Cost estimates of roll-to-roll production of organic light emitting devices for lighting

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Abstract

White organic light emitting devices (WOLEDs) offer distinct advantages as solid state lighting sources, including high energy efficiency, superior color quality, and a flexible, thin profile that can accommodate a vast array of possible fixture designs. Recent advances in device lifetime and high speed deposition suggest that mass production of WOLED panels is approaching an inflection point. To understand the tradeoffs in the volume manufacturing of WOLED lighting panels, in this work we estimate the cost of white WOLED panel production based on vacuum and vapor phase deposition in a roll-to-roll production line envisioned to yield an annual capacity of at least $6x10^6$ m^2. Assuming a WOLED operating luminance at 10 klm/m^2, we anticipate a $12.5 /klm cost of a WOLED light engine that includes the cost of the current driver and packaging. With incremental reduction in material and driver costs, and improved luminance, the cost of WOLED lighting can be reduced to $6.3 /klm in the near term, potentially positioning WOLEDs for use in numerous premium lighting applications.

1. Introduction

White organic light emitting devices (WOLEDs) are attractive for solid state lighting (SSL) since they offer higher power efficiencies compared to existing florescent or incandescent sources.[1–4] WOLEDs share many attributes with another SSL source, inorganic LEDs, including the use of low toxicity materials, high color rendering indexes (CRI), tunable spectra, and compatibility with standard control and dimming solutions using direct current (DC) power.[5–7] Unique features, such as a large color gamut, thin and flexible form factor, low glare and heat-free operation, make WOLEDs particularly suitable for aesthetic and pleasant interior lighting.[8] Among challenges of WOLED lighting are that their light intensity and lifetime are lower than conventional LEDs.[9,10] The relatively low brightness of WOLEDs can be mitigated by vertically stacking individual OLED elements in panels, or producing larger area WOLED luminaires that generate diffusive illumination.[11] Recently, a phosphorescent WOLED with lifetime extending to T_{70} = 87 x 10^3 h has been reported, where T_{70} is a time of operation for the light output to drop to 70% of its initial value of 3000 cd/m^2.[12] This exceeds the minimum acceptable LED lifetime of T_{70} = 50 x 10^3 h standardized by the luminaire industry.[13] Furthermore, WOLEDs that feature an efficacy (or luminous power efficiency, LPE) of 109 lm/W and CRI = 89.4 that meet Energy Star® technical requirements for indoor luminaires have also been demonstrated.[6,14]

Competitive performance motivates commercial pilot production of WOLED lighting using equipment and other infrastructure designed for display manufacturing.[10] Estimates of the current cost of illumination for WOLED lighting vary from $50 to 300 /klm based on different assumptions of commercial product margin and panel efficacies.[11,15] The adoption of WOLED lighting ultimately hinges on whether it is cost competitive with other types of solid state lighting appliances, and whether volume production is feasible. High speed fabrication of organic semiconductors on flexible substrates that are compatible, or integrated with roll-to-roll (R2R) processing has been demonstrated,[16–19] yet a detailed cost analysis of manufacturing large area WOLED panels at high volume using R2R methods to our knowledge remain to be explored.[20,21] Furthermore, the cost of drivers adapted to WOLED lighting, and miscellaneous costs such as taxes, administrative, and marketing, need to be considered to estimate the true production costs of this lighting technology.

Due to the inherent differences in the operating principles and form factors between WOLED and conventional lighting products, a fair comparison of lighting or production cost requires consideration of the details of the corresponding luminaire structures. A luminaire is a complete lighting fixture consisting of the light source such as a lamp, and the ballast or driver, together with the parts that distribute the light, position and protect the light source, and connect it to the power supply.[22] For LEDs, the integrated assembly comprising the LED package, a driver and other optical and electrical components is defined as the "LED light engine", which is intended to connect directly to the branch circuit through a custom connector compatible with the corresponding luminaire.[23] WOLED luminaires require few light-directing features due to their natural diffusive area emission. Additionally they can be exceptionally light weight, and form either extremely sleek or complicated architectures that are drastically different from common luminaires. For simplicity of comparison with other lighting technologies, we focus on only the cost of a "WOLED light engine" that we define as the assembly including the WOLED panel that is equivalent to the radiation unit in an LED package, a transparent barrier sheet package, and a current driver that cannot easily be removed by the end user.[22] The counterparts to WOLED light engines are LED light engines with customized connectors, or incandescent, fluorescent, and integrated LED lamps with ANSI standard bases.

Here, we estimate the production cost of WOLED light engines based on assumptions corresponding to Class 4 of the Cost Engineering Classification system.[24] Starting with the introduction of a high throughput R2R WOLED panel manufacturing line with a capacity of > 6 x 10^6 m^2/yr, we estimate the materials, production, capital depreciation, utility, and labor costs. From this, we find that the cost of illumination is $12.5 /klm for an archetype phosphorescent WOLED with CRI = 85 operating at a luminance of 10 klm/m^2. Then, assuming modest, near-term material or component cost reductions and luminance improvements, the total cost of illumination is reduced to $6.3 /klm, which is ~60% higher than current LED lighting. Together with the many possibilities offered by its unique flexible or conformable, color-tunable and diffuse lighting properties, these estimates suggest WOLEDs can be an economical and attractive solution for many lighting applications.

2. Cost assumptions and results

We divide the panel production cost into four categories – capital equipment, labor, utilities, and materials. Additional miscellaneous costs including marketing, general and administrative (G&A), and research and development (R&D) are assumed to be 10% of the total manufacturing cost based on a previous organic electronics manufacturing study.[21] The manufacturing process is determined based on fabricating the complete WOLED light engine illustrated in Figure 1a.

