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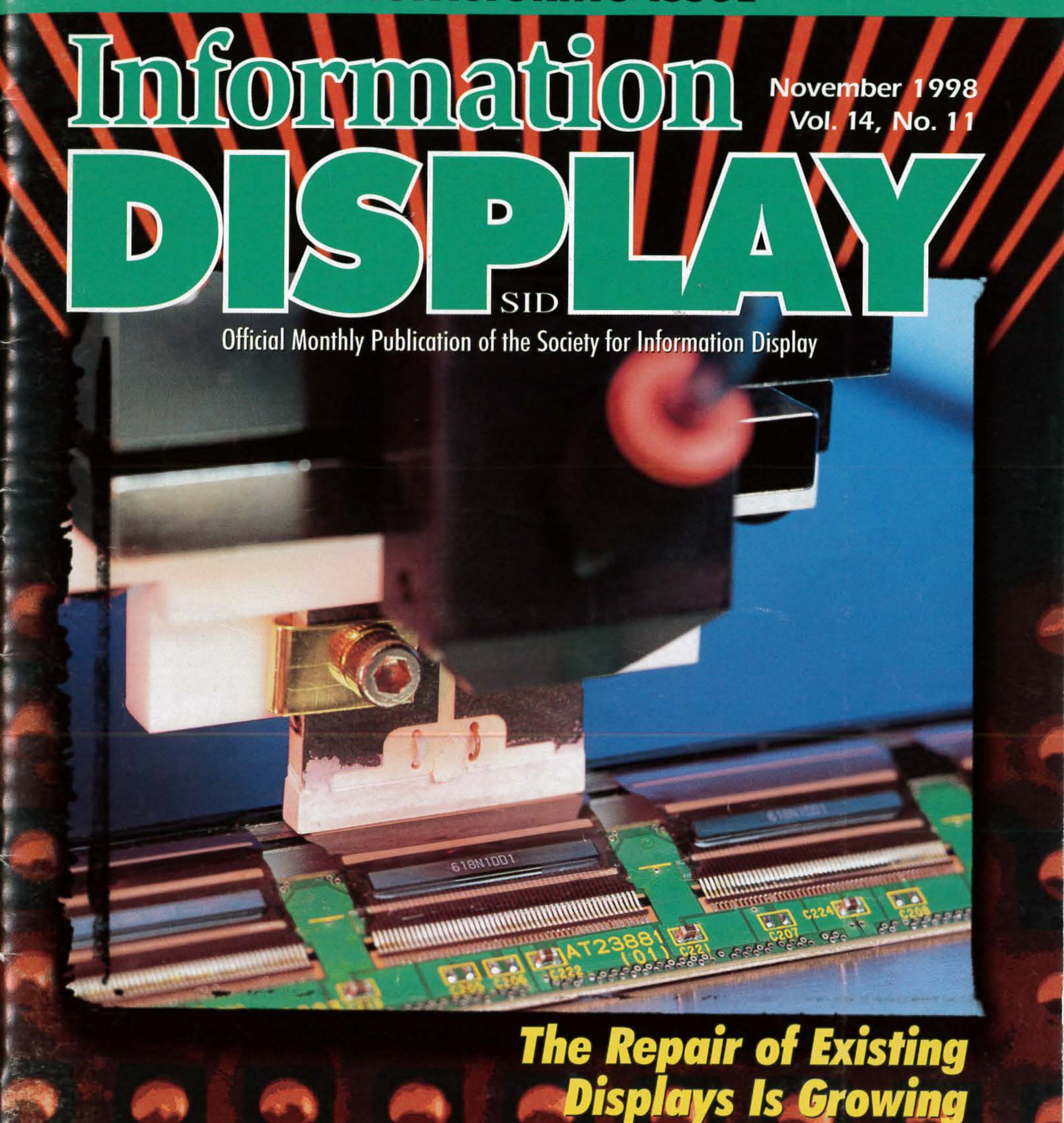

The Repair of Existing Displays Is Growing

- *Repair of Flat-Panel Displays*
- *Air Ionizers*
- *Continuous-Grain Silicon*
- *Manufacturing Cost Structures*
- *A Plasma World*

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Cover: Repair and rework of existing displays is a growing industry, but the equipment needed to make a rework business profitable must be optimized very differently from that which Sharp and NEC use to crank out new displays.

Credit: MicroJoin, Inc.

For more on what's coming in *Information Display,* and for other news on information-display technology, check the SID Web site on the World Wide Web: **http://www.sid.org.**

Next Month in
Information Display

Display of the Year Awards Issue
- The Best of '98
- Microdisplays
- The Military Display Dilemma
- FPD Image Scaling
- Projection-Display Measurements

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Information DISPLAY

NOVEMBER 1998
VOL. 14, NO. 11

editorial

Planning Begins for a Bigger, Better Display Technology Showcase

The First Annual Display Technology Showcase (DTS) was a hugely successful innovation at SID '98. This side-by-side comparison of different display technologies and approaches attracted 4000 of SID's 6200 attendees, and proved to be "the center of attention at SID '98," according to George Kotelly, writing in the July issue of *Vision Systems Design.*

"Most [people] have not seen plasma displays, liquid crystals, projection displays, and CRTs next to each other," said Plasmaco CEO Larry Weber. "When [DTS] puts them all in a line, and all have the same image, you take out all of the trickery that everybody plays in the exhibit hall."

