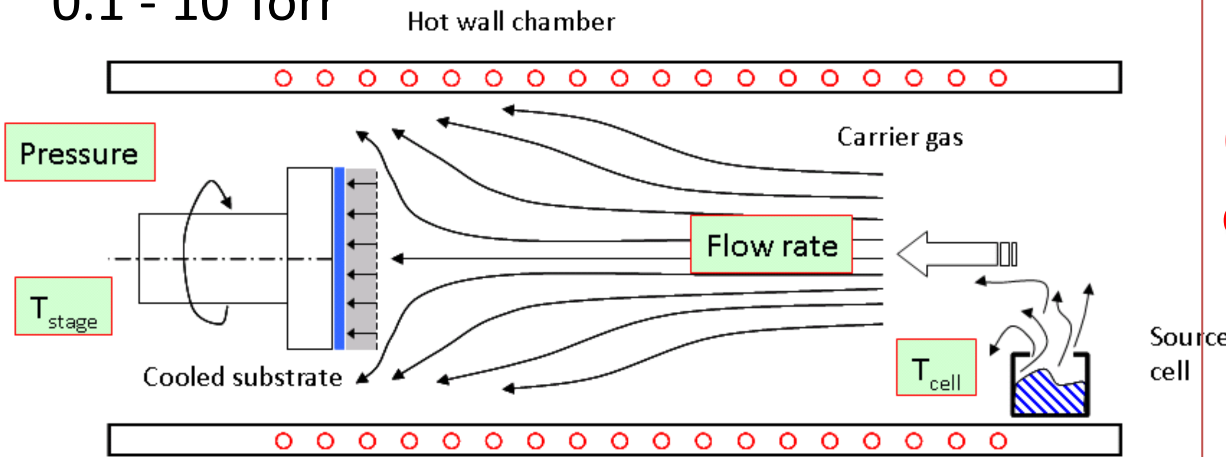
Organic PVD



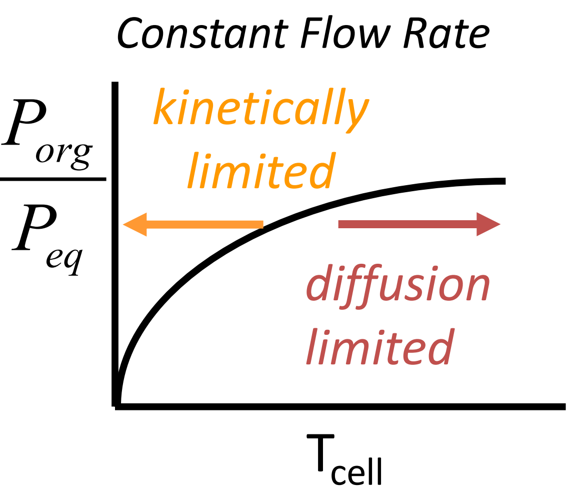
Shtein *et al. J. Appl. Phys.* **93**, 7, 4005 (2003)

