Optimizing OVPD technology towards lowest OLED manufacturing cost

M. Schwambera
Organic Semiconductor Technologies
AIXTRON AG
Kackertstr. 15-17, 52064 Aachen, Germany
M.Schwambera@aixtron.com

Abstract: *We report on Organic Vapor Phase Deposition (OVPD®) as an innovative deposition technology for OLED and organic semiconductor manufacturing. The combination of OVPD® with Close Coupled Showerhead (CCS) technology results in manufacturing equipment with vast potential for cost effective manufacturing of OLED displays commercially competitive to LCD.*

We discuss the actual OVPD® equipment concept and design and continuous implementation of improvements: Comparison of Computational Fluid Dynamic (CFD) modeling with experimental results has proven the excellent deposition properties e.g. high stability and reproducibility, uniformity, high deposition rates and high organic material utilization efficiency of the OVPD®-technology resulting in OLED performance data from devices made by OVPD®, which are superior to those from conventional vacuum thermal evaporation (VTE) techniques.

Key aspects in reducing manufacturing costs enabled by unique features of OVPD® technology have been identified and will be highlighted. Discussion of how equipment hardware related parameters impact OLED manufacturing cost will point out the vast potentials to reduce OLED manufacturing cost.

Keywords: OVPD®; organic; vapor; phase; deposition; OLED; manufacturing; small molecules.

Introduction

Organic semiconductor devices typically consist of thin (< 2000 Å) films of either conjugated polymers or aromatic molecules (small molecular (SM) weight organic materials), each requiring different deposition methods. SM OLEDs today are widely manufactured using Vacuum Thermal Evaporation (VTE), where the organic materials are evaporated or sublimed in high vacuum to form molecular beams towards the substrate.

Organic Vapor Phase Deposition invented by S. Forrest et al. at Princeton University in 1995, provides a novel method for the deposition of organic thin films [1]. Since the introduction of OVPD® the fabrication of numerous organic devices was reported [2-9], which confirms the feasibility of this technique. OVPD® is a technique to deposit small molecular organic thin films utilizing the advantages of gas phase transport. This technology has the potential to overcome the shortcomings of and to substitute VTE in OLED manufacturing. OVPD® is a departure from low pressure CVD; the OVPD® process is based on the evaporation or sublimation of small molecular weight organic materials into an inert carrier gas stream at low pressure. The carrier gas transports the molecules to a cooled substrate within a hot walled deposition chamber. There rapid condensation of the organic molecules occurs forming the desired films onto the substrate. By using multiple sources of organic materials, stacks of organic thin films required for a complete OLED or organic semiconductor device can be deposited.

OVPD Concept and Principle

Figure 1 shows the principle of OVPD®. Source materials are placed in containers; as the materials sublime the inert carrier gas (N_2) gets saturated by the organic molecules and transports them towards the substrate. Different materials (e.g. host and dopant) can be homogeneously mixed in the gas phase prior to arriving on the cooled substrate, where they condense to form the desired film.

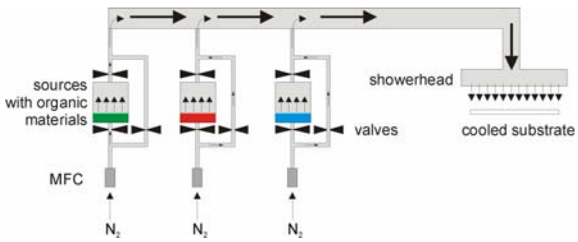


Figure 1. Schematic diagram of the OVPD®

Figure 2 shows the schematic of AIXTRON's OVPD® equipment employing a temperature controlled deposition chamber and the close coupled showerhead design as gas distributor.

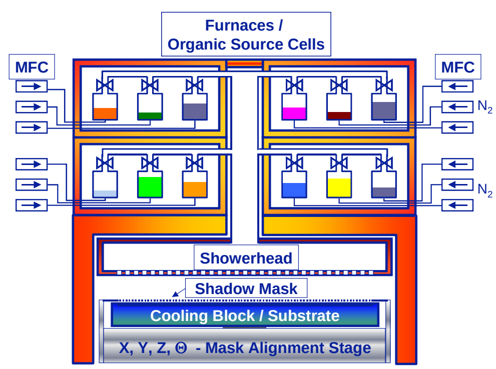


Figure 2. Schematic of the CCS - OVPD® production concept. Organic materials are evaporated/ sublimed in individual source containers and transported by an inert carrier gas into the showerhead, which injects the organic material uniformly across the entire deposition area.