John O'Donnell, Display Consultant, Honeywell Business and Commuter Aviation Systems (Phoenix, Arizona): "I love the display comparison. It shows the performance of the displays under numerous conditions, most of which we don't see in the booths."

SID's DTS Steering Committee, General Manager Nutmeg Consultants, and new Technical Manager Altinex, Inc., are now beginning the planning for the second DTS, to be held May 18-20, 1999, as part of SID '99 in San Jose, California. The floor space allocated to DTS will be more than doubled for '99 (from 3500 to 8000 $ft.^2$), the organizers are anticipating that the number of participating displays will grow to more than 60 (from about 30 last year), and management is substantially increasing the promotion and advertising budget.

This coming year, DTS will be in an enclosed pavilion adjacent to the show floor for high exposure and extensive interaction with the overall exhibition, and, for the first time, digital as well as analog signals will be available to the participating displays. Altinex also has innovative ideas for greater viewer interaction with the test suite.

A meeting of the DTS Technical Committee, which will include representatives of actual and potential participants, is tentatively scheduled for November, so now is the time for interested companies to check in with the organizers.

DTS is an exciting and very valuable event both for participants and the many attendees. Last year, the organizers called DTS "a side-by-side comparison of leading-edge display technologies to help you match technologies and applications." One of the participants commented that he obtained more requests for information about his display in DTS than for the identical display on the show floor. Another appreciated the knowledge gained from the set-up process and the interaction with DTS's technical management.

This is the time for display manufacturers and marketers to begin planning their participation in SID 1999's "center of attention." It is an ideal way to communicate with the display community and the rapidly increasing population of display integrators, display application engineers, and product designers who attend the SID Symposium.

Entry packages can be obtained from Dian Mecca at Nutmeg Consultants (telephone 203/853-7069, fax 203/855-9769, e-mail: kwerner@home.com), or you can fill out an electronic entry form at www.sid.org.

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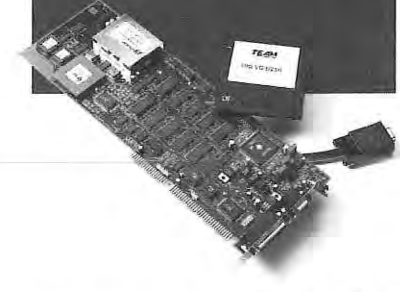

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Circle no. 2

The Waves of Change ...

by Aris Silzars

The traffic light at the top of the hill had turned green and I was anxious to get home. However, the flag-person, wearing her bright orange vest and holding a most official-looking red stop sign, clearly had other ideas: she was standing squarely in front of me with the stop sign planted between her feet. And good thing too, because just then from my left came an incredibly large dump truck towing an even more impressive multi-wheeled trailer, both heaped high with dirt. This truck must have known that it was the biggest darn truck on the road and thereby had the right to go and do pretty much whatever it wanted. And at the moment what it wanted - at about 20 miles per hour - was the piece of road immediately in front of my car. Apparently, "immediately" meant I could have the last six inches between his wall-like bumper and my much-more-delicate hood emblem. Fortunately, the flag-person was also allocated a similar approximately six-inch clearance.

Ten or fifteen seconds later, just as my adrenaline level was peaking, came another truck and trailer just like it, also loaded with two mountains of dirt, seemingly in hot pursuit of the first one. Whew, another close encounter of the scary kind.

The gently sloping valley and the rolling hillside behind it, which until a few days ago had been a grass- and tree-covered pasture, had now become the playground of trucks, tractors, and various other dirt-moving machinery. Soon 200+ apartments could be expected to sprout on this spot.

The environmentalist in me was sad, but the technologist was fascinated. I have always had a love of nature and the outdoors, but at the same time, as far back as I can remember, I have been intrigued by construction projects - the larger the better. When I was much younger and had more control over how I spend my time, I could watch large dirt-moving machines for hours on end. The passing years have not dimmed my interest in observing and analyzing the construction progress on a new building or other major project - I've apparently just lost the time to pause and watch.

The environmentalist in me is becoming increasingly concerned that we are running out of room on planet earth, while the technologist in me wants to see the building of even more advanced machines and structures. Are my environmental concerns well-founded? ***Are*** we running out of room? Looking down, from the ever-more-crowded airplanes on which I spend a good bit of my life, I sometimes get the feeling that we humans are like a virus or a mold gradually spreading our colonies to cover the planet's surface. Now, that's not a very complimentary way to think about you and me, and most days I certainly don't envision myself as a fungus, but seeing the population centers spreading and modifying nature's surface can't help but make a person a bit concerned. How much more of this can our planet support?