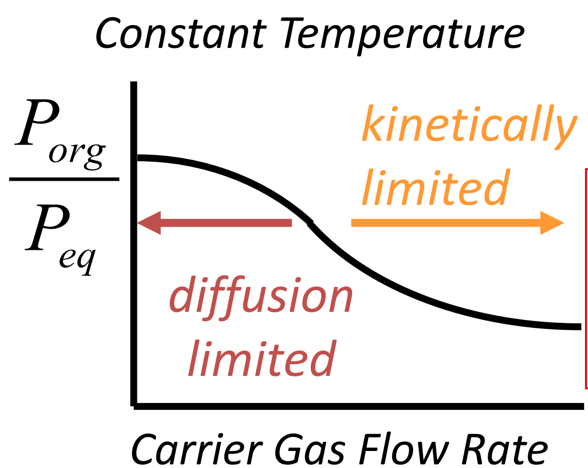
Organic Vapor Phase Deposition: Concept

0.1 - 10 Torr



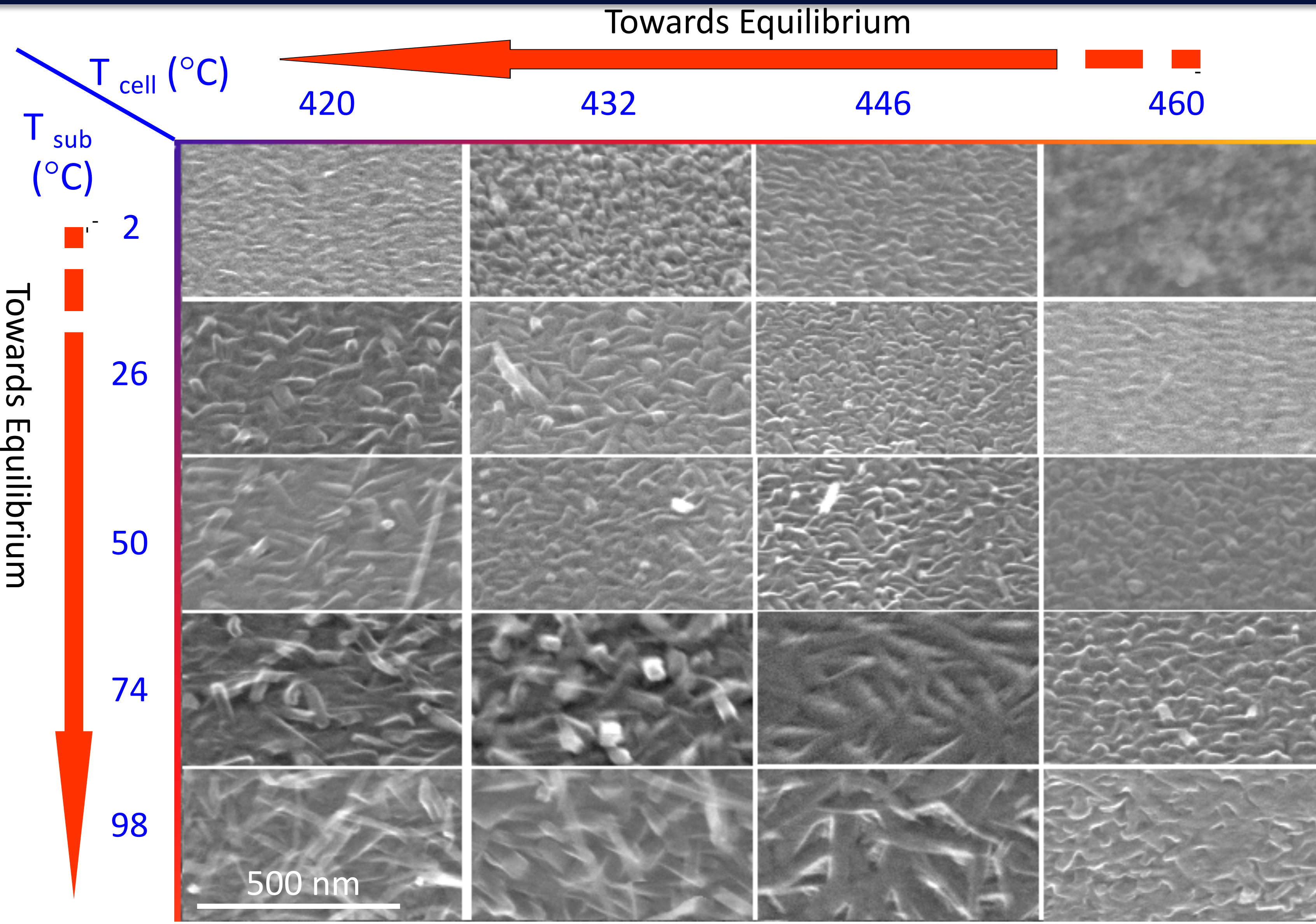
- Controlled and accurate doping **(gas saturated with organics - equilibrium)**
- Dust free chamber
- Efficient materials use
- Control of film crystal structure
- Very high, controlled deposition rates





$$r_{out} = \frac{\dot{V}_{src}}{RT_{cell}} \cdot \frac{P_0 \exp(-\Delta H / RT_{cell})}{1+\dot{V}_{src}/A_{evap}\cdot k}$$

