# Manufacturing Cost of Active-Matrix Liquid-Crystal Displays as a Function of Plant Capacity

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*Abstract*— **This work models the cost of 10-in class active-matrix liquid-crystal display (AM-LCD) manufacturing as a function of plant capacity for both first generation plants in 1993 and second generation plants in 1995. In order to model manufacturing costs as a function of plant capacity, this work distinguishes between capacity-dependent and capacity-independent costs. Among the costs included in our model are the costs of capital equipment, materials and labor. Decreases in materials and components costs and improvements in process yield are shown to be the primary factors driving reductions in manufacturing cost per display for large-scale plants. The minimum efficient scale is found to be roughly 57 000 displays per month for a first generation plant and roughly 150 000 displays per month for a second generation plant.**

## I. INTRODUCTION

### A. Overview

THE active-matrix liquid crystal display (AM-LCD) market is one of the fastest growing segments of the semiconductor industry. During the past several years the market for active-matrix liquid crystal displays (AM-LCD's) has been growing at over 30% per annum and is expected to grow to over $11 billion by the year 2002 [1]. This has been largely due to the portable computer market which has created a growing market for AM-LCD's with diagonal lengths of approximately 10 in. While the growth rate of this market is expected to slow down, other potentially larger market opportunities will exist when the cost of displays decreases. AM-LCD's presently compete in a commodity-like market. Display price is a primary basis of competition, particularly among displays of the same size and resolution [2]. Furthermore, the price of AM-LCD's has been falling and is expected to continue to fall as AM-LCD production technology matures.

Processing equipment for AM-LCD fabrication is typically much larger in size than VLSI manufacturing equipment due to the large-area substrate requirements. The AM-LCD process can be divided into the front-end, where arrays of thin film transistor (TFT) pixel drivers are fabricated on a glass substrate, and the back-end, where the glass substrate is cut into individual displays and each display is assembled and tested. The choice of the display size largely determines the substrate size that a manufacturer will use, which in turn dictates the substrate handling and processing requirements of the front-end manufacturing equipment. The first generation of front-end equipment varied widely, with the most common substrate size being 300 × 400 mm. This size could accommodate two 10-in class (9.4- to 10.4-in diagonal) displays. The 365 × 465 mm size substrate is the most common size for the second generation AM-LCD plants that have come on line in 1994 and 1995 [3], [4]. These larger substrates could accommodate four 10-in sized displays or two larger desktop sized displays (11 to 13-in diagonal). This paper defines a "first generation" technology as one that produces two 10-in class displays per substrate, and "second generation" technology as one that produces four 10-in class displays per substrate.

The objective of this paper is to model the manufacturing cost of AM-LCD's. Specifically, we will decompose the manufacturing cost of an AM-LCD into its main components, and then show how that manufacturing cost depends on the size of the manufacturing plant. To provide insight into future cost trends this paper will show how this cost structure changed in the transition from first generation plants in 1993 to second generation plants in 1995. In addition to the number of displays per substrate changing from first generation to second generation plants, the cost of display components such as IC's and color filters also decreased from 1993 to 1995. For example, a first generation plant operating in 1995 would have the same component costs as a second generation plant in 1995, but the original capital investment for the plants would be different because the production equipment in the two plants would be different. This paper contrasts first generation plants in 1993 to second generation plants in 1995 to analyze trends in component costs as well as capital costs.

As stated above, 10-in class displays have become a commodity product competing on price, resulting in production cost being a primary determinant of competitiveness. On the other hand, there are other smaller niche markets for displays with special display characteristics. For such factories, the ability to rapidly adapt to changes in technology or market demand could be a more important determinant of competitiveness. The scope of this paper is limited to the dominant commodity 10-in display market, and only considers the effect of factory size on cost as opposed to adaptability.

The rest of this section will summarize our motivation for analyzing the production cost of AM-LCD's. Section II of this paper will then summarize the AM-LCD production process and other data used to model production costs. Section III of this paper will introduce a simple model to provide insight into

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manufacturing costs and economies of scale, and then apply those models to AM-LCD's using the cost data in Section II. Finally, Section IV will summarize the key conclusions of the model.

### *B. Motivation*

At the time this paper is being written, almost all of the market for AM-LCD's is filled by factories operating in Japan. Although some of these factories are joint ventures that include firms outside Japan, firms and governments in other countries including the United States, South Korea, and Taiwan have expressed intentions to increase their respective shares of total display production [5], [6]. Gaining share of the display market may be approached by building conventional AM-LCD factories or introducing or refining other display technologies to supplant AM-LCD's. For firms wishing to enter the AM-LCD market, key issues to be considered include 1) the relative magnitude of different production cost components, 2) the cost components driving the reduction in AM-LCD production costs, 3) the effect of plant size on production cost per display.

A decomposition of AM-LCD costs can provide a useful benchmark to which other competing technologies can be compared. Examples of potentially competing technologies include refined predecessors to AM-LCD's such as super twisted nematic (STN) LCD's [7], variations on conventional AM-LCD's such as AM-LCD's based on polycrystalline silicon transistors instead of amorphous silicon [8] or less established technologies such as ferroelectric LCD's [9], [10], field emission displays [11], or digital micromirror displays [12]. Most of these competing technologies will not change the entire production process. Insights into which cost components of AM-LCD's dominate the overall production cost would be useful in exposing the biggest competitive opportunities for alternative technologies. AM-LCD cost models representative of both first and second generation processes can also provide insight into the main production technology factors responsible for the historic decrease in AM-LCD production costs.

The minimum size of an AM-LCD plant necessary to achieve cost competitiveness is apparently still an unresolved issue. The first generation of high-volume manufacturing plants reported capacities ranging from 20 000 to 100 000 displays per month. Second generation high-volume production plants have projected capacities ranging from 80 000 to 200 000 displays per month corresponding to a range in capital investment from $180 million to $450 million [3], [4]. This range in capacity was broad enough to create significant differences in plant amortization costs per display between the low- and high-volume manufacturers [13]. Furthermore, the announced capacities of contemporary AM-LCD manufacturing plants in the U.S. range from less than 1000 displays per month to about 3500 displays per month [15]–[17].