The perception of this spread is accelerated if you happen to reside near one of the transition boundaries between the already developed and the rural. Seemingly overnight the land is cleared, new streets and utilities are installed, and houses, apartments, businesses, and new malls appear like batches of cookies from an oven. The back roads that formerly could be counted on for a quiet

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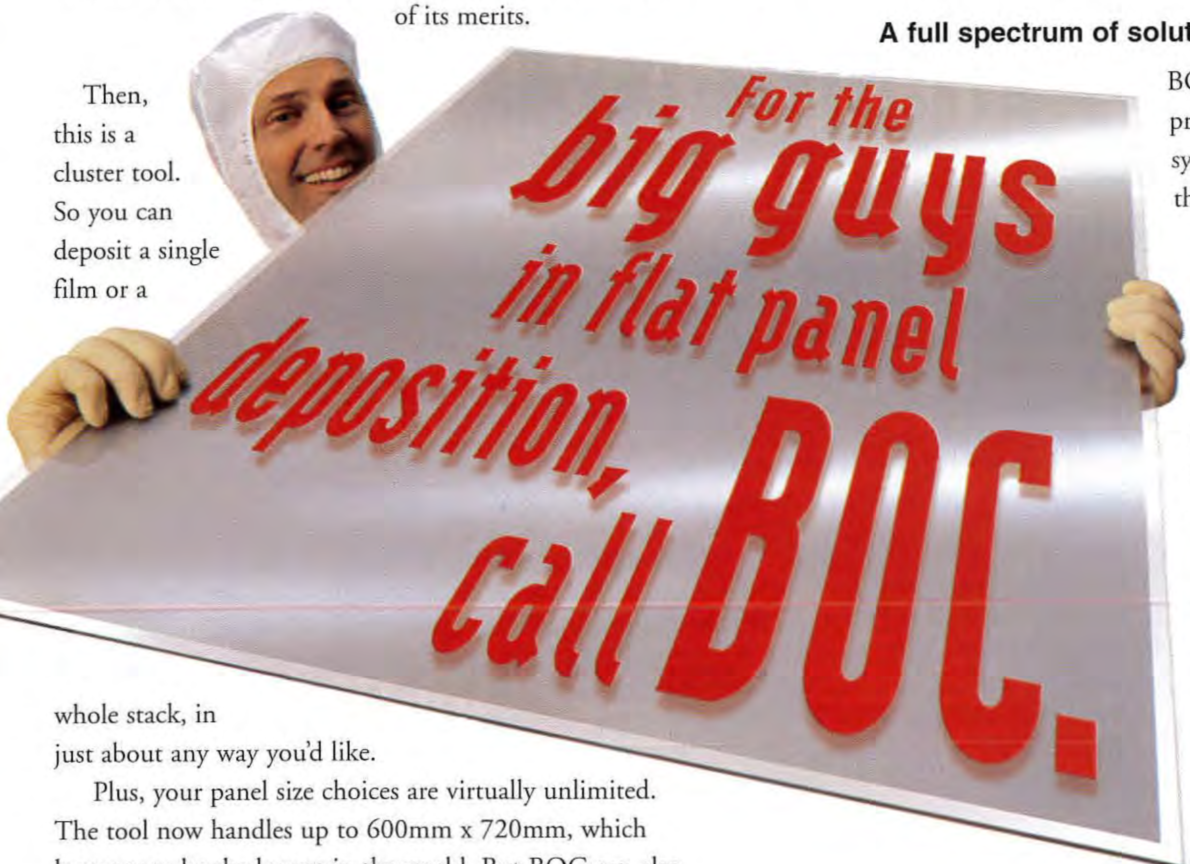

Then, this is a cluster tool. So you can deposit a single film or a whole stack, in just about any way you'd like.

Plus, your panel size choices are virtually unlimited. The tool now handles up to 600mm x 720mm, which happens to be the largest in the world. But BOC can also configure it for even larger sizes upon request.

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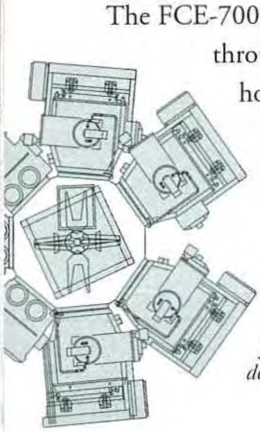
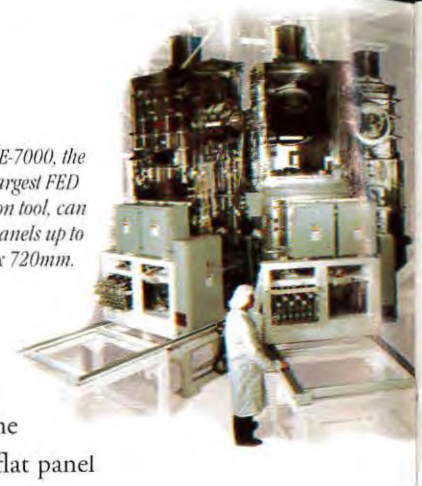
The FCE-7000 is a proven production tool that generates throughput speeds of from 10 to 60 panels per hour – and even up to 70 and 75 on certain processes. And when you combine that kind of throughput with high production quality levels, you get a very attractive return on your investment.