Nanomorphology control by temperature

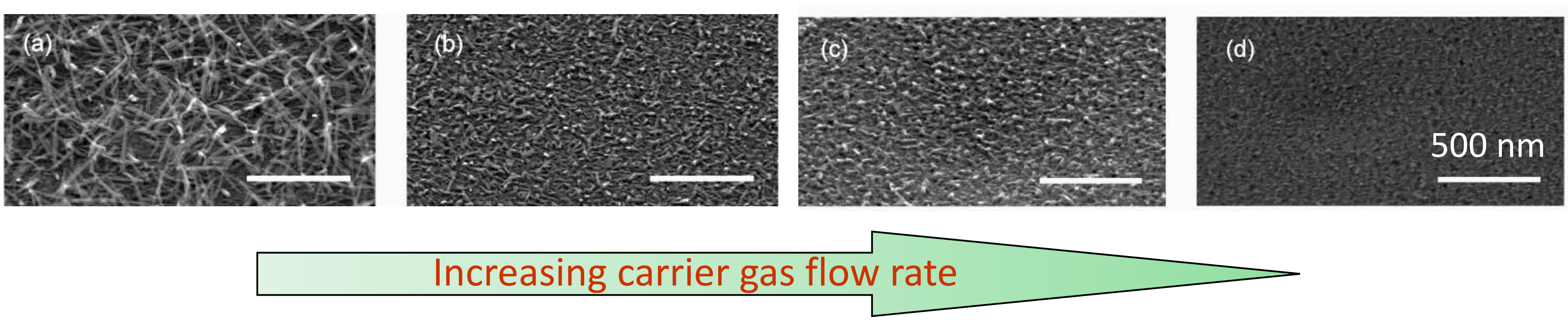


(flowrate = constant, pressure = constant)

Nanomorphology control by flow rate

(fixed source and substrate temperatures)