The total fixture costs must take as a starting point the cost of the production of the WOLED stack itself. For this purpose, we base our estimates on the archetype, multilayer electrophosphorescent structure shown in Figure 1b that has demonstrated the high performance required for practical lighting sources.[6] (see Support Information Figure S1 for organic molecules considered in this study) Starting from a flexible transparent substrate comprising a sub-electrode microlens array (SEMLA) that has been demonstrated to outcouple approximately 50% of the emission when used with an external microlens array (MLA) attached to the distal surface of the substrate,[25,26] the stacked WOLED comprises 37 individual organic layers, consisting of three mixed red-green emission layer (EML) elements, a single blue element, and three charge generation layers (CGL) located between each EML element. The WOLED is capped with a metal cathode and sandwiched between two thin film encapsulation (TFE) layers comprising 30 nm-thick Ti/Al oxides.[27–29] This device utilizes phosphorescent dopant materials to yield an efficacy of 47.2 lm/W, CRI = 85, a correlated color temperature of CCT = 2890 K, and T_{70} = 50 ± 15 x 10^3 h from an initial brightness of 1000 cd/m^2. The operating luminance of the WOLED panel is assumed to be 10 klm/m^2, which is equivalent to ~3000 cd/m^2 given its Lambertian emission profile.

A flow chart of the panel manufacturing process and the associated material choices are provided in Figure 2. A roll of transparent polyethylene terephthalate (PET) substrate is first laminated with a SEMLA layer prior to fabricating an indium tin oxide (ITO) anode via sputter deposition and laser scribed patterning.[21] The coated substrate roll is then transferred into a series of chambers to deposit neat organic transport layers (TLs) and blended EMLs by vacuum thermal evaporation (VTE) and organic vapor phase deposition (OVPD), respectively. Unlike VTE, OVPD growth occurs at low pressure (typically ~ 0.1 – 1 torr) in a hot-walled reactor, where the organic source material is vaporized into a non-reactive carrier gas stream (typically N_2) and is transported to a cooled substrate where it condenses into a thin film. While conventional VTE using linear sources has been widely employed for OLED display manufacturing and provides an immediate solution to lighting panel production, OVPD has been proven to be equal, if not superior to VTE in achieving precise layer doping and high material utilization efficiency during co-deposition at high growth rates, along with an EML layer morphology suitable for achieving high efficacy.[16] All deposition procedures are completed within a single R2R production line that consists of multiple interconnected vacuum chambers to prevent damage to the WOLED from air exposure, as shown in Figure 3.

Following organic layer deposition, the top metal contact is deposited and patterned into stripes via sputtering through a shadow mask.[30] The active device region is defined by the overlap between the transparent and metal electrodes. Finally, the WOLED stack is encapsulated by coating TFE layers with water vapor transmission rate (WVTR) < 10^{-6} g/m^2/day on both sides of the substrate in a continuous atomic layer deposition (ALD) tool integrated with the R2R apparatus.[31–33] The complete WOLED panels on rolls are subsequently spliced into the desired sizes via laser scribing, and packaged into WOLED light engines by laminating scratch resistant, and environmental barrier sheets (WVTR < 10^{-4} g/m^2/day) on both sides of the panel, and wiring current drivers to the contacts. Prior to packaging, an external MLA is attached to the outside of the barrier sheet adjacent to the transparent electrode for substrate mode light outcoupling.[25,26,34]

The substrate roll web width is assumed to be 1.5 m, which is compatible with high uniformity OVPD and VTE deposition systems with 1.5m x 1.5m deposition windows.[35] The lamination and cleaning platform, as well as the laser scribing equipment are operated in ambient atmosphere.[21,36] The high vacuum VTE and sputtering chambers are connected to low pressure OVPD and ALD chambers through two-stage differential pumping channels, where an oil-free mechanical pump and a turbo pump remove gas at the first and second stages near the low pressure and high vacuum chambers, respectively.

A list of required manufacturing equipment and their annual costs assuming 10 year linear depreciation is provided in Table 1. The cost of each deposition chamber is estimated by proportionately scaling the cost of corresponding commercially available tools based on their web width ratios.[37,38] The total capital cost of the WOLED panel production equipment is $293M.

For comparison, we include a cost estimate of an all-VTE R2R system with similar panel productivity, where blended EMLs are grown by dual-source VTE chambers instead of the OVPD chambers in the hybrid systems. The total number of deposition chambers is the same in both instances. The depreciation of VTE chambers in the all-VTE system is $540k and $667k /yr for single and dual-source deposition, respectively. They differ from the value in hybrid VTE/OVPD production lines ($571k/yr) because the differential pumping is eliminated and dual-source evaporators are required in all-VTE systems. The total capital cost of the all-VTE production line is $233 M.

Labor and utilities costs, and production parameters are provided in Table 2. A maximum organic deposition rate of 5 nm/s is assumed to maintain quality control and thickness uniformity of each layer.[16,39] The roll translation speed is, therefore, set to 0.15 m/s to ensure the complete deposition of the thickest organic layer (50nm of a 2,7-Bis(2,2′-bipyridin-5-yl)triphenylene, BPyTP2, electron transport layer) of the WOLED structure in a single pass across the VTE deposition windows.[40] Considering 5% roll preparation time during the manufacturing cycle, 11 month/yr and 24 h/day equipment utilization, the annual WOLED panel production area is 6.1 x 10^6 m^2.[21] We assume one unskilled personnel per lamination and scribing station, and one skilled personnel per 3 deposition tools, resulting in a total of 3 unskilled and 13 skilled labor per production line. With 55% employee benefits, \$15.4 /h and \$25.0 /h unskilled and skilled wages, the annual labor cost is \$4.8 M. The electricity cost for each tool is estimated to be \$154k /yr based on a 150 kW power consumption and an industrial electricity rate of \$0.07/kWh.[41] Additional utilities costs such as process chilled water are \$100k /yr. A maintenance and calibration cost of \$10k /yr is assumed for each tool in the production line. The cost breakdown of the WOLED panel is primarily presented as cost per square meter of product, since the production cost scales more closely with panel area rather than light output. With the above assumptions, the manufacturing cost of WOLED light engines in Table 3 is calculated by dividing the total cost of annual production by the area produced.