### *C. Past Work*

For the past few years, display manufacturers have been predicting that the price of the most popular display product, the 10-in VGA AM-LCD would drop to about $500 (assuming a ¥100 to $1 conversion rate) by 1995 [3], [14]. Little, however, has appeared in the open literature on the economics of manufacturing AM-LCD's at high volumes in the current generation of manufacturing plants. Studies by Resor, Morozumi, and Mentley have concluded that materials costs are a significant portion of the final cost of AM-LCD's in first generation plants [18]–[21]. Mentley has also examined the effect of TFT-array yield on the yielded cost of materials [21]. Morozumi has assumed a fixed capacity and the more realistic case of different yields for front-end and back-end processing [20]. Another more detailed study, starting with similar assumptions, has examined or predicted the manufacturing cost of first generation lines for 1993 and second generation lines for 1995–1996 [2].

Only one of these works attempted to find the minimum plant capacity required to achieve economies of scale [19]. Their conclusion was that small mini-fabs producing 400 000 displays per year would be sufficient to capture economies of scale and that a fab producing 550 000 displays per year would be of optimal size. This conclusion, however, was based on a fifteen-year business model for manufacturing 14-in HDTV's. Since this business model included the cost of a television receiver as well as the display, the results do not necessarily extend to AM-LCD manufacturing. Furthermore, there is reason to believe that the economics of AM-LCD manufacturing have evolved significantly from when this work was first published. One key assumption made in this work is that cumulative manufacturing yield would increase by 5% per year over the initial eight years of manufacturing. While this was a reasonable assumption in the early 1990's, recent reports of yield figures in the 60% to 80% range indicate that the yield ramp has proceeded much more quickly [2]–[4], [20], [31].

This work models the cost of AM-LCD manufacturing as a function of plant capacity for a first generation plant operating in 1993 and a second generation plant operating in 1995. (These plants will be referred to simply as the "first generation" and "second generation" plants in the rest of this paper.) Our model separates both the capacity-dependent and capacity-independent costs of manufacturing in order to predict manufacturing costs as a function of capacity. Among the costs included in our model are the costs of capital equipment, materials and labor. By including recent estimates of the yields for front-end and back-end processing, we model the manufacturing costs per display for different plant capacities to estimate the minimum efficient scale of operation.

## II. BACKGROUND AND DATA

The manufacturing process for color AM-LCD's may be likened to making a sandwich [22]–[24]. The bottom substrate is an array of amorphous silicon TFT's fabricated on a glass substrate in a process similar to conventional IC fabrication processes. The top substrate is the color filter plate and is typically purchased from outside vendors. These glass substrates are joined together in what is called the cell assembly process. During cell assembly, the liquid-crystal material is sandwiched between the two substrates. The final major step in the process is module assembly where the integrated circuitry that provides the video signals and controls the display is attached along with a backlight unit. The rest of this section will discuss the data and assumptions used to model AM-LCD manufacturing costs. The data that follows assumes VGA resolution displays.

### A. TFT-Array Fabrication

The most common process sequence for TFT fabrication is the inverse-stagger structure that places the gate at the bottom of the device structure [25]. The TFT fabrication process sequence is a series of deposition, lithography and etch sequences that define the various layers of the pixel transistor and electrode structure. Deposited films are typically from 500- to 5000-Å thick. A process flow for the inverse-stagger TFT with an etch-stop layer is listed in Table I [20], [22]. The process flow shown in Table I is abbreviated and does not show some of the repeated cleaning and visual inspection steps. There are chemical pre-cleans prior to every deposition and sputter step in the process. There are also cleaning steps during photolithography—one prior to the coating of the resist and another one after the resist stripping.

Table II shows the capital cost, maximum throughput, and fraction of time available for first and second generation front-end processing equipment. The data for the first generation was gathered from various sources in the literature [2], [3], [14], [20], [22], [26]. For the second generation, much of the equipment data was obtained from an AM-LCD manufacturer and a survey of equipment vendors. These data were averaged with sources available in the literature [2], [3], [27].

TABLE I
TYPICAL TFT FABRICATION PROCESS FOR AN A-SI INVERSE-STAGGER DEVICE STRUCTURE WITH AN ETCH-STOP

| Process for a-Si TFT Array Fabrication | Equipment Type |
|---|---|
| Initial glass substrate clean | Ultrasonic wet clean |
| Gate Electrode: Deposit 300 nm MoTa | MoTa sputterer |
| Gate Electrode: Lithography | Coater / Stepper / Developer |
| Wet etch | MoTa Wet Bench |
| Gate Dielectric: Deposit 300 nm $SiO_2$ | Atmospheric pressure CVD |
| Gate Channel: Deposit 230 nm $SiN_x$ / 100 nm a-Si / 250 nm $SiN_x$ | PE-CVD (a-Si : $SiN_x$) |
| Etch Stop: Lithography (back exposure) | Coater / Projection Aligner / Developer |
| Dry etch | $SiN_x$ dry etcher |
| Source / Drain: Deposit 50 nm n+ a-Si | PE-CVD (n+ a-Si) |
| Channel: Lithography | Coater / Stepper / Developer |
| Dry etch | a-Si dry etcher |
| Contact: Lithography | Coater / Stepper / Developer |
| Dry etch (SiN / $SiO_2$) | SiN / $SiO_2$ dry etcher |
| Pixel Electrode: 200 nm ITO | ITO sputterer |
| Pixel Electrode: Lithography | Coater / Stepper / Developer |
| Wet etch | ITO Wet Bench |
| Source / Drain metal: Deposit 500 nm Al | Al sputterer |
| Metal: Lithography | Coater / Stepper / Developer |
| Wet etch | Al Wet Bench |
| Dry etch | n+ a-Si dry etcher |
| Passivation: Deposit 300 nm $SiN_x$ | PE-CVD ($SiN_x$) |
| Contact Pads: Lithography | Coater / Stepper / Developer |
| Dry etch | $SiN_x$ dry etcher |
| TFT Electrical and parametric testing | TFT device tester |