N_2 flow rate: 100 sccm　125 sccm　150 sccm　200 sccm

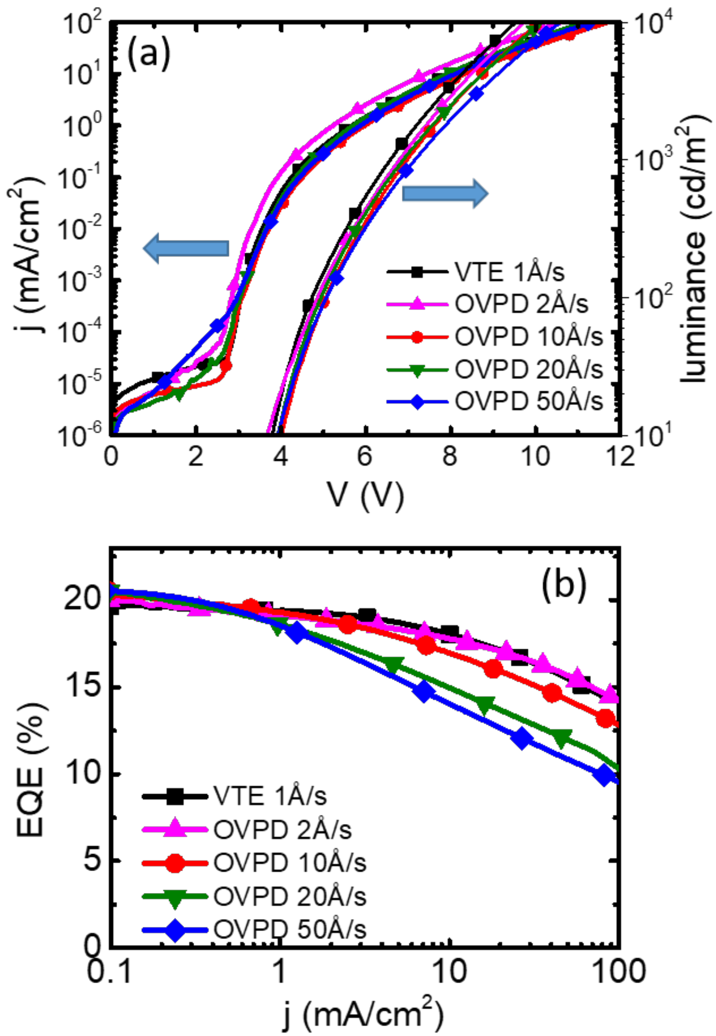


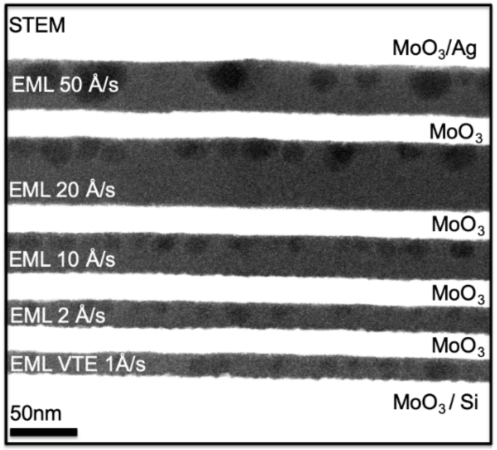
Crystals	Needle morph. Long, large	Flat morph. Uniaxial, small
Source temperature	Low	High
Substrate temperature	High	Low
Carrier gas flow rate	Low	High
Chamber pressure	Low	High