A. Materials for hybrid and all-VTE systems

The source material cost for the WOLED panel is divided into the organic and the inorganic costs. For hybrid VTE/OVPD systems, the organics cost for each layer is the product of the weight of material consumed based on the corresponding thickness, and the source material cost per weight, assuming 30% material utilization efficiency for neat layers grown by VTE, and 60% for blended EMLs grown by OVPD.[16,35,42] Using a density of 1.8 g/cm^3 for the organic layers, and bulk costs for organic materials ranging from \$10 to \$500 /g,[43] we obtain \$50.2 /m^2 for all organic materials in the device stack. For example, the cost contribution from the hosts equals the product of the total equivalent host layer thickness of 158 nm, the organic layer density, the unit host material cost of \$30/g, and the reciprocal of the 60% material utilization efficiency, which yields \$14.2 /m^2. Cost estimates for vacuum-deposited inorganic materials, including the cathode metal and the thin film encapsulation are \$4.5 and \$0.3 /m^2,[38] based on a sputtering and ALD material utilization efficiencies of 30% and 50%, respectively.[44] The combined cost of the ITO coating and the PET substrate is \$5.0 /m^2.[21] These materials costs are shown by the base case in Figure 4.

For the all-VTE system, the organic material cost is similarly calculated as \$86.0 /m^2, which is larger than in hybrid systems because the material utilization efficiency of VTE is only half that of OVPD. With unchanged inorganic material contributions, the total material cost for the all-VTE system is 44% higher than that for the hybrid systems.

B. Outcoupling Layers

The implementation of the MLA and the SEMLA within the WOLED light engine for light outcoupling introduces additional material costs. Since SEMLA costs are unavailable, we sum estimates of the capital, labor, utility and material costs of a nanoimprint lithography process used in its volume production.[45] A schematic illustration and itemized cost estimates of the SEMLA fabrication process is provided in Support Information. A master mold of the SEMLA is fabricated prior to producing SEMLA patterns using the corresponding lens replicas. The nanoimprint equipment utilizes gravure rollers to coat photoresist on the PET substrate, and imprint rollers to produce SEMLA features at a throughput of up to 50 m/min.[46] A high index polymer is coated on top of SEMLAs for waveguiding and planarization of the SEMLA surface using doctor blades. The 10-year capital depreciation cost of the nanoimprint equipment is \$ 0.87 /m^2 based on a \$ 37M equipment cost.[46] The combined utility and labor cost for SEMLA manufacturing is estimated to be \$0.06 /m^2, which is comparable with operating three deposition stations by one skilled technician, as discussed previously. The material cost consists of \$0.09 /m^2 for the imprint masters and replicas, with 10 µm pattern features,[34] \$0.50 /m^2 for chemicals used for imprinting, and \$20.3 /m^2 for the high index polymers.[47] Assuming the same throughput as for the R2R WOLED panel production, we obtain \$21.8 /m^2 for the total SEMLA production cost, with the polymer material cost as the dominating factor. The flexible external MLAs with similarly scaled features can be directly fabricated on top of transparent barrier sheets, also via imprinting, while omitting the polymer planarization step. The cost of MLAs is thus estimated at \$ 1.4 /m^2.

C. Drivers and packages

A current driver is required to convert the in-house AC power source to low voltage DC for the WOLED panel to operate as a dimmable and tunable lighting source. For an SSL ceiling-mounted luminaire with a minimum Energy Star® standard light output of 800 lm, the required WOLED panel area and power supply are at least 0.08 m^2 and 17 W, respectively.[13] The use of a single current driver for such a luminaire results in a cost of \$7.3 /m^2, estimated by applying a 20% bulk purchase discount from the commercial price of an LED driver with an output power of 20W.[48] A combination of two layers of transparent barrier sheets, which provide mechanical support and scratch resistance, are laminated on both sides of the encapsulated WOLED panel to form a complete light engine, since naturally diffusive WOLED lighting requires no additional structures for light redirection or glare reduction. The cost of the barrier sheet package without the external MLAs is estimated at \$3.0 /m^2.[49]

Summing all cost contributions, the production cost of WOLED light engines is \$99.3/m^2 for the hybrid system, and \$134.1/m^2 for the all-VTE system, without accounting for the product yield in either case. The geometric fill factor (GFF) of the functional WOLED area on the substrate roll is assumed to be 95%, with the rest comprising panel bezels for contacts and adhesion, and losses incurred in scribing and cutting. With an assumed qualified WOLED panel yield of 90% from R2R manufacturing, GFF = 95%, and an additional 10% miscellaneous cost premium, we arrive at a total WOLED light engine cost of \$125.5 /m^2 for the hybrid, and \$170.4 /m^2 for the all-VTE production scenarios.