Designed for production, BOC's flexible cluster configuration lets you deposit a single film or an entire stack.

And this system also reduces downtime and requires less maintenance.

Plus, it provides more advanced automation and higher materials utilization. So you can see how it achieves the lowest cost of ownership of any flat panel deposition system in the industry.



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Circle no. 5

Circle no. 9

Repair and Rework of Flat-Panel Displays

Automation, consistent TAB processes, and efficient cannibalization are the core competencies needed to become a successful rework house.

by Thomas Todd

THE CONTINUOUS ADVANCEMENTS in flat-panel-display (FPD) technologies over the past decade have fueled unprecedented growth in the markets for portable and mobile computing devices. Riding on the coattails of these primary FPD shipments is a rapidly expanding market segment focused entirely upon FPD repair, with a new breed of service providers and equipment suppliers able to meet the segment's special requirements. The unique challenges of FPD rework and repair require an in-depth understanding of both the technologies and the market dynamics involved.

According to a recent report by *Electronic Trend Publications,* the worldwide market for FPDs is expected to expand at a compound revenue growth rate of more than 14% per year – from $14.0 billion in 1997 to approximately $27.2 billion in 2002 (Fig. 1). "As this market grows," says the report, "it is becoming increasingly complex. New technologies are moving to market, and new applications are opening up." This clearly creates growing opportunities for the repair and rework industry.

Key Repair Opportunities

High-end laptop FPDs represent key repair opportunities. While there is relatively little demand for repair of the small lower-cost screens used in personal digital assistants (PDAs), digital cameras, and hand-held TVs, the larger double-supertwisted-nematic (DSTN) and thin-film-transistor (TFT) displays used in notebook and laptop computers carry enough intrinsic value to make them good candidates for repair instead of replacement. And the mobility of notebook computers produces high damage rates that feed the repair industry.

The global nature of the mobile-computer industry poses logistical challenges for FPD rework and repair houses. The largest FPD manufacturers are located in the Pacific Rim, but end users of their products are dispersed around the world, with heavy concentrations in North America and Europe. Because of rapidly increasing volumes, market demand for quick turnaround, and logistical constraints, primary FPD manufacturers typically contract with regional and localized outside service providers for repair work.

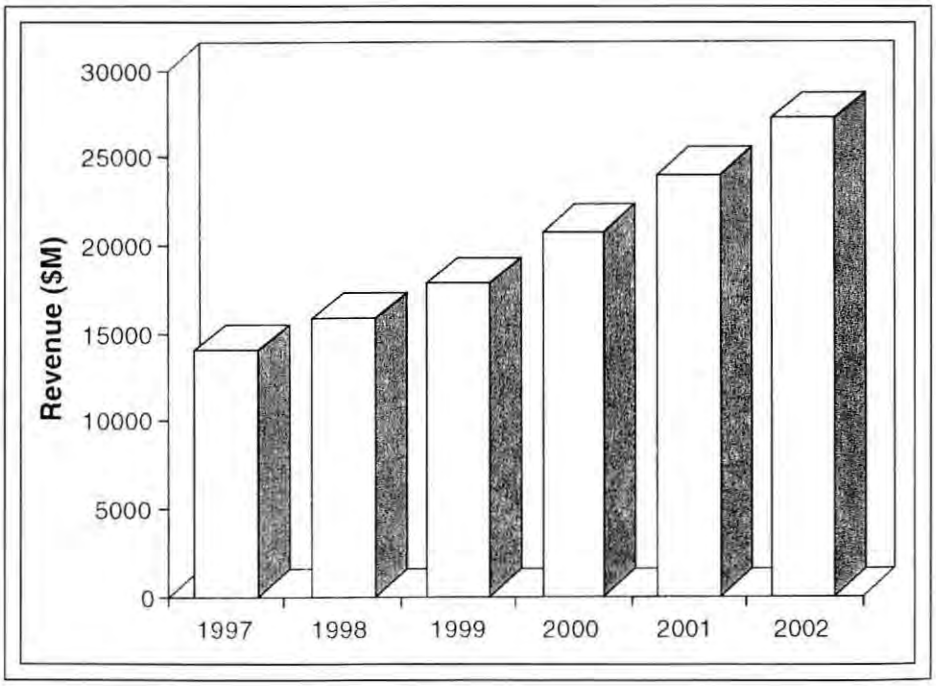

Fig. 1: The strong continuing growth of FPD production, and the increasing variety of FPD technologies and applications, is presenting repair and rework houses with increasing opportunities, as well as difficult investment decisions. (Source: Electronic Trend Publications*)*

Thomas Todd is President of MicroJoin Inc. (formerly Toddco General), the leading manufacturer of bonding equipment for the FPD repair industry, 13535 Danielson St., Poway, CA 92064; telephone 619/877-2100, fax 619/877-2110, e-mail: ttodd@microjoin.com.