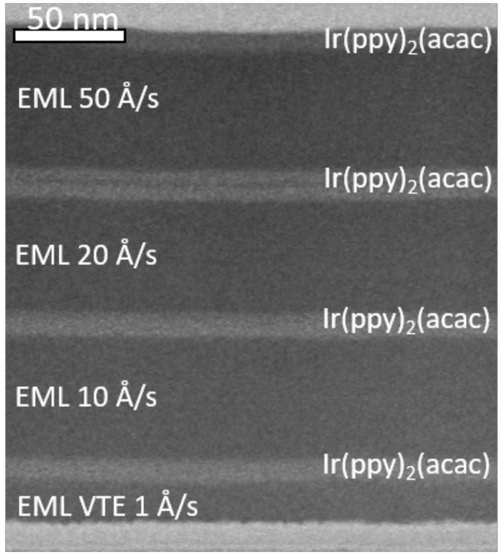
OLED Performance vs. Growth Rate

Increased Roll-Off at Highest Growth Rates

Heterogeneous Nucleation of Defects at High OVPD Growth Rates

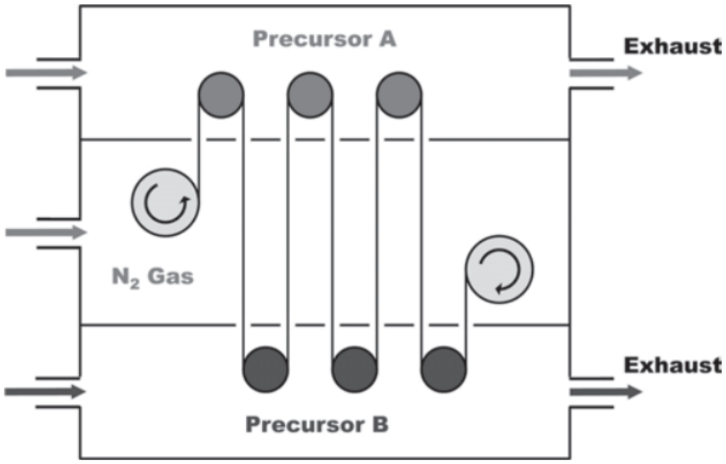






Alternative R2R encapsulation: ALD

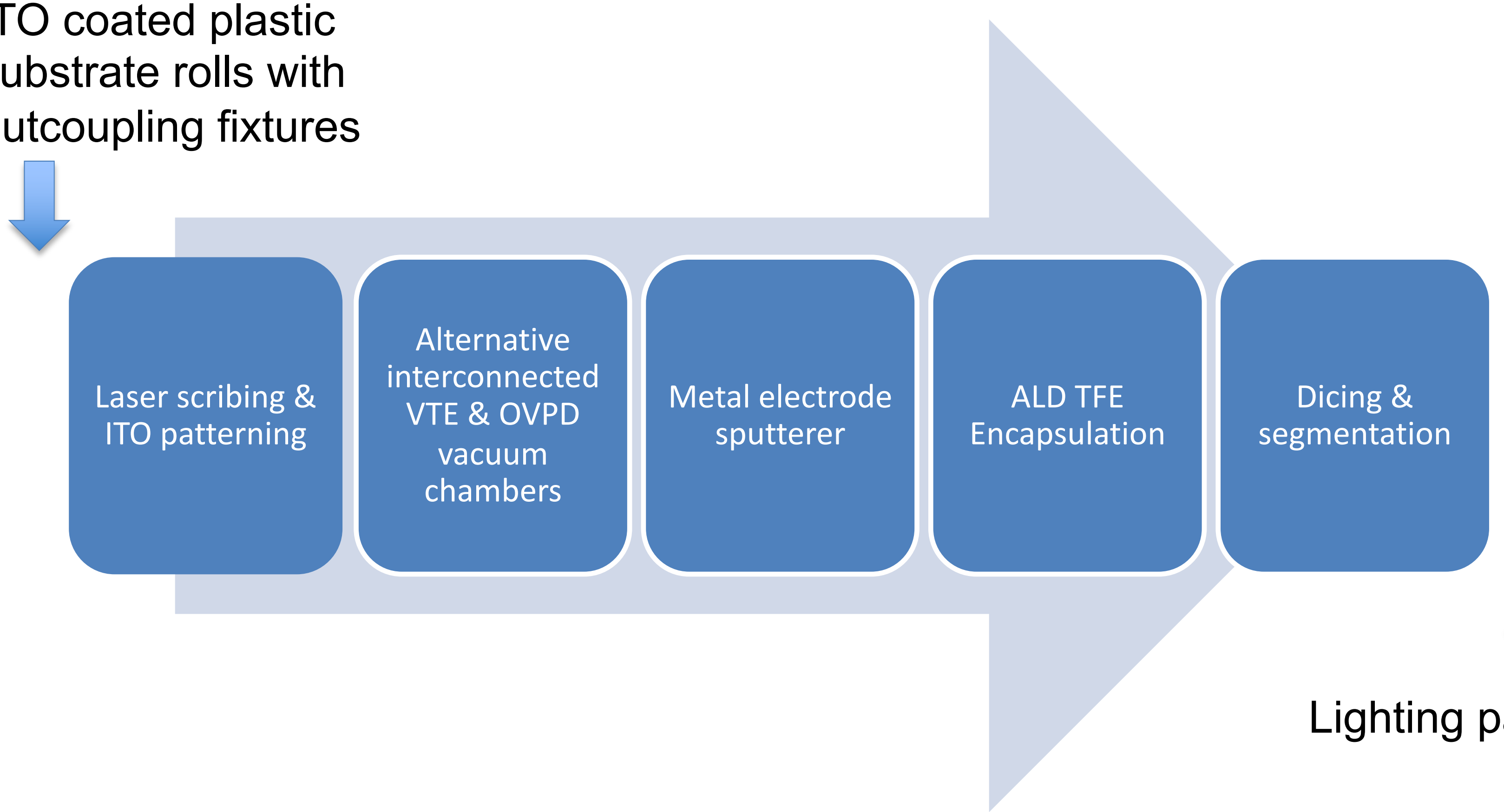
- Current OLED display encapsulation: CVD thin film encapsulation (TFE)
- Atomic layer deposition (ALD) advantages:
  - Pin-hole free layer
  - R2R compatible
  - Low WVTR < $2x10^{-6}$ (Ref. E.G. Jeong, et al, Journal of Information Display, 2020)
- Approach at U of Michigan:
  - Test package: electrical Ca-test circuit covered by ALD-grown metal oxide TFEs
  - Test set-up: customized acrylic box with epoxy seal and controlled humidity
- Impact on cost analysis:
  - One or two additional vacuum chambers
  - Negligible material cost increase



Ref. S.M. George, et al, 2011 Society of Vacuum coaters, 2011.