### B. Back-End Processing: Cell and Module Assembly

Prior to the injection of the liquid-crystal, both the TFT plate and color filter plate are coated with an orientation layer such as polyimide [28], [29]. Microgrooves are then formed in these layers by mechanically brushing (rubbing) the layer so as to align the liquid crystals in a preferred orientation. This critical step differs from other processes found in semiconductor fabrication. The TFT plate is then sprayed with spherical plastic spacers which are required to maintain a critical 6-$\mu$m gap spacing between the two plates. An epoxy seal is applied to the color filter plate which is then aligned to the TFT plate. The two plates are then laminated with thermal cycling to set the seal. The plates are then scribed to the appropriate display dimensions and placed in a vacuum chamber where the liquid crystal material fills the spacing between the two plates as the chamber is vented to atmospheric pressure. The fill ports are then sealed and polarizers are laminated to both plates. The plates are then inspected optically. Module assembly includes the packaging of the IC's and the attachment of the backlight unit. The most popular method for packaging the driver IC's and the control circuitry is with the tape-automated bonding technique (TAB) [30]. The display then undergoes a final optical inspection and electrical testing.

Any yield loss in back-end processing is usually unrecoverable and results in the loss of the both the TFT array and materials such as color filters or the integrated circuit drivers. The range of prevailing materials and component costs during first generation manufacturing will be presented later in Table VI. The figures given for second generation materials costs are projections and may not be achievable for technical reasons or material supply constraints [2], [3].

### C. Yield Issues

As in the IC manufacturing industry, yield data is a closely guarded secret in the AM-LCD industry. Several sources have made estimates and projections of industry yields at different points in time [2]–[4], [7]. The average of these estimates are presented in Table III. The simplifying assumption behind these estimates is that the cumulative yield, $Y_{\rm cum}$, is the product of the independent yields of: TFT fabrication ($Y_{\rm tft}$), cell assembly ($Y_{\rm ca}$), and module assembly ($Y_{\rm ma}$)

$$Y_{\rm cum} = Y_{\rm tft} \times Y_{\rm ca} \times Y_{\rm ma}. \tag{1}$$

As can be seen from Table III, the increase in yield for second generation plants is largely the result of improvements in cell assembly yield. For example, automated substrate handling has been described as playing a significant role in improving $Y_{\rm ca}$ [31]. Also, TFT processing equipment improvements [32] and improved process control using in-line monitoring [33] reduced particle densities, improving $Y_{\rm tft}$.

Because the final determination of whether a display is considered to have yielded is in part made on the basis of visual inspection at the end of the manufacturing process, there is no exact operational way to determine where in the process the yield limiting defects are being introduced. For the purposes of our model we assume the yield at each stage of

TABLE II
DATA FOR FIRST AND SECOND GENERATION FRONT-END EQUIPMENT FOR FIRST AND SECOND GENERATION SUBSTRATE SIZES INCLUDING: PRICE, THROUGHPUT AND AVAILABLE TIME DATA

| Equipment Type | First Generation (1993) | | | Second Generation (1995) | | |
|---|---|---|---|---|---|---|
| | Equipment Cost ($Millions) | Available Time | Raw substrates per hour | Equipment Cost ($Millions) | Available Time | Raw substrates per hour |
| PE-CVD SiNx/a-Si/SiNx | 6 | 0.55 | 17 | 6.6 | 0.80 | 32 |
| PE-CVD SiNx | 3.25 | 0.60 | 28 | 5 | 0.80 | 43 |
| PE-CVD n+ a-Si | 3.25 | 0.60 | 28 | 5 | 0.80 | 43 |
| AP-CVD SiO2 | 2.5 | 0.80 | 36 | 2.5 | 0.80 | 48 |
| Sputter-MoTa | 3.12 | 0.60 | 42 | 3.35 | 0.75 | 46 |
| Sputter-Al | 3.12 | 0.60 | 42 | 3.35 | 0.75 | 46 |
| Sputter- ITO | 3.12 | 0.60 | 42 | 3.35 | 0.75 | 46 |
| Dry-Etch SiNx | 2 | 0.80 | 26 | 2.7 | 0.80 | 36 |
| Dry-Etch SiO2 | 2 | 0.80 | 26 | 2.7 | 0.80 | 36 |
| Dry-Etch a-Si/SiNx | 2 | 0.80 | 26 | 2.7 | 0.80 | 36 |
| Wet-Etch MoTa | 0.8 | 0.85 | 43 | 1.56 | 1.00 | 53 |
| Wet-Etch Al | 0.8 | 0.85 | 43 | 1.56 | 1.00 | 53 |
| Wet-Etch ITO | 0.8 | 0.85 | 43 | 1.56 | 1.00 | 53 |
| Coat/Bake/Pre-clean | 1 | 0.85 | 53 | 1.1 | 0.95 | 51 |
| Stepper | 2.3 | 0.85 | 47 | 3.5 | 0.90 | 40 |
| Develop/Strip/clean | 1.3 | 0.85 | 52 | 1.8 | 0.95 | 51 |
| Projection Aligner | | | | 0.9 | 0.95 | 36 |
| Asher | 0.5 | 0.85 | 48 | 1.7 | 1.00 | 50 |
| Pre-deposition Clean | 0.5 | 0.85 | 52 | 1.1 | 1.00 | 52 |
| Substrate Clean | 0.5 | 0.85 | 52 | 1.1 | 1.00 | 52 |
| TFT Electrical Tester | 0.8 | 0.90 | 15 | 0.85 | 0.95 | 15 |

the manufacturing process to be that fraction of capacity which passes inspection and advances to the next stage of production. Note that this may include some displays which may be bad, but simply fail to be rejected by the inspection equipment.