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The Real World of FPD Repair

Pixel Interconnect, Inc. (Portland, Oregon) is a process-engineering services firm that focuses specifically on FPD design and manufacturing methods. President Scott Cockey: "If we assume the notebook industry's track record of a 4% repair FPD rate along with their high dollar value, FPDs easily comprise the most critical cost component of laptop-computer repair. With more laptops shipped every year, the portion of the installed base requiring repair is constantly increasing in value, while simultaneously outstripping the overall capacity of the rework and repair channels. Exacerbating this situation is the fact that display technologies keep changing to track with market demands. The half-life of the typical notebook FPD design has fallen to only 6 months. The combination of all these factors is forcing repair houses to make capital-equipment investments that not only maximize automation and throughput, but also provide enough flexibility and extensibility to handle tomorrow's design changes."

Pix Electronics, Inc. (Lanham, Maryland) is a successful repair organization that is dedicated solely to serving the FPD repair marketplace, including warranty, post-warranty, and end-user repair channels. Gail Hansborough, V.P. of Operations: "One of the main changes we've seen in the industry over the years is the increased challenge of alignment for fine pitch. In older displays, the pitch on the screen was so coarse that a technician could effectively align the TAB with the aid of a microscope, tack it into place, and then pick up the whole assembly and move it to the bonding system. Now with today's large fine-pitch displays, such as SVGAs and XGAs, TAB-driver replacement has become a task that requires both superb optics and the ability to perform the repair right in place. In making our equipment decisions, we firmly believe that, even though much of FPD repair is oriented to trailing-edge products, the real volume opportunities to provide warranty repair require an investment strategy that constantly looks ahead to meeting tomorrow's requirements."

The Cerplex Group, Inc. (Tustin, California) is one of the world's leading computer-repair organizations and has recently committed significant resources to establishing in-house FPD repair capabilities in the U.S. and Europe. Brian Campbell, Director of Business Solutions and Development: "When we look at the FPD repair market we see approximately 16 million notebooks sold last year and an installed base of somewhere around 25 million that are actively being used. By figuring a 5% overall return rate – 25% of which is attributable to the LCD – we come up with somewhere over 500,000 LCD-oriented returns per year. At a projected average of $100 per repair, even a relatively small 10% of the available market results in a $5 million stand-alone business opportunity. Even more importantly for a full-service comprehensive service outsourcing repair organization like Cerplex, there are significant additional synergies by integrating LCD repair with our mainstream repair business."

Sequel, Inc. (Santa Clara, California) is a leading notebook-repair company that has successfully expanded into the FPD repair market. Sequel also offers FPD repair as a stand-alone business. Steve Ball, Senior LCD Process Engineer: "As part of our commitment to the LCD repair market, and our role as a worldwide repair partner for Mitsubishi, we have already set up full LCD repair facilities in the United States, Taiwan, and the U.K. over the past few years. Because our repair activities have to simultaneously deal with both end-of-life issues and warranty repair of new products, it is critical that TAB-recovery equipment be able to produce high yields of usable product, regardless of the pitch dimensions. We are also just getting into repair of smaller screens, such as PDAs and other handhelds, where fine pitch is paramount. From what we've seen, all of the PC makers are significantly stepping up pressure on FPD manufacturers to provide repair facilities throughout the world and thereby reduce repair-pipeline delays. This clearly represents the major opportunity for top-tier repair organizations that are able to invest in leading-edge capabilities and processes required to optimize turnaround times and product yields."

The profile of an FPD repair house can range from a targeted regional operation to a multinational full-service third-party repair operation (see sidebar, The Real World of FPD Repair). Whatever the profile, a common factor that sets successful repair houses apart from limited garage-shop operations is their investment in automated capabilities for efficiently handling the larger screen sizes and sophisticated fine-pitch interconnects used in today's state-of-the-art FPDs.

Technical Challenges of FPD Repair

A review of typical industry-wide failure modes for LCD-based FPDs shows some very consistent Pareto dispersion patterns. By far, the highest LCD failure mode is blank horizontal rows or blank vertical columns resulting from either bad drivers or broken driver-to-LCD interconnects. These failures, which require driver recovery and rebonding, run between 40 and 50% of all LCD failures. (The next most significant failure modes – damaged polarizers, failed backlights, and bad PCB electronics – typically have frequencies of 12% or less.)

The high incidence of driver failure makes the efficient replacement of LCD drivers a capability that is critical for success, with a high likelihood of quick payback on investment. In addition, the ability to effectively recover and rebond LCD drivers is now often a fundamental prerequisite for disassembling the FPD to accomplish other repairs.