The organic source materials are heated in physically separated source containers, which are arranged in separate furnaces remote from the deposition chamber, and transported by an inert carrier gas into the hot-walled deposition chamber.

Individual valves switch the source flows to enable rapid on/off control of the respective deposition, which offers high precision control of layer interfaces as well as minimization of material waste. The organic molecules are homogeneously mixed in the gas phase prior to being introduced uniformly through the heated showerhead injector across the entire substrate surface where they condense to form the desired film. The integration of a high precision mask alignment system allows fabrication of full color OLED displays.

Requirements to OLED manufacturing

Increasing the productivity for OLED and organic semiconductor devices is necessary to decrease manufacturing cost. This can be achieved either through increasing the size of the mother glass to produce more panels simultaneously or by reducing TACT time to simultaneously handle more than a single substrate in the same time.

In the LCD industry both routes have been followed: whilst the mother glass size was increased from Gen2 in 1993 to Gen8 (mass production expected for 2006) as can be seen from Figure 3, TACT time has been reduced below 1 minute. Currently, OLED mass production is typically conducted on Gen2 mother glass size with TACT times in the range of 5 to 15 min.

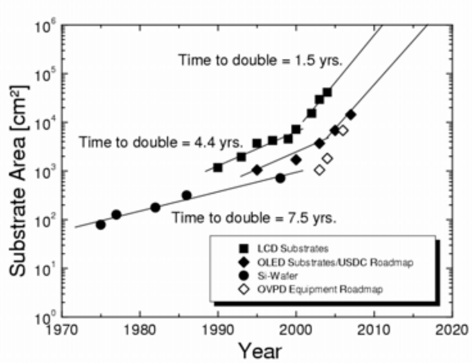


Figure 3. Development of substrate area [10]

OVPD® offers a joint strategy to increase productivity through both reducing TACT time and increasing mother glass size. To date controllable deposition rates up to 30 Å/s have been achieved [11] offering even higher deposition rates through improved source design and/or multiple source utilisation. Hence, the values currently achieved by OVPD® already exceed state-of-the art VTE manufacturing equipment by an order of magnitude, which can lead to significantly reduced TACT times. Consequently OVPD® offers potential to realize OLED production lines with TACT times similar to those used in LCD manufacturing.

Scaling of the CCS deposition chamber used for OVPD® is a straight forward procedure: the nature of CCS only requires a 2-dimensional resizing of the deposition chamber, i.e. the distance between the showerhead and the deposition area remains constant with unchanged uniformity of the deposited thin films. Just as important as the uniformity is maintaining high deposition rates with increased deposition area. Material utilization efficiency can be increased with larger substrate sizes due to a better area to circumference ratio of the substrate. As described above the deposition rate based on molar flow of organic materials is determined through carrier gas flow at constant source temperature and dependent on chamber geometry. Proper design of the internal of the source containers allows increased flow of organic molecules from the solid or liquid source materials into the gas stream, thus increasing the molar flow towards the deposition area. Further on the molar flow can be increased through utilizing multiple organic sources in parallel without affecting the deposition performance. As a consequence OVPD® can be scaled to larger deposition areas without increasing source temperatures, which in turn may be critical to the stability of the organic source materials.

OVPD® deposition to date has been performed on mother glasses up to Gen2 sizes, where processes can be easily transferred between different products due to the nature of gas phase transport techniques. Concepts for larger dimensions have already been developed. As shown in Figure 3 the development of larger OVPD® equipment is following the market demand, which is also driven by the sizes of OLED products.

Optimisation of Cost of Ownership

For the optimization of cost of ownership of future OVPD® equipment we selected following boundary conditions, based on actual market data and requirements:

Fixed and optimized OVPD® hardware geometry on basis of Gen4 mother glass (730 x 920 mm²) are setting the starting conditions for numerical modeling and simulation of the equipment hardware. Typical OLED device thickness is assumed to 120 nm, with densities of organic material of 1.1 to 1.3 g/cm³. The average cost of the organic materials was determined to be 100 $/g based on today's market prices. Uptime of greater than 95 % and a yield of 98 % are completing the set of fixed parameters. For optimization of the OVPD® process we varied the total flow Q_{tot} and source flow Q_s. The total flow Q_{tot} is the sum of all carrier gas flowing through the deposition chamber, whereas the source flow Q_s is the amount of carrier gas going through an individual source container per time having the unit milliliter or liter per minute.