## III. RESULTS AND DISCUSSION

### *A. The Model*

A simple cost model [34] will be used to provide insight into manufacturing cost and economies of scale in AM-LCD fabrication. Specifically, the cost of manufacturing a display when the plant is operating at full capacity is used as a benchmark to show the effects of the transition from first-generation to second-generation production technologies. This cost benchmark will simply be called "cost per display" in the rest of this paper. If a plant is operated at less than its full capacity, then the actual cost per display would be higher than the cost per display benchmark because fixed costs would be amortized over a smaller number of displays.

The cost per display benchmark will be used in two related ways. First, economies of scale can be measured by showing how cost per display changes with the size of a plant. The relationship between cost per display and plant size will be used to estimate the minimum size of an efficient plant and also show the cost penalties of smaller-sized plants. Second, breakdowns of the cost per display into smaller cost components will expose the most important determinants of both production cost and minimum efficient scale.

To provide insight into determinants of minimum efficient scale, we will divide production costs into three categories which are described as follows.

**Incremental capacity cost** $(m)$ is the average incremental operating cost of adding and then utilizing capacity of one additional display per time period (e.g., the minimum cost in dollars per year to increase plant capacity and production by one display per year). The incremental capacity cost includes both fixed costs such as annual depreciation of production tools, and variable costs such as the cost of the glass substrate. The incremental capacity cost is measured in dollars per display, and provides a minimum achievable cost per display.

Incremental capacity cost is calculated by summing up the minimum contribution of each process step to cost per display, using the formula

$$m = \sum \frac{\varphi_j}{\mathrm{TR}_j} + v_j. \tag{2}$$

In the above equation, $j$ is an index for each process step. Costs are thus calculated for each process step and then summed together to get $m$. In the equation, $\varphi_j$, is the annual operating cost of one piece of equipment that the process step $j$ is performed on (including depreciation and service). For process step $j$, the corresponding $\mathrm{TR}_j$ is the product of 1) the raw throughput rate in Table II, 2) the available time in Table II, and 3) the product of the yields in Table III downstream of the process step. The term $v_j$ is the additional variable cost of step $j$ to a yielded display (e.g., materials and direct labor).

**Capacity-independent cost** $(M)$ is the annual fixed operating costs that are independent of plant capacity. Examples

TABLE III
YIELD FIGURES FOR FIRST AND SECOND GENERATION TFT AM-LCD MANUFACTURERS. SECOND GENERATION FIGURES ARE PROJECTIONS

| Process Yields | 1st Generation(1993) | 2nd Generation(1995) |
|---|---|---|
| | (%) | (%) |
| TFT Fabrication ($Y_{tft}$) | 91 | 95 |
| Cell Assembly ($Y_{ca}$) | 79 | 93 |
| Module Assembly ($Y_{ma}$) | 92 | 92 |
| | | |
| Cumulative Yield ($Y_{cum}$) | 66 | 80 |

of costs contributing to $M$ are the fab manager's salary, depreciation of off-line equipment, and depreciation of the minimum clean room area necessary for gown-up. The units of $M$ are dollars per year.

**Cost of granularity** ($c_{\text{gran}}$): Process equipment must be purchased in integer numbers which results in a granularity cost. For example, the throughput rate of the plant may require 8.5 steppers, so 9 steppers are purchased. The cost of 8.5 steppers would be captured in $m$, but the last 0.5 stepper would result in an additional cost. The sum of all the operating costs of "extra" fractions of equipment (including depreciation and service contract costs) is the granularity cost. The units of granularity cost are the same as for $M$ (dollars per time period). Unlike $M$ and $m$, the granularity cost is a function of fab capacity.

The total operating cost of a plant (measured in dollars per time period) can be expressed as

$$\text{fab operating cost} = M + c_{\text{gran}} + m \cdot \text{TR}_{\max} \tag{3}$$

where $\text{TR}_{\max}$ is the fab capacity measured in displays per time period (e.g., displays per year).

The minimum achievable cost per display in a plant is determined by dividing the plant operating cost by the fab capacity

$$\text{minimum cost per display} = \frac{M + c_{\text{gran}}}{\text{TR}_{\max}} + m. \tag{4}$$

Both the capacity-independent cost ($M$) and the granularity cost result in an economy of scale. Specifically, as the size of the fab (expressed as $\text{TR}_{\max}$) becomes larger, the total cost per display tends to decrease. The cost per display does not necessarily decrease monotonically because $c_{\text{gran}}$ may be increasing over certain small ranges of fab capacity. The economy of scale associated with $M$ results from the capacity-independent cost being amortized over more displays per time period. The economy of scale associated with $c_{\text{gran}}$ results from factories being easier to balance as the plant gets larger.

The value of $m$ provides a lower bound on the minimum cost per display at any capacity. As $m$ becomes a larger fraction of minimum cost per display, there are diminishing opportunities to further decrease cost per display by increasing plant capacity.

