CH2MHILL
CONSULTING REPORT

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Subject: Imagine Designs Technology Manufacturing Comparison Consulting Project

Introduction

Imagine Designs, Inc. (IDI) has requested assistance with the preparation of an analysis of the manufacturing advantages of the IDI technology over the incumbent liquid crystal display (LCD) technology for a mobile phone display application. IDI is requesting a professional opinion on the feasibility of manufacturing the IDI technology. IDI estimates that the IDI technology eliminates a number of layers of films that are required in an LCD; creating a lower BOM cost, less time to build, a higher yield, reduced floor space, shorter production time, and lower tooling cost.

Scope of Services

CH2M HILL's scope of work includes IDI's request for a professional opinion from CH2M HILL on the following questions:

1. How much less floor space might be needed for a production line using the IDI technology compared to current LCD technology?
2. How much less labor/people might be needed?
3. What increase in yield might be expected?
4. Based on the answers to the preceding three questions, what is the estimated relative cost difference for the manufacturing facility and process equipment, compared against the incumbent LCD technology and the IDI technology?
5. Generally, in CH2M HILL's opinion, what is the feasibility of manufacturing the IDI technology?

Approach

CH2M HILL used an existing internal LCD cost model as the basis for a comparison of the manufacturing cost of a similar process, modified for the IDI device flow. The model is excel based, and describes a standardized LCD process flow step by step. For each step, parameters such as throughput, floor space, labor, and material consumption are entered. The inputs are based on information from tool vendors and CH2M HILL's experience in the industry. The model uses the inputs to calculate total factory size and cost, and to calculate a product cost of goods sold (COGS) for a particular display size and production volume. The COGS is meant to be comprehensive, including factors like depreciation and utility costs.

In general, the IDI process has basic similarities with a standard LCD process, in that it requires a thin film transistor (TFT) array to actuate the pixels, but differs in that it does not require all of the LCD process steps. The LCD cost model was therefore modified by removing process step blocks relating unnecessary layers, and by modifying some process steps with difference materials, labor, or other cost assumptions. The modified model was compared to the standard model in order to obtain a relative measure of the manufacturing parameter differences.

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The data populating the existing LCD model is from 2004, and so does not reflect the current cost situation, but can be used to gauge the relative cost of the two technologies. Additionally, the LCD model was designed for a larger size panels, suitable for TV products, and a larger motherglass than would normally be used for cell phone displays. Despite these limitations, CH2M HILL believes that the relative cost comparison between the technologies remains valid.

Process Analysis

The LCD manufacturing process used in the analysis consisted of approximately 180 discrete process steps. The basic process includes creating a TFT array and a colour filter (CF) array, aligning and attaching them together with a liquid crystal (LC) material sandwiched between, and then attaching the backlight and other parts of the module.

In comparison, the IDI technology does not require several process steps, layers, or components that are necessary in an LCD display. Below is an itemized list of the differences that were used in the manufacturing calculation.

1. In an LCD process, after creating the TFT array, a transparent pixel electrode is fabricated in order to allow light from the backlight to pass through the pixel to reach the viewer. The material is normally indium-tin-oxide, or ITO, and the layer is created by sputtering followed by photolithography. In an IDI device, since the actuator can be positioned behind the opaque reflecting element, there is no requirement for transparency, and so this layer can be eliminated. In order to created the actuating electrode, it is recommended to use the source-drain (SD) metal layer from the standard TFT process. This involves a simple modification of the photolithography mask for that layer, and does not incur any additional cost.

2. After the LCD TFT array process is complete, there is normally a multi-stage test and repair process, which is intended to identify electrical shorts in the array, and remove them by laser ablation. In the LCD device, it is critical to use very narrow lines and spaces in the pixel design, in order to allow the maximum area for light transmission. These tight design rules result in a greater number of electrical shorts, and thus require thorough testing and repair. In the IDI device, there is no such requirement, and so the line widths and spaces between lines can be larger and more forgiving for manufacturing. Because of this, CH2M HILL recommends to eliminate 1 of the 2 stages of array testing and laser repair.

3. In the LCD process, the TFT array is mated together with the CF array, with LC material in between, to create the completed cell. The LCD CF process is less complex that the TFT process, but still does consist of many process and test steps. A typical LCD CF starts with a glass substrate, then goes through a repetitive photolithography process to create a black matrix (BM) around each sub-pixel, and red, green, and blue primary colour filters within the BM. On top of those layers, there is a passivation layer and another ITO layer. For larger displays, there will usually be additional layers for viewing angle compensation and other functions.