For the majority of today's FPD designs, the primary method of interconnecting drivers to the LCD is by means of tape-automated bonding (TAB). The use of TAB drivers enables designers to incorporate the fine pitches required by high-resolution laptop screens, which can be as small as 62 μm on a 1280 × 768 display with a 12–14-in.-diagonal screen size. As a result, effective process control for consistent alignment and attachment of fine-pitch TAB drivers has now emerged as the core challenge for success in the FPD repair industry.

Repair Yield: The Key to Success

A repair house's competitive position and bottom-line profitability hinge on how high a "yield" of good displays it can obtain from a given number of failed FPDs. This emphasis on yield is a result of the shortage of new replacement parts available from FPD manufacturers, which makes effective cannibaliza-

MicroJoin Inc.

***Fig. 2:** A TAB-driver repair and rework machine as used at Pixel Interconnect to fix damaged flat-panel displays. This machine is by MicroJoin (formerly Toddco General).*

tion a fundamental component of any FPD repair strategy.

Because most repair houses are in competition with each other to act as subcontractors to computer OEMs and FPD manufacturers, the ability to commit to a specified yield level is a critical differentiating factor. If a repair house promises to return 60 good panels out of every 100 failed panels it receives, this implies that the other 40 panels will be scrapped in order to provide good replacement parts such as TAB drivers, backlights, connectors, and PCBs.

Clearly, a repair house that can commit to a 60% yield has a significant competitive advantage over a house that can only commit to a 50% yield. Of course, the bottom line will depend upon the repair operation's being able to meet the specified yield commitment in a cost-effective manner, without consuming too much time, labor, or materials. Because TAB-driver recovery and rebonding is a critical factor in overall yield, those repair companies that can implement these operations efficiently - and without damaging good components - will be able to deliver higher yield commitments.

Since the Holy Grail for most repair houses is to become a warranty-repair subcontractor to a major FPD manufacturer, they know that the ability to maximize yield often becomes the primary selection factor. Paradoxically, after being chosen as a warranty provider, the repair house often gains some degree of cushion on the yield front by gaining priority access to the limited supply of new replacement parts. But yield remains a key component of an FPD repair house's overall business success, whether the house is a warranty provider or not.

Equipment Requirements

Entering the FPD repair market requires a significant initial investment that can range from tens of thousands to over a million dollars, depending upon the types of repairs offered, the levels of automation required, and the overall volumes anticipated. For instance, automated polarizer-repair equipment can require a $50,000 initial investment plus over $1000 in tooling for each type of display panel. Although automated polarizer alignment can greatly increase yields, it requires at least a moderate volume - more than 100 per day - of a particular display type for the increased yield to amortize the additional costs.

When it comes to TAB-driver repair, any serious rework operation should include a specialized capability for pulse-heated anisotropic-conductive-film (ACF) bonding/recovery, with tight process control over the heat and pressure profiles, plus precision positioning, alignment, and coplanarity management. While some low-end FPD repair "kits" supposedly give garage shops the ability to conduct TAB-driver repairs with a soldering iron, such methods simply can't provide the fine pitch alignments and consistent yield a company needs if it is to compete as a full-fledged FPD repair provider.

There are several reasons for using specialized ACF recovery/rebonding equipment to make TAB connections. Repair-oriented systems must control the critical process parameters of time, temperature, pressure, and alignment even more closely than the original panel manufacturers. The original manufacturer is concerned about maintaining a high production rate at a reasonable first-pass quality level. By electing not to control these parameters optimally for each TAB, the manufacturer increases throughput, but at the price of having a higher rate of subsequent failures in the field. Repair-oriented equipment, on the other hand, must be optimized to control all four process parameters for every single TAB.

The original manufacturer must also trade off production-rate requirements against optimal cure time of the adhesive. Improperly cured adhesive can relax over time, causing the connection to open - the most common cause of failure.

Repair-oriented ACF TAB-bonding equipment must have built-in process-development capabilities. MicroJoin systems, for instance, incorporate external thermocouple inputs to show the actual ACF-material temperature plotted over time. The hot-bar commanded temperature and the measured ACF temperature can be compared in real time to assure optimum process setting for that type of bond.

Another factor that contributes to the loss of connection over time is a larger than normal gap between the glass and TAB. This gap is determined by the hot-bar coplanarity and flatness over the length of the bond. For ACF balls from 5 to 10 μm in diameter, an even pressure over the bond length is required to properly crush each ball. Using silicon rubber or Kapton can compensate for minor variations in hot-bar flatness, but consistency can be difficult to achieve and maintain in the face of larger variations over a long metal hot bar under varying manufacturing conditions. In its equipment, MicroJoin keeps these variations extremely small by using a ceramic material. Unlike metal, the ceramic material does not warp or change shape when heated and cooled.

In the high-volume production lines of panel manufacturers, as many as 10–14 TABs may be bonded in one operation. The production rate is high, but achieving the optimum ball crush over a long length is a compromise. Flatness across the bond directly determines the number of balls being crushed to the proper height, so repair-oriented equipment should be optimized for ball crush over a single TAB.