3. Discussion

The U.S. Department of Energy (DoE) projects a cost breakdown of WOLED panels produced by conventional methods (sheet-to-sheet vacuum deposition, see Table 4) of \$480 /m^2, comprising a material contribution of 58% based on a 5 x 10^5 m^2/yr capacity by 2025,[50] and assuming a total capital cost of \$200 M. In our analysis based on R2R processing, the capital cost is 16.5 % (all-VTE) and 46% (hybrid) higher due to the complexity of incorporating different deposition techniques in a single, continuous production line. However, R2R processing reduces the takt time and increases the throughput by more than ten times compared to batch-processing methods. The fixed costs scale inversely with the area produced, whereas material, driver and package costs scale linearly. Materials comprise 76% of the total WOLED light engine cost by hybrid R2R production in our analysis. This agrees with previous analyses where the decrease of the cost of WOLED lighting is achieved through reduction of depreciation and labor cost from manufacturing scale-up, making materials the dominant cost contributor.[5,8,15]

The most expensive tools in the proposed R2R production line are the OVPD chambers, which cost 87% more than the VTE chambers. The cost premium of OVPD compared with VTE primarily results from multiple gas and pressure control units, temperature control units for both sources and substrates, and external heating units for the chamber walls. The all-VTE production line yields similar productivity as the hybrid system since the throughput speed is only limited by the VTE deposition of the 50nm-thick transport layer. Comparing the all-VTE to the hybrid system, the 22% reduction in equipment cost of the former is overwhelmed by the increase of the organic material cost. This indicates the adoption of OVPD in R2R production of layers employing costly host and dopant materials is economically preferred.

A potential scenario for materials cost reduction without including the 10% miscellaneous cost contribution is shown in Figure 4. The most expensive panel component is the organic stack due to high source materials cost. Chemical synthesis with fewer steps, less expensive starting materials and higher production yield can significantly reduce the costs of organic compounds when the volume is expanded 10-fold by R2R processing. For example, archetype emitter dopants based on tris-cyclometalated Ir(III) complexes can be prepared with nearly twice the current yield (85% vs. 45%) when a dichloro-bridged dimer is used as the starting precursor instead of the conventional option of Iridium acetylacetonate.[51] The combined cost of organic materials can be reduced by 40% based on the similar yield improvements, or the use of low cost precursors for host and transport materials, leading to a total material cost reduction of 25%. The SEMLA is the second most expensive component, primarily due to planarizing and waveguiding by the high refractive index polymer, which contributes more than 90% of its total cost. We assume the SEMLA cost has elasticity once mass production of the planarizing polymer is achieved, ultimately leading to a polymer cost reduction of 50%. This results in a further total material cost decrease of 12.7%. The cost of high quality transparent substrates with ITO sheet resistances < 10 Ω/square and TFE layers can be further reduced as alternative, cost-effective transparent substrate (e.g. ultrathin glass) or electrode material choices are made available.[52,53] With the assumption of 50% future reduction in the transparent substrate and electrode, metal contact and TFE costs, the material cost can be reduced from a base case of $94.6 to $53.6 /m^2 in the near future.

The WOLED light engine cost including the driver, package and 10% miscellaneous cost premium is shown in Figure 5. The cost is converted to that of illumination in units of $/klm based on the assumption of 10 klm/m^2 operating luminance. Accounting for material cost reduction in Figure 4, the WOLED light engine cost changes from a base case of $12.5 to $8.0/klm. Provided that WOLED efficacy approaches 120 lm/W,[11] the WOLED can be operated at 20% higher intensity than the initial assumption of 10 klm/m^2, which results in an equivalent reduction in cost of illumination of 16.7%.

Most current WOLED products utilize drivers optimized for LED operation without low current output and short-circuit protection, which often results in a reduction in lighting efficacy. Customized WOLED current drivers with conversion efficiencies approaching 95% can further reduce the cost of WOLED lighting by improving the overall luminaire efficacy.[10] Assuming an additional 50% reduction in current driver cost when WOLED dedicated drivers are widely available, WOLED light engines are projected to reach $6.33/klm.

Commodity residential lighting is the most price-sensitive sector in the US market, but nevertheless shows a wide price distribution, depending on luminaire features, efficiency and aesthetics. The luminaire prices range from approximately $30 to over $300, introducing an average LED downlight luminaire price of $22.5 /klm in 2020.[54] In terms of lamps or light engines, the average LED illumination price is $7.74 /klm,[54] whereas the production costs of a typical residential LED light engine is $4.0 /klm.[55] A comparison of costs of current LED light engines and those projected by the US DoE for WOLEDs produced by batch processing methods, as well as WOLEDs produced by R2R manufacturing, are summarized in Table 5. Only the light source, package, optics and integrated drivers are included to provide a fair comparison. While the cost of drivers and optical schemes are comparable, the cost difference between WOLED panels and LED dies dictates the economics of WOLED and LED lighting. We find that R2R production reduces the cost of WOLED lighting by more than 50% compared with batch-to-batch processing, and furthermore, is only 57% higher than LED lighting within the foreseeable future. Despite the higher cost, WOLED lighting shows advantages in commodity commercial and specialty lighting sectors, including the architectural, hospitality, and transportation industries. The thin, cool, and flexible or conformable profile of WOLED panels that do not require heat sinks and light guides enables creative designs that marry the illumination fixture design with different material surfaces, from wood to textiles, giving a richer user experience.

Note that the cost of LED light engines has decreased by ~ 80% since LED A-type lamps became available to consumers in 2007, and is projected to be further reduced by at least another $0.3 /klm in 2035.[54,56] Similar cost reductions and the growing momentum for adoption in niche markets may bring WOLEDs into the premium residential lighting market within the very near future. Current LED light engines contribute to less than 40% of the luminaire cost, with the rest composed of the thermal, mechanical and electrical housing structures, and assembly costs.[56] In contrast, WOLED light engines are nearly stand-alone luminaires when they are implemented as surface-mounted light sources that require few support structures. This brings the overall cost of WOLED luminaires much closer to LED luminaires for residential lighting, provided that high volume production via R2R technologies match a growing consumer need.