R2R System Design: Cost Analysis

ITO coated plastic substrate rolls with outcoupling fixtures

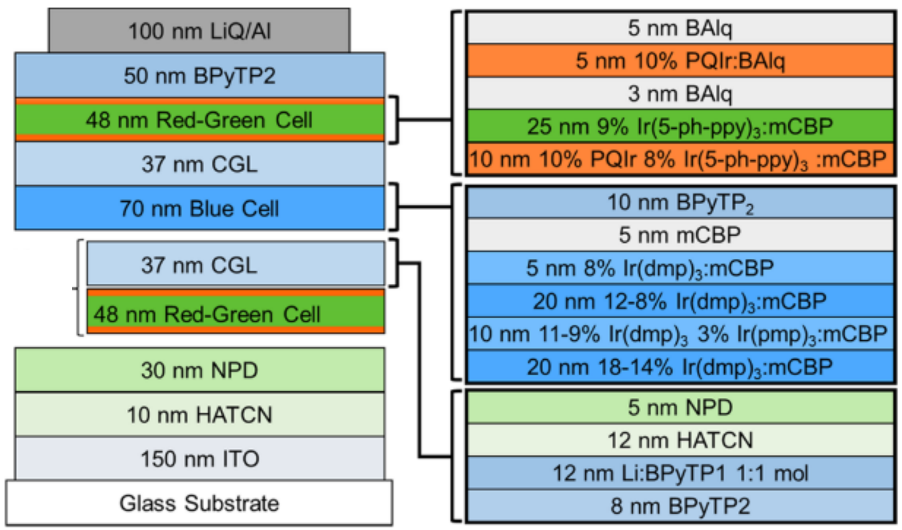


Lighting panels

Target: \$10 /klm or \$100 /m^2 (lighting at 10 klm/m^2)

Stacked WOLED Structure

Reliable efficient WOLED structure design



Ref. Caleb Coburn, et al, ACS Photonics, 2018.5

- 3 R-G cells and 1 Blue cell
- CRI = 85.2, CCT = 2890 K
- EQE =141% with outcoupling scheme
- LPE= 47.2 lm/W at 1000 nits.
- T70 = 50000 hr.
- Intensity: 200k cd/m^2
- [CGL+ETL+HTL+cathode] in VTE
- [R-G-B EML] in OVPD
- 24 VTE subchambers +10 OVPD subchambers (blends) + sputterer (Al)