TABLE IV
CAPITAL COSTS CONTRIBUTING TO THE DEPRECIATION COMPONENT OF CAPACITY-INDEPENDENT COST, $M$

| Capacity Independent Costs: M | 1st Generation | 2nd Generation |
|---|---|---|
| **Depreciation Component** | Capital Cost | Capital Cost |
| | ($Millions) | ($Millions) |
| Buildings & Facilities | | |
| Acid/Hazardous Chemicals Tanks | 7.50 | 7.50 |
| Plumbing/Gas Delivery | 4.00 | 5.00 |
| Clean-room Space | 2.65 | 2.65 |
| Subtotal | 14.15 | 15.15 |
| | | |
| Equipment | | |
| Back-end: Cell & Module Assembly | 26.56 | 43.02 |
| Front-end: Non-in-line Equipment | | |
| Test Measurment | 3.90 | 3.90 |
| Defect Inspection | 1.40 | 1.40 |
| Laser Repair | 1.80 | 3.60 |
| FA/Automated Carrier System | 4.00 | 6.00 |
| Computer Integrated Manufacturing | 5.00 | 5.00 |
| Installation (3% of Capital cost) | 1.13 | 1.74 |
| Installation(indpendent of capacity) | 2.50 | 2.50 |
| Subtotal | 46.29 | 67.16 |
| | | |
| Totals | 60.44 | 82.31 |

TABLE V
RECURRING COST COMPONENT OF CAPACITY-INDEPENDENT COST, $M$

| Capacity Independent Costs: M | 1st Generation | 2nd Generation |
|---|---|---|
| **Recurring Cost Component** | $Millions/year | $Millions/year |
| | | |
| Staff/Administration | 6.00 | 7.80 |
| Subtotal | 6.00 | 7.80 |
| | | |
| Parts (4% of Capital cost) | 1.71 | 2.52 |
| Service Contracts (2% of Capital cost) | 0.85 | 1.26 |
| Property Insurance & Tax | 0.17 | 0.17 |
| Masks | 1.00 | 1.00 |
| Subtotal | 3.73 | 4.95 |
| TOTAL ($Millions/year) | 9.73 | 12.75 |

## *B. Capacity-Independent Costs: M*

The two cost components of $M$ are depreciation and recurring costs. Depreciation includes the depreciated cost of buildings, facilities, and off-line equipment that are independent of the plant's capacity. Recurring costs include plant administration and other indirect labor costs that are relatively independent of fab capacity, and parts and service contracts for the off-line and assembly equipment [31].

Table IV shows the various capital equipment and facilities costs which are independent of plant capacity. Many of the equipment costs used were found in a detailed study on Japanese TFT-LCD manufacturing lines [2]. Assuming five-year straight-line depreciation, the capital depreciation is approximately \$12.1 million per year for the first generation plant and \$16.5 million per year for the second generation plant. Back-end assembly equipment is included in $M$ rather than $m$ and $c_{\text{gran}}$ because assembly equipment count is generally independent of plant capacity over the range of plant capacities considered in this paper. Most major pieces of assembly equipment, for example, have capacities of 60 or more substrates per hour. The higher cost for back-end equipment in the second generation line reflects both the increased substrate size and increased level of automation from the first generation line. Even though a TFT fab may have several test and measurement tools, each of these tools is generally dedicated to a particular operation. Only one test

TABLE VI
INCREMENTAL CAPACITY COSTS, $m$, IN DOLLARS PER 10-in VGA DISPLAY

| **Incremental Capacity** | First Generation Costs (1993) | | Second Generation Costs (1995) | |
|---|---|---|---|---|
| **Costs: m** | Unyielded | Yielded | Unyielded | Yielded |
| | ($ per display) | ($ per display) | ($ per display) | ($ per display) |
| **Front-end:** TFT Array | | Yield =.9x.79x.92 | | Yield=.95x.93x.92 |
| Equipment | 54.52 | 82.60 | 26.68 | 33.35 |
| Direct Labor | 40.19 | 60.90 | 26.01 | 32.51 |
| Materials & Components | | | | |
| Glass Substrate | 31.00 | 46.97 | 19.50 | 24.38 |
| Others | 20.00 | 30.30 | 10.00 | 12.50 |
| Subtotal | 51.00 | 77.27 | 29.50 | 36.88 |
| Total | 145.71 | 220.77 | 82.19 | 102.74 |
| | | | | |
| **Back-end:** Cell Assembly | | Yield =.79x.92 | | Yield=.93x.92 |
| Direct Labor | 40.19 | 55.30 | 26.01 | 30.40 |
| Materials & Components | | | | |
| Color Filter Plate | 179.00 | 246.29 | 89.00 | 104.02 |
| Polarizers,Liquid Crystal | 16.00 | 22.01 | 8.50 | 9.93 |
| Subtotal | 195.00 | 268.30 | 97.50 | 113.96 |
| Total | 235.19 | 323.60 | 123.51 | 144.35 |
| | | | | |
| **Module Assembly** | | Yield =.92 | | Yield=.92 |
| Direct Labor | 53.59 | 58.25 | 34.68 | 37.70 |
| Materials & Components | | | | |
| Driver LSI | 117.00 | 127.17 | 67.00 | 72.83 |
| Controller | 45.70 | 49.67 | 29.00 | 31.52 |
| Backlight | 33.00 | 35.87 | 20.50 | 22.28 |
| Packaging,etc. | 32.00 | 34.78 | 34.00 | 36.96 |
| Subtotal | 227.70 | 247.50 | 150.50 | 163.59 |
| Total | 281.29 | 305.75 | 185.18 | 201.28 |
| | | | | |
| Total Cost | 662.20 | 850.13 | 390.88 | 448.37 |

or measurement tool is required for each of these operations over the practical range of fab capacities considered in this paper, so front-end test and measurement is considered a capacity-independent cost.

Table V shows the recurring cost component of $M$ which includes the plant overhead costs that are independent of plant capacity and parts and service contracts associated with the equipment of Table IV.

### *C. Contributions to Incremental Capacity Cost: $m$*

One of the key contributors to the incremental capacity cost for AM-LCD manufacturing is the cost of materials and components. From various sources in the literature [2]–[4], [20], [21], [27] we have taken average values of the materials prices assuming a conversion rate of 100 yen to the dollar. Because the materials and component prices charged for R&D or low-volume pilot line production can be significantly higher than their high-volume counterparts, we limit our analysis to a minimum capacity of 5000 substrates per month. For factories with capacities exceeding 5000 substrates per month, we assume that the purchasing price of materials and components is independent of capacity. Finally, we assume that the color filter plate is outsourced for both generations and that module assembly is done in-house.