4. Conclusion

Our estimate of the manufacturing cost for WOLED panels used for general lighting suggests that high throughput R2R fabrication processes can enable large-scale production of cost- and energy-effective luminaires. A R2R production line that produces WOLED panels at the rate of 6 x 10^6 m^2/yr requires a capital investment of $293 M, or $ 233 M for hybrid OVPD/VTE or all-VTE designs, respectively. The WOLED production cost is dominated by materials, while the capital equipment and miscellaneous operational costs are reduced by the anticipated high throughput required for volume manufacturing. The R2R produced WOLED lighting cost is estimated at $12.5 /klm based on current materials costs and device performance, which is significantly lower than the current commercial WOLED cost of > $50 /klm. We expect the hybrid R2R production cost of WOLED lighting can be reduced to $6.3 /klm with realistic, near-term cost reductions. These estimates suggest WOLED lighting has promise for high-end commercial lighting, and can be potentially positioned in the residential lighting market as well due to the many unique features offered by this technology.

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Conflicts of interest

One of the authors (SRF) holds an equity interest in one of the sponsors of this work (UDC). This apparent conflict is under management by the University of Michigan, Office of Research. The University of Michigan also holds a royalty bearing license with UDC.

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Table 1. Equipment cost estimate for manufacturing

Item	Required quantity		Depreciation ($/year/tool)	Reference
	Hybrid VTE/OVPD	All-VTE		
Laminating station	1	1	386K	[36]
VTE chamber	24	37	571K[(a)]	[37]
OVPD chamber	13	-	1071K	[37]
Sputterer	1	1	194K	[37]
ALD chamber	1	1	893K	[38]
Laser scribing & dicing	2	2	107K	[21]
Total capital cost per production line	293M	233M		

[(a)]Value is determined for the hybrid VTE/OVPD system. Depreciation cost for VTE chambers in the all-VTE system are $ 540k and 667k /year for single source and two-source deposition configurations, respectively.

Table 2. Assumptions for cost of ownership estimates

Item	Unit	Value
Roll moving speed	m/hr	540
Roll preparation and loading time	hr/hr	0.05
Substrate width	m	1.5
Production area per system	m^2/year/system	6.09 M
Unskilled labor	/system	3
Skilled labor	/system	13
Unskilled wage	$/system/year	0.6M
Skilled wage	$/system/year	4.2 M
Electricity	$/equipment/year	154K
Utilities – Process chilled water, etc.	$/system/year	100k
Maintenance	$/equipment/year	10K
Maintenance time	month/year	1

Table 3. Itemized manufacturing cost estimates for a hybrid VTE/OVPD production line, in $\$/m^{2}$[(b)]

Layer	Equipment	Utilities	Labor	Materials	driver	fixture	Total
ITO and PET substrate	0	0	0	5.00	0	0	5.00
SEMLA	0.87	0.03	0.03	20.87	0	0	21.80
Lamination	0.06	0.02	0.03	0	0	0	0.11
Splicing and patterning	0.02	0.02	0.3	0	0	0	0.34
VTE grown layers[(c)]	2.25	0.61	0.43	14.43	0	0	17.72
OVPD grown EMLs	2.28	0.32	0.22	35.80	0	0	38.62
Metal cathodes	0.03	0.02	0.02	4.50	0	0	4.57
TFEs	0.15	0.02	0.02	0.30	0	0	0.49
Dicing/segmentation	0.02	0.02	0.03	0	0	0	0.07
Driver	0	0	0	0	7.30	0	7.30
Barrier layer fixture+MLA	0	0	0	0	0	3.00+1.40	4.40
Total (before accounting for yield)	4.81	1.12	0.78	80.90	7.30	4.40	99.31
Total (accounting for yield and GFF)	5.63	1.31	0.91	94.62	7.30	4.40	114.12

[(b)]Values shown are before 10% miscellaneous cost is added.

[(c)]In all-VTE systems, the costs associated to VTE-growth row are \$3.55, \$0.93, \$0.65, and \$86.03 for equipment, utilities, labor and materials, respectively.

Table 4. Comparison of US Department of Energy (DoE) cost targets for OLED panels produced by batch-to-batch and hybrid R2R processing [d]

Item	DoE 2022	DoE 2025	DoE 2035	This work[e]
Capital cost ($M)	75	200	400	293
Capacity(m^2/yr)	60k	500k	2400k	6094k
Depreciation($/$m^2$)	250	80	35	4.8
Organic cost($/$m^2$)	150	80	35	50.2
Inorganic cost($/$m^2$)	450	200	100	30.7
Labors($/$m^2$)	80	15	5	0.8
Others($/$m^2$)	40	10	5	1.1
Total unyielded($/$m^2$)	970	385	180	87.6
Yield of good product (%)	75	80	90	90
Total($/$m^2$)	1300	480	200	97.3

[d]Cost targets for batch processing are reproduced from DoE office of Energy Efficiency and Renewable Energy SSL report "2019 Lighting R&D Opportunities" Table 3.9.

[e]Cost estimates shown in Table is of only WOLED panel from hybrid VTE/OVPD production, does not include driver and package cost or GFF.

Table 5. Comparison of illumination costs for conventional LED and WOLED light engines produced by batch-to-batch and R2R processing, in $/klm.

	Current conventional LED[(f)55]	DoE 2035 batch WOLED[(g)]	R2R WOLED	Future R2R WOLED
Light source	1.50	20	8.47	4.12
Package	-	0.48	0.48	0.48
Optics	0.75	2.81	2.81	1.33
Driver	1.75	0.80	0.80	0.4
Total	4.00	24.09	12.54	6.33

[(f)] Cost of LED light source includes package cost.

[(g)] Cost estimates for the package, optics and driver are adopted from this work.