Production Capacity

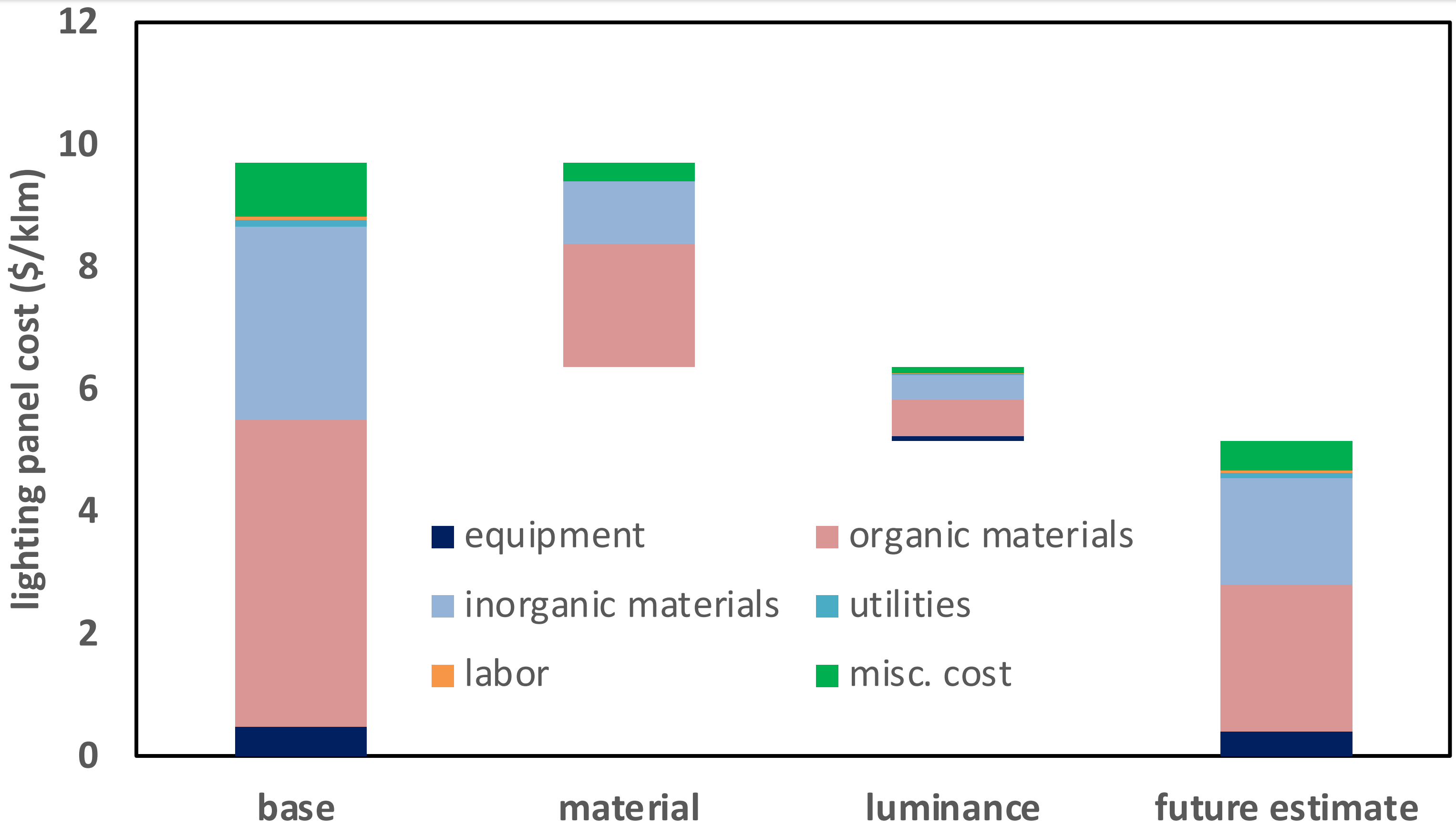
Capacity	Unit	Base case
Rolling speed	m/hour	540
Roll prep / loading time	hour/hour	0.05
Substrate width	m	1.5
Campaign Length	Month	11
Maintenance Time	Month	1
Production per line	m^2/machine/year	6094 k

1.5 m-long growth window, 5 nm/s rate, thickest organic layer 50nm ⇒ 0.15 m/s

5% prep/loading time

Uniform growth in Gen6 chamber (R. Lunt, et al, APL, 2009)

Lighting panel cost



- 10% miscellaneous cost
- Material cost reduction
- 20% higher operation luminance compared to initial assumption (10000 lm/m^2)
- Future estimate: $5.2/klm

Comparison with DoE metrics

	DoE 2019*	DoE 2025*	DoE 2035*	R2R
Capital cost ($M)	50	200	400	293
Capacity(m^2/yr)	25k	500k	2400k	6094k
Depreciation($/$m^2$)	400	80	35	4.8
Organic cost($/$m^2$)	200	80	35	50.2
Inorganic cost($/$m^2$)	600	200	100	31.6
Labor($/$m^2$)	100	15	5	0.5
Others($/$m^2$)	50	10	5	1.1
Total unyielded($/$m^2$)	1350	385	180	88.2
Yield (%)	70	80	90	90
Total($/$m^2$)	1930	480	200	98

* DoE EERE "2019 Lighting R&D Opportunities", Table 3.9. Current status and cost targets for OLED panels produced by traditional methods.

Parting Thoughts

- R2R Systems can combine multiple deposition technologies (including encapsulation) for efficient, high throughput manufacturing
- OVPD provides extraordinary control over morphology, doping concentration, device structure
- DOE cost targets for WOLEDs can be met using high volume R2R deposition

Thanks to the DOE/EERE for support of this work