Roll-to-Roll Manufacturing of Displays: Can it Become a Reality?

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Abstract
A basic assessment is presented of the technical, economic and strategic challenges expected for manufacturing displays in a roll-to-roll format. Two general pathways are considered; one that results in dramatic cost reductions but results in sacrificing product performance, and another which is an extension of the conventional FPD cost-reduction from increased substrate size. While Roll-to-Roll fabrication is fundamentally possible, feasibility experiments will be required to address the most significant technical challenge: achieving and managing acceptable yield. In all respects, the efforts to achieve RTR manufacturing will be assisted by overlapping interests in other application areas such as flex circuit, photovoltaics and large area lighting.

1. Introduction
Over the past decade, both industry and academia have demonstrated steady progress toward developing both active matrix backplane and frontplane technologies for flexible displays, ranging from electrophoretics, OLEDs and LCDs fabricated on both metal foil and plastic backplanes incorporating either silicon or organic-based TFTs. Although this progress has been slower than many researchers had hoped, more and more groups are demonstrating the fabrication of flexible display prototypes. This progress leads to a compelling option for the future display industry: to manufacture in a roll-to-roll (RTR) format. In fact, the question of whether or not flexible displays will be produced in quantities for the civilian consumer market may only be answered when the option of RTR manufacturing has been considered.

Consideration of RTR manufacturing is driven by the expected decrease in cost of manufacture. For more than a century, cost reduction through RTR format manufacturing has been demonstrated in an ever-increasing list of industries ranging from fabrics to stainless steel to diapers to flex circuit production. It is this possibility of cost reduction that may ultimately become the primary motivation for commercialization of flexible displays.

2. Strategy
There are many different scenarios which can be envisioned for RTR manufacture of displays, based on the variety of technologies which are being explored. In general, most of these scenarios fall into two categories; 1) High manufacturing throughput with low performance displays (including passive), and 2) Low throughput with performance matching current AMLCD standards. To a first-order approximation, throughput (equivalent to line speed times web width) of the RTR manufacturing line translates inversely to the cost of manufacturing.

Scenario 1) has a much lower barrier toward production. Lower performance means higher acceptable levels of defects in process steps. These looser specifications should greatly shorten the ramp-up to high yields, and may already be met by many existing RTR tools without modification. This is particularly true for passive displays. RTR production of passive displays had already been demonstrated by Polaroid, and is currently under development at Sipix and Kodak(SID ’05).

A significant disadvantage to scenario 1), however, is the challenge of supply vs. demand: Currently, there is no established large-volume market for such low-performance displays. While many companies have envisioned applications such as advertisement signage and price markers, very large volumes will need to be consumed to justify even just one production line. Assuming that such a future market will materialize, the time it will take to develop such a market may be unacceptably long for most investors to wait for a return on investment. In addition, most, if not all, of the applications envisioned are currently being satisfied by entrenched low-cost paper and print industries which offer immediate aggressive competition. This market barrier makes scenario 1) a path which will be accessible only to companies which are prepared for the time and investment it will

take to develop a market and it's related infrastructure.

Scenario 2) offers an immediate market opportunity to sell product into the existing FPD industry. In fact, for some applications where weight, ruggedness and flexibility may add value, a small premium could occur in price. The most significant challenge to scenario 2) is developing a set of equipment which can meet the very demanding performance and yield requirements of the FPD industry. As mentioned below, few RTR manufacturing tools have been studied and qualified to the required defect levels. Another concern for this strategy is the inability to accurately predict the final cost of operation/production for a RTR factory. Several factory models (e.g. Abbie Gregg Industries presented at 2003 Flexible Displays and Microelectronics Conference, Phoenix) predict a reduction of the cost per product area of a factor of two or more compared to glass panel production for a comparable process flow. However, until a fully qualified equipment set and process flow is developed and studied, only rough estimates can be made of input parameters such as capital costs, equipment utilization, yield projections, manpower requirements, etc. For the gains predicted in scenario 2), changes in these parameters could either improve the predicted cost reductions, or eliminate them entirely.

Even with these uncertainties, scenario 2) is compelling as an approach to continue reducing FPD production costs beyond those being reached by the new Gen 7 and possible Gen 8 fabs. According to Display Search's recent Quarterly Manufacturing Plans Report (Q1'05) the efficacy of cost reduction per area by increasing the substrate size appears to be diminishing greatly at Gen 7.5 as the costs of tools and increased inspection requirements outstrip the gains obtained from increasing substrate size. Even moderate cost reductions which could result from a conversion to RTR production can be significant driver for this industry. Furthermore, partial, or "hybrid" implementation of RTR, whereby the product is sectioned into panels in mid process flow, can offer a lower-risk pathway to scenario 2).

3. Technology/Equipment

Is RTR equipment ready to be deployed? The set of tools which would be used for RTR production depends entirely on the processes you choose, and to answer this question it is again best to separate into the two scenarios presented in section 2.