Figure Captions

Figure 1: (a) Illustration of a flexible white organic light emitting device (WOLED) panel integrated in a light engine with barrier sheets and a current driver. Microlens arrays (MLAs) for outcoupling are attached to the distal side of the barrier sheet. The inset is the detailed structure of the WOLED panel with sub-electrode MLAs (SEMLAs) used to extract waveguided modes. (b) A schematic of an archetype WOLED device structure with thicknesses of emission layers (EMLs) and transport layers (TLs). The total thickness of this device above the SEMLA surface is 430 nm.

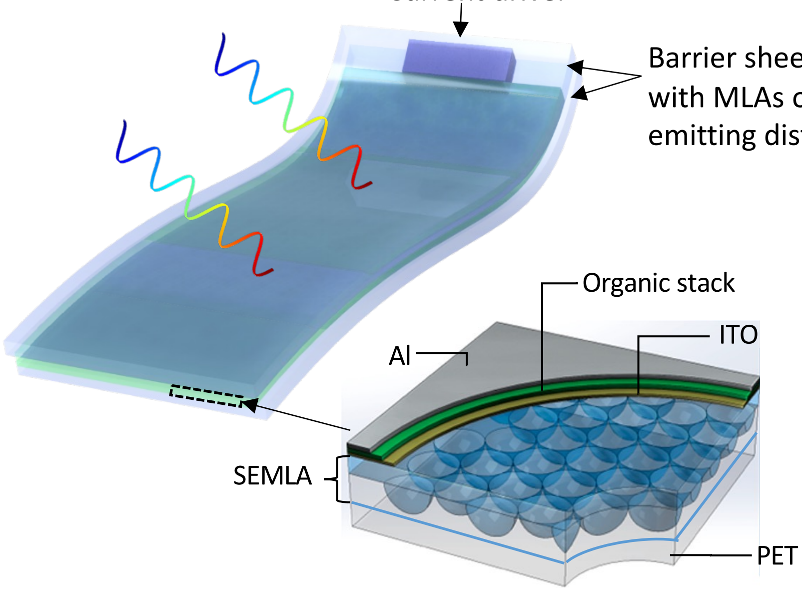
Figure 2: Process sequence for manufacturing WOLED lighting panels on a flexible plastic substrate roll. Neat organic transport materials are grown by vacuum thermal evaporation (VTE) and blended EMLs are grown by organic vapor phase deposition (OVPD) or VTE.

Figure 3: Schematics of the various deposition chambers in an R2R production line that are interconnected through differential pumping. The organic deposition window is 1.5 m-wide.

Figure 4: Waterfall diagram showing materials cost in manufacturing WOLED panels with the impacts of several near-term cost reduction scenarios described in text.

Figure 5: Waterfall diagram showing WOLED light engine cost in $/klm and the impacts of several near-term cost reduction scenarios based on luminance improvements described in text.

a.



WOLED panel structure with SEMLA

b.

30 nm TFE	
100 nm Liq/Al	
50 nm BPyTP2 (TL)	
48 nm Red-Green Cell	40 nm EML + 8 nm TL
37 nm CGL	
70 nm Blue Cell	55 nm EML + 15 nm TL
2 pairs: 37 nm CGL	37 nm TL
2 pairs: 48 nm Red-Green Cell	
30 nm NPD (TL)	
10 nm HATCN (TL)	
150 nm ITO	
SEMLA	
PET substrate	
30 nm TFE	