Our modeling approach is based on the numerical solution (CFD computational fluid dynamics, finite volume method) of flows (e.g. $Q_{tot,}$ Q_s), heat transfer including conduction and mixed convection, mass transport of key chemical species involved in the growth or deposition and mass transport limited on the substrate surface. The computational results are in terms of flow pattern, temperature and species distribution as discussed in the following.

We determined the deposition rate in the Gen4 OVPD® system on the basis of the following equations:

The deposition rate is diffusion limited and proportional to $1/\delta$, where δ is the boundary layer thickness and described by formula (1).

$$\delta \sim 1/\sqrt{\mathrm{Re}_{vert}} \qquad \textbf{(1)}$$

Re_{vert} is the vertical Reynolds number and described by equation (2)

$$\mathrm{Re}_{vert} = \frac{\rho \cdot u \cdot D^2 / H}{\mu}, \qquad \textbf{(2)}$$

where ρ is the density of the gas, u the gas entrance velocity, D the deposition chamber diameter, H the deposition chamber height and μ the gas viscosity.
Note that as ρ is proportional to p and u is proportional to $1/p$ the Reynolds number and thus the deposition rate are independent of the process pressure p.
We discuss in the following the parameter study with varied total flow of 2 to 7 liters per minute and the respective value determination of the deposition rate, material utilization efficiency and resulting tact and cost per mother glass.
Figure 4 shows the dependency of the deposition rate of Alq_3 over total flow. We find that the deposition rate r is proportional to the square root of the total flow $Q_{tot}^{1/2}$ thus the deposition rate increases sublinear with total flow.

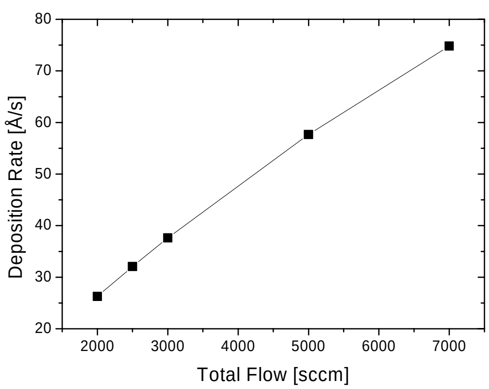


Figure 4. Deposition rate effect of total flow

However we find a different behaviour for the material utilisation efficiency η, which is defined by the ratio of deposited material on the target substrate versus the evaporated material inside the source. The material utilisation efficiency η is proportional to δ/H thus we find that it is proportional to the negative square root of the total flow $Q_{tot}^{-1/2}$ and deposition chamber height $H^{-1/2}$.
Figure 5 shows the dependency of the material utilisation efficiency η over total flow. We find that the effiency decreases with increasing total flow.

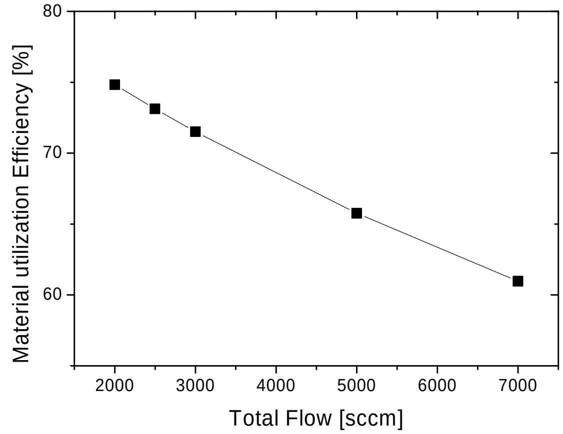
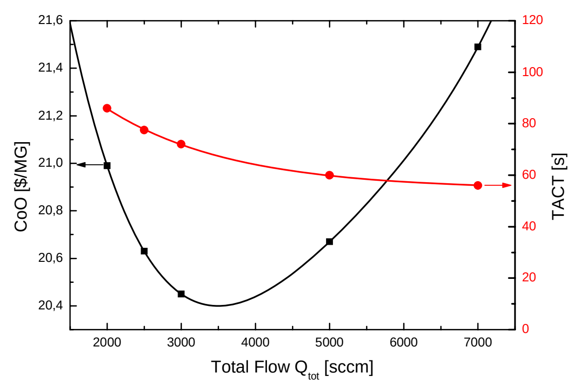


Figure 5. Material utilization efficiency effect of total flow

In conclusion this means for the determination of the cost of ownership (CoO) that we have to find a trade-off between achieving high deposition rates thus low TACT times versus lowest material cost dependent on the material utilization efficiency.
Figure 6 shows that we of course find lower TACT times with increasing total flow, as deposition rates increases. However, in terms of CoO the decreasing material utilization efficiency with increasing total flow is a counterproductive effect thus this problem describes a extreme value exercise. Solving this trade-off behavior results in a minimum cost of ownership of \$ 20.4 per mother glass (MG) at a 68 s TACT time and total flow of 3.5 liter per minute.