   In the IDI device, there is no need for a colour filter. The 3 primary colours can be created by switching individual red, green, and blue LED's on and off sequentially within one video frame. This technique is often referred to as "time-sequential" switching. It is commonly used by projection displays, such as Texas Instruments' digital micro-mirror device, or DMD, and so is well-established as a drive technique for high quality video displays. Accordingly, the red, green, and blue layers of the CF can be eliminated. In addition, the IDI device does not require passivation or ITO. It does require a BM layer, which will act as the contrast-enhancing aperture for the focused IDI reflector beams.

   The CH2M HILL LCD model does not include a detailed process breakdown for CF manufacturing, as completed CF's are commonly purchased from a 3^{rd} party in volume production. However, an estimate of the cost impact of the process simplification can be made. The glass used for CF's is the same as that used for TFT arrays, and so that cost is known. The remainder of the CF cost represents the process and materials portion. For the IDI device, only 1 of the 6 LCD process steps is required. The BM, R, G, B, and ITO steps are similar in complexity and cost, while the passivation step is simpler. CH2M HILL assumes that the cost of doing the

BM only would be approximately 1/5 of the process and materials cost of the entire LCD process. This portion of the cost, together with the glass substrate cost, has been used in the analysis.

4. Before the LCD and CF substrates are mated together in an LCD, they require alignment films to be laminated to their inner surfaces, and rubbed with a cloth roller in order to create microscopic grooves and ridges in the surface. These physical features cause the LC material molecules to align properly on each side of the cell. The IDI device has no need for such layers. Similarly, there is no need for LC material dispensing, degassing, or fine scale gap measurement.

5. In order for an LCD cell to function, the light passing through it must be uniformly polarized. There is a polarizer film (really a filter that only allows light of a particular polarization to pass through) between the backlight and the cell, and another on the front (viewing) side of the cell. The LC material in the cell modifies the polarization of the light passing through it, causing the light to either be transmitted or blocked by the front polarizer. These polarizer films are attached to the cell by lamination. The IDI device, which does not depend on polarization in order to modulate the light output, has no need for such layers.

6. A typical LCD cell stack will allow about 5% of the light from the backlight to pass through to the viewer when the pixels are turned fully on. This means that in order to have a final luminance of 500 cd/m2 (typical for the TV set), the backlight must be producing the equivalent of 10,000 cd/m2 of highly uniform, unpolarized, white light. This is a difficult specification to meet, and requires a large number of either cold cathode fluorescent lamps (CCFL's) or light emitting diodes (LED's) in order to meet it. This adds to the complexity, size, power requirement, and cost of the backlight unit (BLU).

   In the case of the IDI device, because there are no polarizers or colour filters required, the overall light transmission is estimated by IDI to be in the range of 30%, or about 6 times greater. This means that the cost of the light source and the power supply for that source should be reduced by a factor of 6. It also means that the structural cost of the backlight can be reduced. There remains a need for a waveguide, and the diffusion and reflector films are also required. CH2M HILL recommends that for modeling purposes, the total cost of the BLU be reduced to 15% of the equivalent cost of a unit for an LCD.

7. As mentioned above, the IDI device will use larger feature sizes for a given pixel resolution, resulting in improved yields and/or reduced need for inspection and rework steps. By using a time-sequential colour drive scheme, the sub-pixel size in increase by a factor of 3, and since the TFT array does not need to be transparent, the line and space widths could be increased substantially. For a 3.5" 480 x 320 pixel display, such as might be used in a smartphone application, the sub-pixel pitch is a mere ~50 microns. Assuming an aperature (transparency) requirement of 75%, this leaves only 10 microns for routing gate and data electrodes, or 3.3 microns line and space (each electrode needs a space on both sides), and even smaller dimensions for the TFT structure itself.

   The same device, made using the IDI technology, would have ~150 micron pixels. Assuming that the actuating electrode could occupy 50% of the space, that leaves ~40 microns for gate and data electrode routing, or about 13 microns for lines and spaces. Those dimensions are very comfortable for large area photolithography, and should enjoy very high yields. They are approaching the range that can be done by direct printing techniques, such as screen, offset, gravure, or inkjet printing. If such technologies can be used in the future, then further cost savings in capital and material utilization could be realized. For the purposes of this analysis, CH2M HILL assumes that traditional photolithography will be used, and that yield losses for relevant process steps will be reduced by half.

   In the standard LCD process, there are many test and measurement steps used before and after each major process block. These include things like automated optical inspections (AOI), critical dimension (CD) measurements, and defect inspections and review. Some of these steps are automated, and others are manual or semi-manual. Normally these are sampling steps, which means that only a portion of the product goes through them. The sampling rate woud typically be in the range of 5% to 15%. For the reasons outlined above, CH2M HILL recommends that the IDI device process be modeled at half of the sampling rate compared to the LCD process. This reduces the number of tools and operators necessary for manufacturing.