Fig1

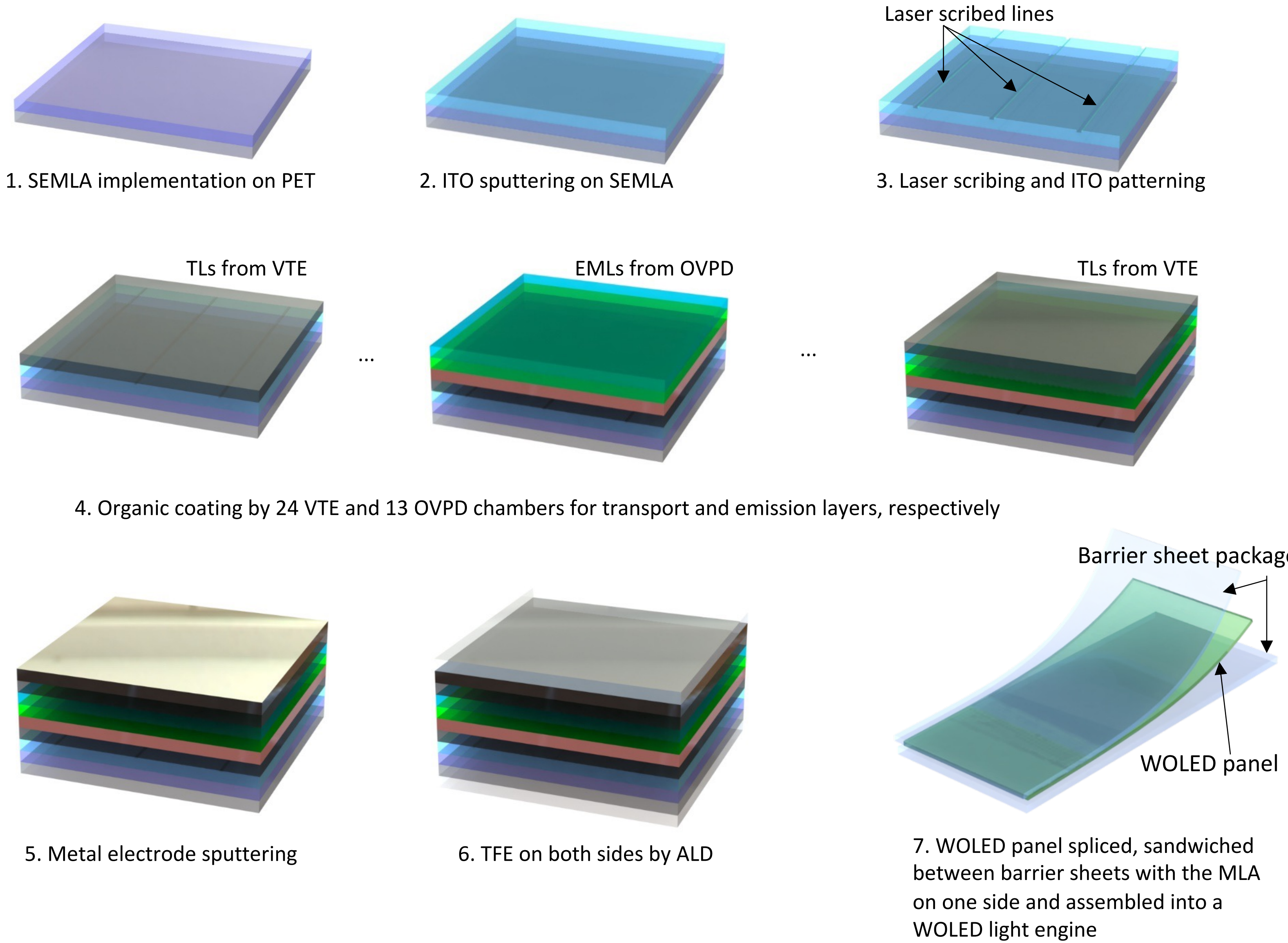
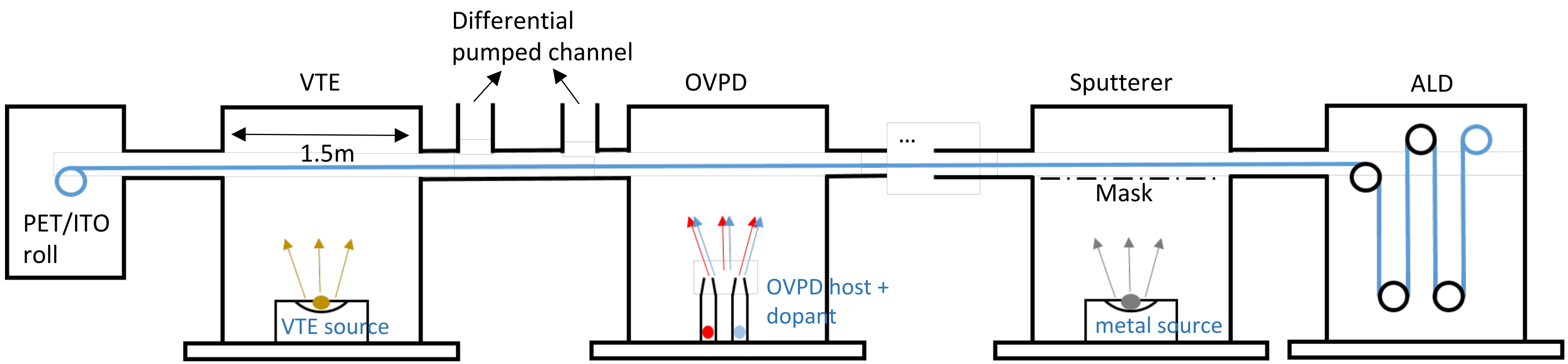

Laser scribed lines
1. SEMLA implementation on PET
2. ITO sputtering on SEMLA
3. Laser scribing and ITO patterning
TLs from VTE
EMLs from OVPD
TLs from VTE
...
...
4. Organic coating by 24 VTE and 13 OVPD chambers for transport and emission layers, respectively
Barrier sheet package
WOLED panel
5. Metal electrode sputtering
6. TFE on both sides by ALD
7. WOLED panel spliced, sandwiched between barrier sheets with the MLA on one side and assembled into a WOLED light engine