Table VI lists the various cost components that contribute to the incremental capacity cost, including in-line fabrication equipment, materials, and direct labor costs. The cost components for $m$ are grouped according to the three main stages of the AM-LCD manufacturing process. At the end of each of these major stages, the display can be tested or inspected to determine functionality or yield. The yield losses in Table III were used to determine the increased plant throughput needed to achieve the final yielded capacity of the plant. Costs before and after taking yield losses into account are shown in Table VI. The relative yielded cost contributions for the front-end and back-end processes are summarized in Fig. 1. As the figure shows, back-end labor and materials contribute over two-thirds of the value of $m$. The dominant component of the back-end costs are the yielded materials costs. As mentioned above, we considered back-end equipment costs to be a component of $M$ because assembly equipment counts were generally constant over the range of plant capacities that we consider. Had we made back-end equipment a component of $m$ instead, the contribution of the back-end equipment would have been approximately \$10.50 per display for a first generation plant and \$7 for a second generation plant.

Decreases in materials and components cost are the primary factor behind the decrease in $m$ between the first

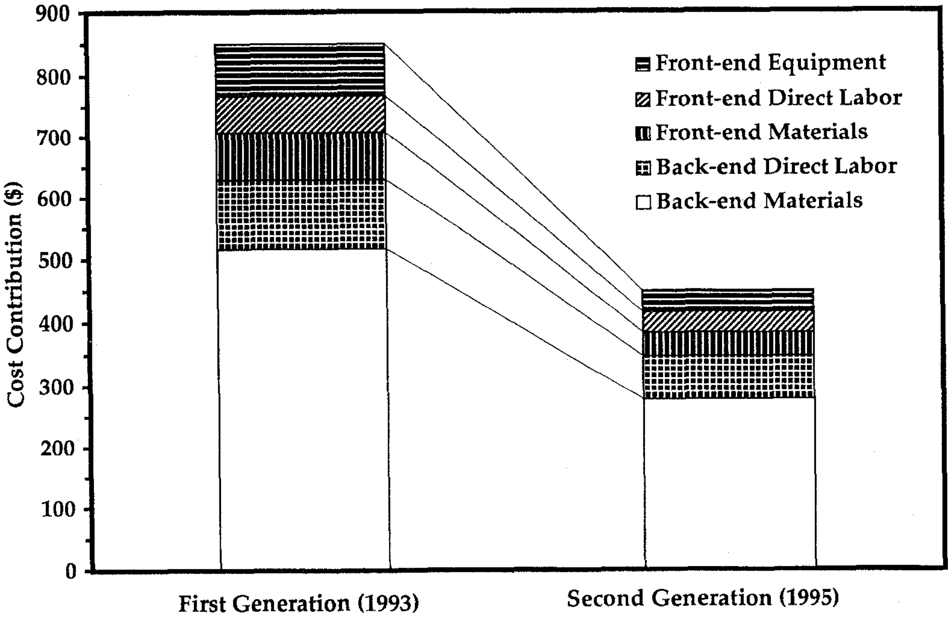

Fig. 1. Breakdown of the various components of $m$.

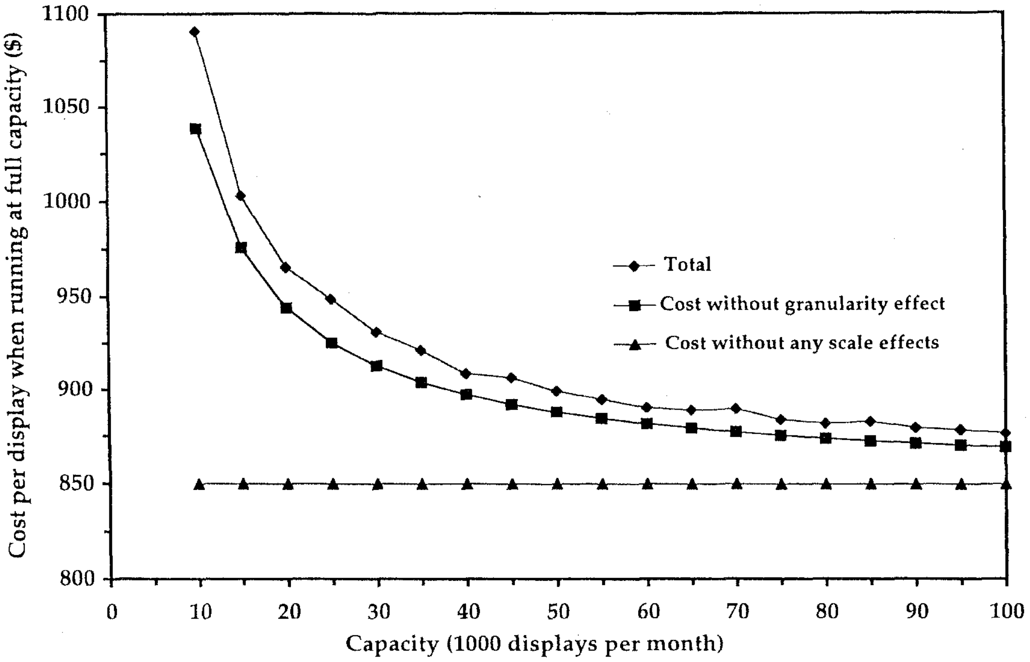

Fig. 2. Cost per display as a function of capacity for a first generation (1993) plant with two displays per substrate.

and second generations, accounting for 48% of the cost reduction. The increased yield expected for second generation plants accounts for another 34.2% of the cost decrease. The remaining 18.8% of the cost decrease is due to labor and capital productivity improvements from larger substrates, equipment throughput improvements, increased availability, and increased automation.