As with any manufacturing process, variability between separate steps in the process can occur, thereby causing defects in alignment. The original manufacturer optimizes for production rate by aligning two or more TABs in one operation and then moving them to a separate bonding operation. Since the TABs are not bonded at the alignment station, they can move out of alignment during transport. Repair-oriented bonding equipment should allow for both alignment and final bonding of each TAB without transporting between operations (Fig. 2).

The price range for pulse-heated systems capable of repairing ACF-bonded TAB drivers is from $15,000 to $150,000, so it is important for a repair house to consider how it will be using its equipment investment. Since the name of the game is to maximize yields for lots of different display types with fast turnaround and minimum labor investment, repair-oriented equipment is necessarily different from production-oriented equipment. For instance, a repair-oriented system for TAB-driver recovery and replacement must be able to step the operator quickly through any specific process, and it must have the flexibility for quick changeover to effectively repair a wide variety of display types.

In the real world, a repair operation may be faced with replacing any of 10 or more TABs on each of more than a dozen different LCD panel types. The work flow in such a high-mix environment may be beyond the control - or even the forecasting ability - of the repair house. Depending upon the volumes and mix of displays being repaired, automation features such as integrated machine-vision and pattern recognition may greatly improve throughput by automatically pre-positioning the machine over the TAB driver specified by the operator.

Planning for Larger Panels

The FPD repair and rework market typically lags slightly behind the technology curve, but the rapid pace of technological change demands that repair houses must always balance the cost of today's capital investment against the potential risk of obsolescence by tomorrow's market changes. One area of ongoing risk is the ability of existing TAB-repair bonding systems to handle bigger displays. For instance, as 15-in.-and-larger displays move into volume production for laptops, repair houses must already have systems in place with the X-Y positioning capabilities to handle large panels. As large-format-FPD costs become more competitive with conventional CRTs in the desktop-monitor market, the enormous volume potential of monitor FPDs and the increase in repair value-added opportunities will likely become the driving forces for all future capital-equipment decisions in the FPD repair industry.

The inevitable push to larger screens and greater resolutions will enhance the value of FPD repairs, and this will expand today's already lucrative business opportunities. But this implies that FPD repair houses will increasingly have to depend on highly automated techniques for handling the minute alignment and bonding demands of fine-pitch connections on steadily growing screen sizes.■

Air Ionizers in TFT-LCD Manufacturing

Electrostatic discharge plays havoc with yields – can it be prevented?

Haruyuki Togari and Arnold Steinman

STATIC CHARGES are more than a nuisance that can cause hair to become unruly and clothes to cling; they create a variety of problems in high-technology manufacturing that result in damage and yield losses totaling more than $1 billion each year. These problems are only going to get worse as we move toward smaller device sizes, faster operating speeds, and larger manufacturing substrates. Unless static charges can be controlled effectively in manufacturing facilities, the losses can only grow larger.

Three different types of static effects create production problems. Electrostatic attraction (ESA) increases the rate of particle deposition on charged surfaces, resulting in product defects even when products are manufactured in cleanrooms. ESA also causes unwanted movement and sticking of materials, leading to equipment jamming and product breakage. Electrostatic discharge (ESD) damages products directly, frequently melting small-geometry features (under 1.0 μm) or damaging thin-film coatings. ESD also generates electromagnetic interference (EMI) that interrupts the operation of production equipment.

Problems for LCD Production

Production of thin-film-transistor liquid-crystal-display (TFT-LCD) panels is particularly susceptible to electrostatic problems. The four distinct areas of the manufacturing process – array, color filter, cell assembly, and module assembly – each pose unique electrostatic problems. As the industry works to increase yields, the need for effective controls becomes increasingly important. The presence of insulators throughout the LCD fabrication process makes it difficult to impossible to rely on physical controls. As a result, air ionization remains the most effective and widely implemented approach.

The market for electrostatic-control products exceeds $300 million annually, and air-