Fig2



Interconnected R2R production

Fig3

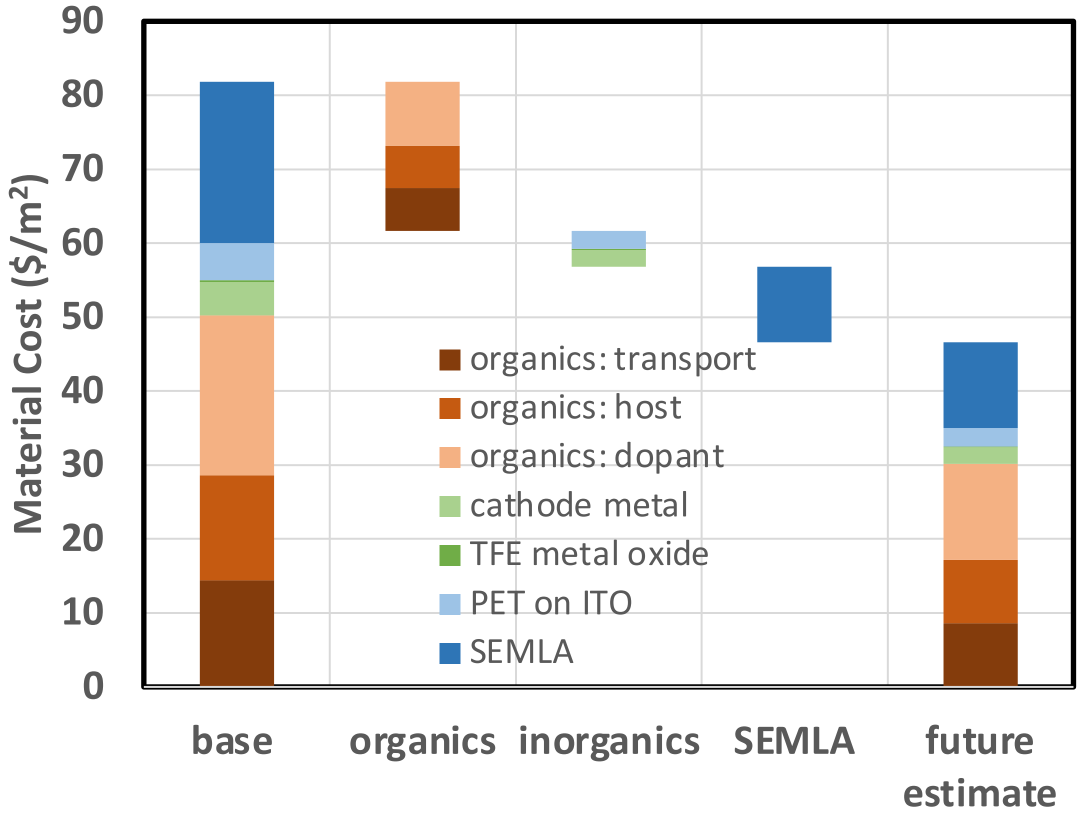
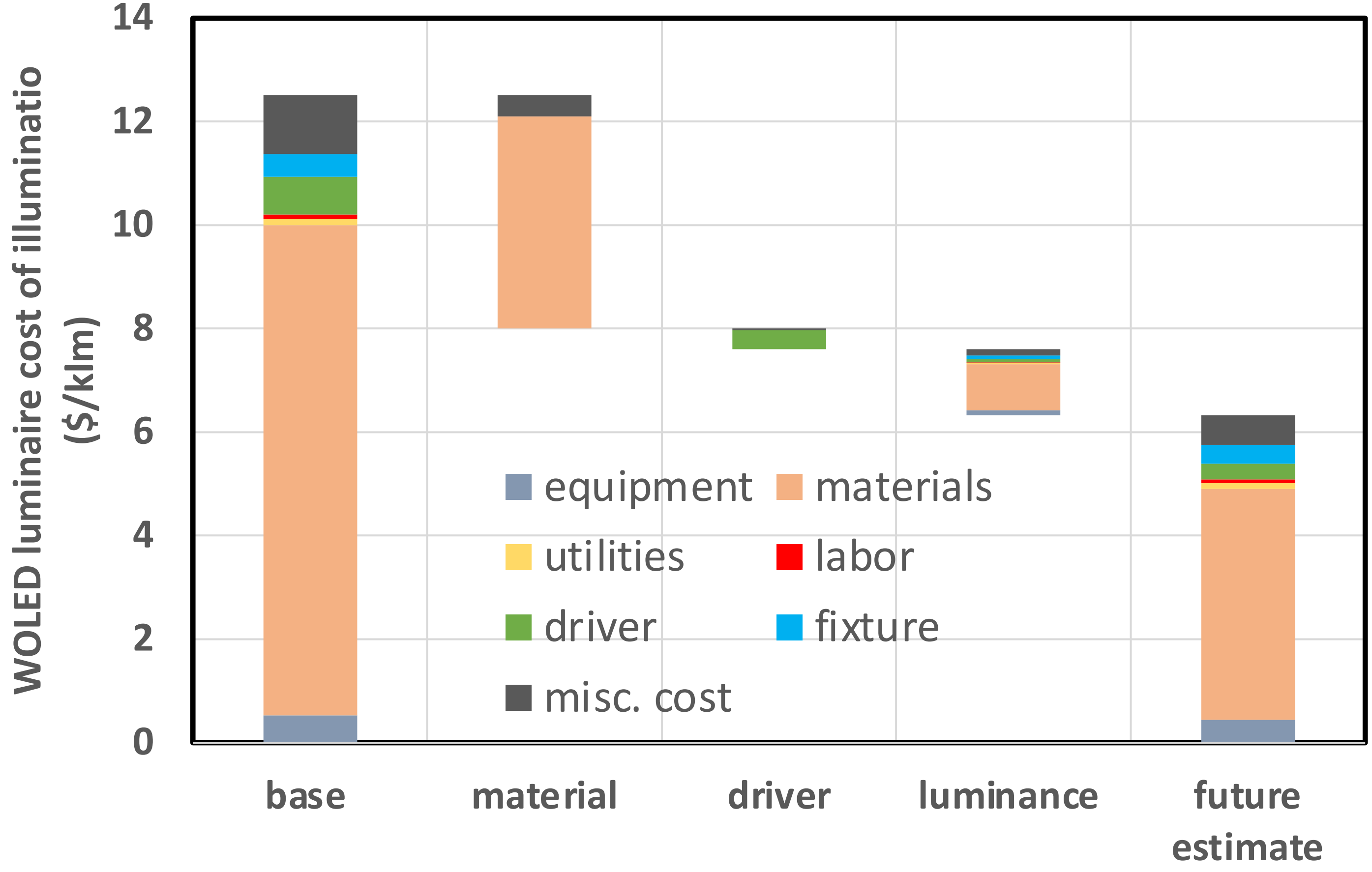

90
80
70
60
50
40
30
20
10
0
Material Cost ($/m2)
organics: transport
organics: host
organics: dopant
cathode metal
TFE metal oxide
PET on ITO
SEMLA
base
organics
inorganics
SEMLA
future estimate

Fig4



WOLED luminaire cost of illuminatio
($/klm)
14
12
10
8
6
4
2
0
equipment
materials
utilities
labor
driver
fixture
misc. cost
base
material
driver
luminance
future
estimate

Fig5