Conclusion

OVPD® is a novel technique for the deposition of small molecular organic materials that overcomes many of the limitations of VTE. Its superiority with respect to precise, stable and reproducible control of the deposition processes could, and excellent uniformity across large areas together with high deposition rates and material utilisation efficiency when combined with Close Coupled Showerhead technology has been demonstrated [12, 13]. OLEDs deposited by OVPD® show similar or better performance compared to similar devices made by VTE. Scalability, increased yield and throughput in OVPD® are important factors towards making OLED products commercially competitive to LCD. Reduced organic material consumption and reduced maintenance requirements contribute further to the reduction in manufacturing cost, which makes OVPD® the technology of choice for the next generation manufacturing of OLED displays and for the manufacturing of next generation organic devices.

Acknowledgement

The author gratefully acknowledges the support and valuable contributions of M. Gersdorff, N. Meyer, B. Marheineke, G. Strauch, C. Martin and D. Brien at AIXTRON AG, Germany, who performed most of the work reported in this article.

Part of this work was financially supported by the Federal Ministry of Education and Research in Germany (BMBF, No. 001BD153).

OVPD® is a registered trademark. OVPD® technology has been exclusively licensed to AIXTRON from Universal Display Corporation (UDC), Ewing, N.J. USA for equipment manufacture. OVPD® technology is based on an invention by Professor Stephen R. Forrest et. al. at Princeton University, USA, which was exclusively licensed to UDC. AIXTRON and UDC have jointly developed and qualified OVPD® pre-production equipment

REFERENCES

1. P.E. Burrows et al., "Organic vapor phase deposition: a new method for the growth of organic thin films with large optical non-linearities", *J. Cryst. Growth* 156 (1995) 91-98

2. T. Zhou et al., "Stable and efficient electro-phosphorescent organic light-emitting devices grown by organic vapor phase deposition", *APL* 86, 021107 (2005)

3. M. Schwambera et al., "Process Controllability and Stability in Organic Vapor Phase Deposition", *IMID* 04 Digest, 25-6, 2004

4. S. Hartmann, A. Janssen, H. Blei, H.H. Johannes, W. Kowalsky, N. Meyer, M. Heuken, G. Strauch, unpublished data, Technical University Braunschweig and AIXTRON AG, Germany

5. M. Shtein et al., "Effects of film morphology and gate dielectric surface preparation on the electrical characteristics of organic-vapor-phase-deposited pentacene thin-film transistors", *APL* 81(2), 268-270 (2002)

6. S.R. Forrest, "The path to ubiquitous and low-cost organic electronic appliances on plastic", Review article in *Nature*, Vol. 428, 2004, 911-918

7. F. Yang et al., "Controlled growth of a molecular bulk heterojunction photovoltaic cell", *Nature Materials*, Vol. 4, 2005, 37 – 41

8. M.A. Baldo et al., "Low pressure vapor phase deposition of small molecular weight organic light emitting device structures", *APL* 71(21), 3033-3035 (1997)

9. S. Hartmann et al., "First Hybrid OLED by Organic Vapor Phase Deposition and its advantages in deposition rate control for OLED manufacturing", Digest of Technical Papers, Vol. XXXV, (50.4), *SID,* 2004

10. AKT Inc. 2003, USDC and Display Search)

11. B. Marheineke, OVPD: OLED manufacturing coming of age, 2005, *Proc. of SPIE* Vol. 5961 596101-1

12. M. Schwambera et al., "Modeling and fabrication of Organic Vapor Phase Deposition (OVPD) Equipment for OLED Display Manufacturing", Digest of Technical Papers, Vol. XXXIII, No. II (895), *SID*, 2002

13. M. Schwambera et al., "OLED Manufacturing by Organic Vapor Phase Deposition", Digest of Technical Papers, Vol. XXXIV, No. II (419), *SID*, 2003