### *D. Minimum Efficient Scale*

Figs. 2 and 3 show the total manufacturing cost per display as a function of yielded monthly capacity for first and second generation factories respectively. In each of the figures, the top curve is the manufacturing cost per display as a function of plant capacity ($\mathrm{TR}_{\max}$). This is the cost defined in (4). The manufacturing cost per display assumes that any given plant is operating at its full capacity. In the context of this paper "full capacity" means that the bottleneck equipment in the plant processes displays for all of its available time previously shown in Table II.

The middle curve shows what the cost per display would be if all granularity effects could be removed. In other words,

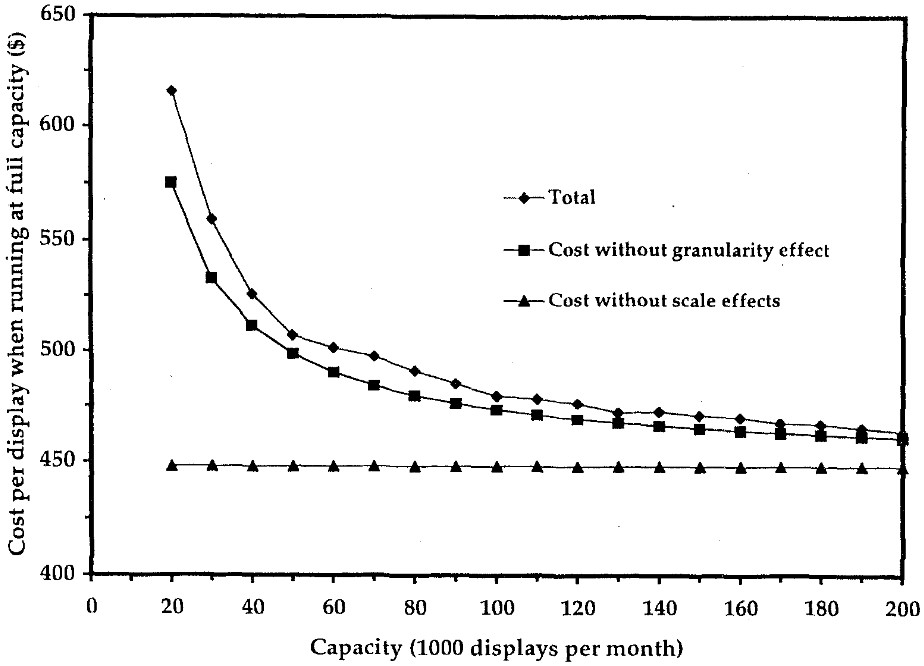

Fig. 3. Cost per display as a function of capacity for a second generation (1995) plant with four displays per substrate.

the middle curve assumes that the plant could be perfectly balanced at all capacities with all front-end equipment fully utilized. This cost is obtained by removing the $c_{\text{gran}}$ from (4)

$$\text{display cost without granularity} = m + \frac{M}{\text{TR}_{\text{max}}}. \quad (5)$$

The straight line at the bottom of each of the figures is a lower bound on the cost per display at any capacity. The straight line does not include either granularity effects or the effect of any costs that are independent of capacity, and is simply equal to $m$.

As expected, the manufacturing cost per display decreases with increasing plant capacity. Figs. 2 and 3 also show that this economy of scale is mainly a result of amortizing the capacity-independent costs $(M)$ in Tables IV and V over an increasing number of displays per period. The effect of granularity (i.e., how well the front-end TFT fab can be balanced) contributes much less to scale economies. A second interesting observation from Figs. 2 and 3 are the plant capacities required to achieve low-cost production. For example, one could arbitrarily define the minimum efficient scale of a plant as one where granularity and capacity-independent costs contribute no more than 5% of the total manufacturing cost per display. In this case, the minimum efficient scale would be 57 000 yielded displays per month for a first generation plant (Fig. 2) and 150 000 yielded displays per month for a second generation plant (Fig. 3). For example, at a capacity of 57 000 yielded displays per month the first generation plant can achieve a cost per display of $895 and the capacity-independent and granularity costs contribute $895 − $850 = $45 to that cost per display. Because $45 is about 5% of $895, the 57 000 displays per month is defined as the minimum efficient scale of the first generation plant. It should be noted that the minimum costs in Figs. 2 and 3 could be decreased further with improvements in yield or productivity. The figures show minimum costs with current materials costs and productivity levels.

The basic cost model is constructed to easily see the impact of assumptions on the production cost per display. As shown previously, Table VI decomposes $m$ and Tables IV and V decompose the depreciation and recurring cost components of $M$. Changes in assumptions that increase $m$ will increase the minimum achievable cost per display. Changes in assumptions that increase $M$ will increase the cost per display by an amount that diminishes as the plant gets larger, and will also increase the minimum efficient scale of the plant.

The actual plant capacities observed in Japan for first generation plants was an average of 52 000 displays per month [13]. The four largest second generation plants are reported to have capacities ranging from 110 000 to 130 000 displays per month [35]. Over this capacity range, capacity-independent and granularity costs are at most 6% of total cost, which is roughly consistent with our definition of minimum efficient scale.

### *E. Improvements in Second Generation TFT-Array Processing*

As Figs. 2 and 3 show, the production cost of a display decreased significantly from the first to second generations. For factories operating at an efficient scale, the value of $m$ dominates the production cost per display. Referring back to Table VI, reductions in back-end materials costs were responsible for the biggest portion of the reduction of $m$. As Fig. 1 showed, back-end materials costs continue to dominate $m$ in second generation AM-LCD production as well.