Results

The process and materials differences listed above were used to modify the LCD manufacturing cost model, and the results of that modification relative to the requested scope of work are discussed below.

1. How much less floor space might be needed for a production line using the IDI technology compared to current LCD technology?
   - The IDI device manufacturing facility as modeled requires 76% of the total floor space as compared to the LCD process. This calculation includes only the TFT array and module assembly. The CF floorspace difference, which is not included, would be larger. Based on the number of CF process blocks that are not necessary for the IDI device, CH2M HILL estimates that the CF portion of the process would require only about 25% of the floorspace. Based on experience, the CF floorspace should be about 80% of the TFT array space. Using that assumption in this model, the total floorspace for an IDI device facility, including CF, would be 66% of that required for an LCD process.
   - Since the yield is different between the 2 facilities, the total number of modules output is different. The IDI facility outputs 21% more modules. In order to address this, we also modeled a facility with a lower motherglass start rate, and the same output. In this case, the IDI device manufacturing facility as modeled requires 61% of the total floor space, not including CF, and including CF, 53% of that required for an LCD process.
2. How much less labor/people might be needed?
   - The calculation indicates that the number of operators required for an IDI device facility would be approximately 76% of the number required for an equivalent LCD facility. Again, this accounts for only the TFT array and module assembly portions. The CF facility would also require fewer operators, however the overall impact on the total will be lower, as the majority of the operators are needed in the module assembly portions of the process. Process steps such as attaching wiring harnesses and printed circuit boards are usually done manually, and because they occur after the motherglass is scribed, the unit throughput needs to be very high. For a 3.5" smartphone display on a G4 line, there could be more than 100 displays per motherglass, which means that the unit throughput after scribing must be 100x higher. In addition, for the IDI process, since the yield is assumed to be higher, the number of modules going through module assembly is greatly increased, which inflates the number of operators required.
   - For a facility with equal output, the operator headcount for an IDI facility is 62% that of an LCD facility.
3. What increase in yield might be expected?
   - Based on the assumptions outlined above, the model indicates a 15% increase in net yield.
4. Based on the answers to the preceding three questions, what is the estimated relative cost difference for the manufacturing facility and process equipment, compared against the incumbent LCD technology and the IDI technology?
   - Comparing the IDI device with a standard LCD in all cases: for the toolset, the number of tools is about 70%, the cost of the tools is about 83%, and the cost of the facility is about 76%. Because of the yield difference mentioned above, it is more instructive to look at the relative COGS numbers,

which distribute the absolute costs over the output. Table 1 below shows the relative COGS results for the major cost categories.

- Considering the facility with equal output, the number of starts is 82% of the LCD's, the number of tools is about 56%, the cost of the tools is about 65%, and the cost of the facility is about 61%. The COGS comparison is shown in Table 2.

Category	IDI / LCD COGS
Depreciation	68%
Materials	46%
Electronics	98%
Labor	55%
Maintenance	68%
Total	56%

Table 1 - COGS comparison for equal motherglass starts

Category	IDI / LCD COGS
Depreciation	65%
Materials	46%
Electronics	98%
Labor	54%
Maintenance	65%
Total	55%

Table 2 - COGS comparison for equal module output

5. Generally, in CH2M HILL's opinion, what is the feasibility of manufacturing the IDI technology?
   - In general, with the exception of fabricating the micro-reflector film, the IDI device can be made using processes that have been developed for the TFT LCD industry. These processes, such as TFT array fabrication, BM fabrication, and module assembly, and very mature, and turn-key toolsets can be purchased from a number of reputable vendors.

     The micro-reflector film is unique to the IDI device. That having been said, conceptually it does not appear to be overly challenging to manufacture. It is a polymer film, embossed with a repetitive pattern, and metalized to become highly reflective. The pattern pitch is on the order of 150 microns or larger, and the smallest features are on the order of 10 microns. These are not difficult dimensions to work with. As an example, we consider the CD / DVD manufacturing industry, which manufactures functionally similar structures with much smaller features with very high yield and throughput.

     As such, CH2M HILL believes that the IDI device would be very feasible to manufacture in high volume. It will be necessary for IDI to validate that the performance and reliability of such devices is suitable for the intended applications, as such analysis is outside the scope of this report.

Conclusions

This analysis indicates that the IDI device requires fewer process steps, materials, and subcomponents to manufacture, can be produced with higher yield in a smaller facility, and will be lower cost and more power efficient than an equivalent LCD-based device. CH2M HILL believes that the majority of the manufacturing processes necessary for such a facility are mature today because of extensive use in LCD manufacturing. The micro-reflector process needs validation, as does the device performance and reliability.

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