For scenario 1) with high throughput/low performance, manufacturers will consider use of tools/processes not conventionally used in the display industry, but well proven in their capability in the flexographic, flex circuit and other industries. Lithography with 20 micron features and acceptable yield can be obtained at high speeds using methods such as direct emboss, printing and soft-contact expose tools. Wet coating with slot-die and gravure methods are well established with micron-scale thickness and exceptional uniformity. Wet etch, develop, strip and cleaning tools are also readily available. A large variety of vacuum deposition systems are also available which can provide the gambit of thin film processes from sputter, evaporation and PECVD. Although these tools will all require qualification and modification, their established use in the flex circuit, passive display and other industries demonstrates performance in the range desired.

For scenario 2) the picture is not so clear. To a first approximation, what is desired is a toolset that mimics the current toolset and process flows used in conventional AMLCD production. While we can reference the same set of tools as in scenario 1) above, there is little or no knowledge of how these systems will perform for high performance FPD production. The industries which are generally served by the RTR industry today, e.g. food packaging, medical products, optical coating, photographic film, etc., have requirements which are often orders of magnitude less severe than what FPD manufacture demands. Defect levels in FPD equipment are on the order of 0.1 cm^{-2} for defects of 1 micron or greater, and zero for particles greater than approximately 5 microns. For most current RTR tool manufacturers to supply to the FPD industry, a cultural shift will be needed: While some RTR equipment manufacturers are aware of the stringent requirements of the display industry, and the years of often painstaking work that has been required for the development of FPD equipment to meet these requirements, most are not.

There are several likely gaps in the toolset for scenario 2). Dry-etch of inorganic thin films is not currently demonstrated by RTR equipment manufactures. Although some plasma etching has been implemented in RTR, it is generally used only for organic film removal, and is far from the process

requirements used in conventional display manufacture. Other likely gaps are in the area of defect inspection. Although technically feasible by adapting the existing batch methods, inspection for RTR scenario 2) is likely to push the envelope in implementing this technology.

Outside of either scenario 1) or 2) are new, unconventional tools and processes which are being considered for RTR display manufacture. In particular, new types of embossing, imprinting and inkjet printing methods are being explored by a variety of groups. These offer very disruptive pathways for RTR production, but remain unproven.

In all cases of considering the manufacturing equipment, the overriding unknown remains the ability to maintain low defect levels and high yields. RTR manufacturing differs from batch in that the substrate will be subject to bending, tensile stretching, front-surface contact upon winding, unwinding and possible other points of handling. These can all generate defects from particles, scratching, film cracking and delamination. There are also many strategies which could be used to reduce defects. However, to develop complete, useful data on yield and yield management will require the integration of many types of tools into one line.

4. Converging Interests

Perhaps the most significant barrier to RTR manufacture of displays is the financial risk associated with developing a complete manufacturing line, a step which is required to answer many of the current unknowns. Estimated expenditures for this development range from $100M to $500M. This considerable financial risk is a motivation to seek as many alternative resources as possible. One compelling approach is to share resources with other industries that have related interests in high-precision RTR.

As mentioned in section 3, many of the required tools are already in use in a variety of industries. When the product value of those industries is high, there is considerable interest in improving yield and overall precision.

One such industry is Flex Circuit. The present state of R&D for flex is very much aligned with the development required for RTR display manufacture. In order to push below the current 20-micron resolution for state-of-the art flex, manufacturers are contending with issues of throughput, yield, and substrate stability. These issues are further confronted as methods of embedding or integrating passive and active components are researched.

Another industry is the lighting industry, where large area lighting using OLEDs and similar materials are being developed. RTR fabrication of these devices is inevitable as low cost is an absolute threshold for commercialization. These devices have very demanding specifications to yield product.

The photovoltaic industry shows signs of steady growth in RTR production (e.g. Energy Conversion Devices Inc. recently announced plans for a second RTR production line). Nevertheless, the overall volume of growth will still be capped by the cost of production, as photovoltaic cells continue to be a high cost energy source. This industry has steady interest in lowering product defects for RTR production, and improving the production purity and quality of inorganic thin films and their interfaces.

The converging interests of these various industries is creating the critical mass of interest to establish efforts both by government and industry to invest in improvements in the available RTR toolsets.

5. Conclusions

In spite of many foreseen hurdles, RTR manufacturing of flexible displays remains a compelling possibility, driven by the potential reduction of cost of manufacture. Although many tools and processes are already available in RTR format, the question of whether RTR production will be economically feasible cannot be answered without study of the issues surrounding defect generation, product yield and yield management. Such studies can only be confidently performed by an integration of RTR tools into full process flows. Toward this end, it may be possible to leverage the interests and activities of related industries such as flex circuitry, large area lighting, and photovoltaics.