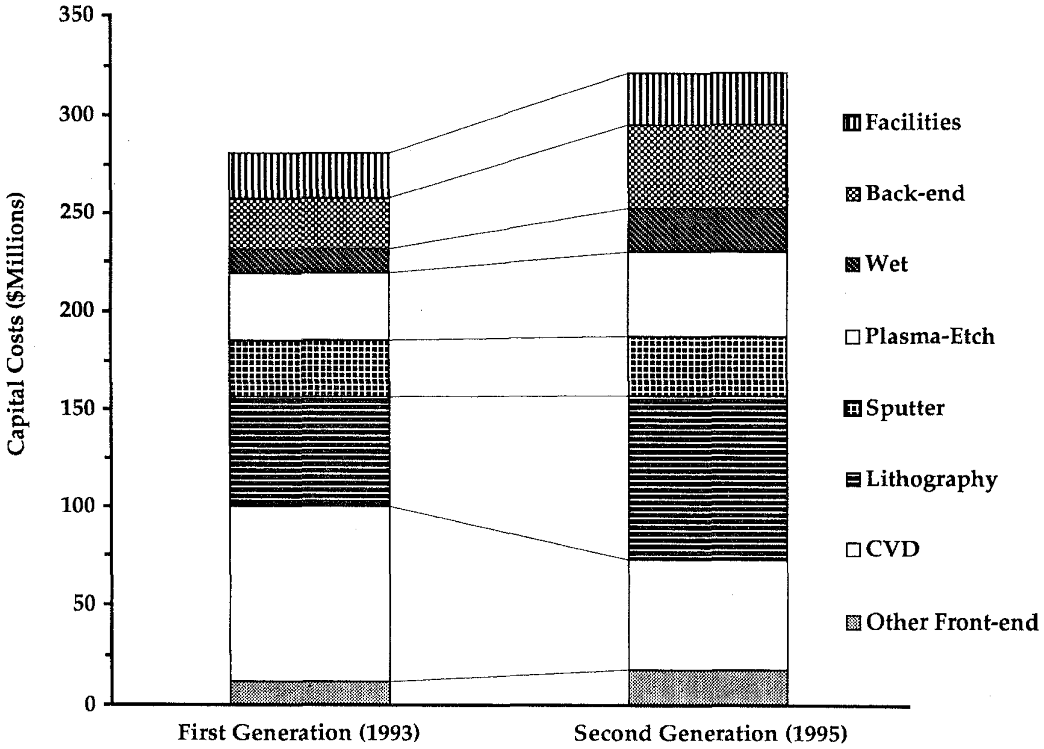

Fig. 4. Capital investment costs for first and second generation plants operating at the estimated minimum efficient scale of 57 000 and 150 000 yielded displays per month, respectively.

In comparison to conventional DRAM chip manufacturing, the cost of equipment amortization for AM-LCD manufacturing makes up a much smaller portion of the total manufacturing costs. Whereas for DRAM manufacturing equipment depreciation is calculated to make up one-third of the total manufacturing cost [36], it was only 7.3% and 5.9% of the manufacturing cost for first and second generation AM-LCD plants respectively. Moreover, the ratio of equipment depreciation to total IC manufacturing cost has historically increased with each generation of technology. In contrast, the recent trend of AM-LCD manufacturing shows this ratio to have decreased, mainly due to the improved productivity of second generation equipment.

Table II showed significant productivity improvements in front-end capital equipment. Even though second generation substrates contained twice as many displays as first generation substrates, the throughput rate (in substrates) of second generation equipment was generally similar to that of first generation equipment. (Steppers were the notable exception.) In addition, Table II also shows improved reliability for second generation equipment, particularly PE-CVD tools. During the first generation, in-line PE-CVD equipment was widely reported to have available times of between 50% and 60% [26]. The second generation plants saw the introduction of single-substrate PE-CVD systems with *in situ* cleaning capabilities that has resulted in available times rising to 80% due to decreases in scheduled downtime for cleaning and maintenance [2].

Even though front-end equipment productivity did not play as significant a role in lowering production cost per display as back-end materials costs did, productivity did have a significant impact on the capital investment required to achieve high-volume production. Fig. 4 compares the capital cost of first and second generation factories operating at their respective minimum efficient scales determined in the previous section. As the table shows, plant capital cost is dominated by front-end equipment. Front-end equipment productivity improvements resulted in second generation plants that could produce roughly two and a half times more displays per year with only a 15% increase in capital cost. These figures are consistent with reported plant capital costs and capacities [4], [13].

## IV. SUMMARY

The cost of AM-LCD manufacturing as a function of plant capacity for both first and second generation plants was modeled. In our model the manufacturing costs are decomposed into capacity-dependent and capacity-independent costs which enables the prediction of the manufacturing costs as a function of capacity.

Our results confirm earlier studies which show that materials and component costs are the major costs of AM-LCD manufacturing. The drop in the yielded cost of materials from the first generation plants of 1993 to the second generation plants accounts for 68% of the decrease in manufacturing costs. Of this 68% reduction, 71% may be attributed to the decrease in the cost of materials alone, while the remaining 29% is due to the reduction of scrapped material from yield improvements. Despite this significant cost reduction, back-end materials costs remain more than 61% of the incremental capacity cost, $m$, for the second generation plant. Hence, reductions in back-end materials costs are likely to remain one of the dominant approaches to reducing the overall production cost per display. Recent reports that several manufacturers have started making their own color-filters indirectly support this observation. Furthermore, the cost of materials of the driver and controller electronics and their packaging is about a fourth of $m$, indicating that competing technologies such as low-temperature poly-silicon, which can integrate these IC's by simultaneously fabricating them with the TFT-array, may be able to achieve a lower minimum cost per display.

The manufacturing cost per display decreases with increasing plant capacity mainly as a result of amortizing the capacity-independent costs $(M)$ over more displays. The effect of granularity contributes much less to scale economies. The minimum efficient scale of a plant (arbitrarily defined as the point where granularity and capacity-independent costs contribute no more than 5% of the total manufacturing cost per display) is about 57 000 displays per month for a first generation plant and about 150 000 for a second generation plant. These conclusions are supported by recent announcements of Japanese plants. Moreover, these results indicate that a cost premium of 20% will be incurred by low-volume manufacturing plants which produce less than 30 000 displays per month in a second generation plant.

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