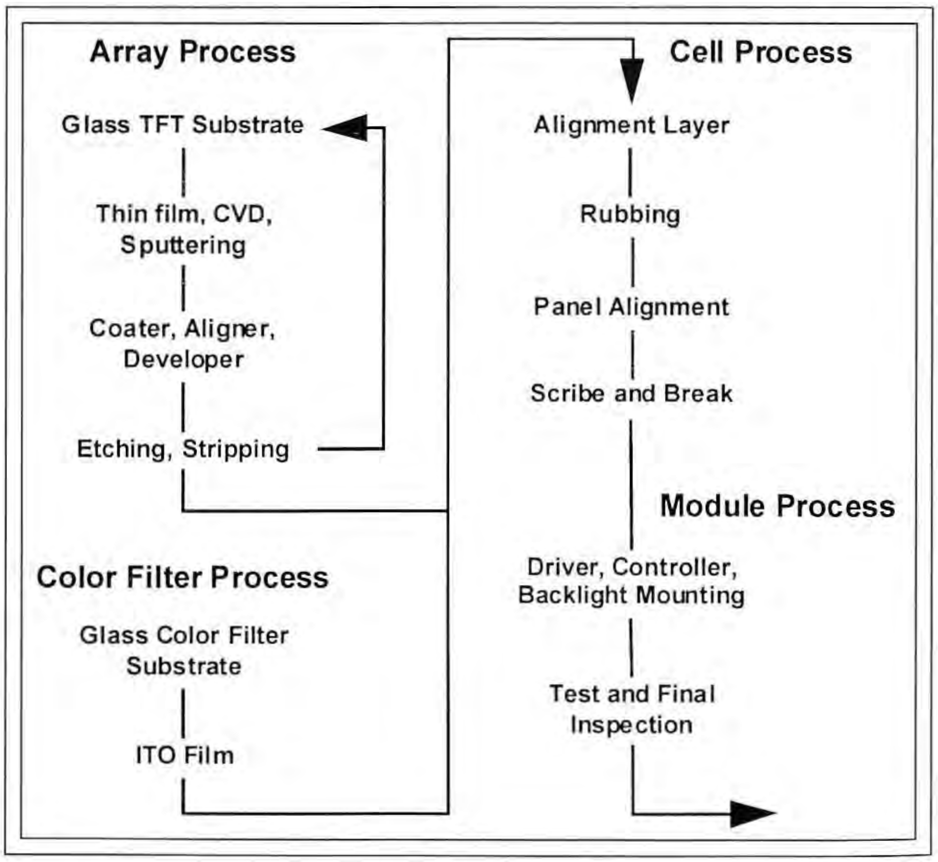

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Fig. 1: *The four segments of the LCD manufacturing process each have their own particular air-ionization requirements.*

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ionization systems account for more than one-quarter of that total. The move to finer panel resolutions and larger glass substrates makes static control even more essential, and so the market for control systems can be expected to grow.

Types of Air Ionizers

Air ionizers work by creating charged air molecules; by either adding or removing an electron, air molecules can be given a negative or positive charge. There are three different types of ionization systems currently used by LCD manufacturers: corona discharge, photon ionization, and nuclear ionization. Each approach has advantages and disadvantages (Table 1).

The corona-discharge ionizer uses a high voltage applied to a sharp emitter point, which produces a strong electric field. This field interacts with the electrons of the adjacent gas molecules, producing ions of the same polarity as the applied voltage. These ionizers are classified according to the electrical current that is applied to the emitter: pulsed dc, steady-state dc, or ac. One limitation of corona-discharge designs is that deposits tend to accumulate on the emitter points as a result of gas-to-particle conversion, chemical reactions caused by the electric field, and high emitter-point temperature. These deposits can reduce the emitter efficiency, and periodic maintenance to remove them may be required. The same process that creates the deposits can also create small particles, which can pose significant problems in cleanroom settings. Cleaning the emitters may be difficult in some operating environments, in which deposit formation can be reduced by sheathing the emitter points with clean, dry, silica-free air or nitrogen gas.

Photon ionization uses a soft x-ray energy source to displace electrons from the gas molecules. Nuclear ionizers use polonium-210 radiation sources to create alpha particles that collide with the gas molecules, displacing electrons. The molecules that lose electrons become positive ions. Neutral gas molecules rapidly capture the electrons and become negative ions. These types of ion generators do not have emitter points, so deposits are not a concern. However, x-ray and nuclear sources must be carefully installed and controlled to avoid creating safety hazards.

TFT-LCD Manufacturing

As mentioned earlier, the TFT-LCD manufacturing process is generally divided into four separate process segments: array, color filter, cell, and module (Fig. 1). The procedures in each segment are carried out in a different class of air cleanliness, and each requires different static-control methods. Careful study of the application environment for each segment is required in order to select the correct air ionizer and to design its installation for optimum operation.

Array Process

During the array process, the TFT elements for the LCD are deposited on a glass substrate. Similar to semiconductor manufacturing, this requires repeated cycles of deposition, photolithography, and etching. The most common static-charge-related problems seen in this process are pattern defects due to particle attraction and bonding, breakdown and performance degradation of the TFTs, and problems during materials handling. The array process requires air cleanliness of class 10 to 100. The same types of ionizers used in semiconductor manufacturing are used in the array process areas, including many that are installed inside the process equipment.

Glass-substrate size has more than doubled recently from 360 × 460 mm to the current 600 × 720 mm. The roadmap for the LCD

Table 1: Features of Various Types of Air Ionizers

Issues	Pulsed-dc	Steady-State dc or ac	Ionizing Blowers (Steady-state dc or ac)	Photon Ionizers	Nuclear Ionizers
Airflow	Airflow shortens decay time. May be used without airflow.	Required	Included in the design.	Airflow shortens decay time. May be used without airflow.	Required
Effective area	1.2 × 1.2 m for each pair of positive and negative emitter points	0.6 × 0.6 m directly underneath the ionizer	0.6 × 0.6 m with the blower centered over the area	1.0 × 1.0 × 1.0 m volume	Depends on length of nuclear source or available airflow
Effective distance	0.3–3.0 m	0.1–0.3 m	0.3–1.5 m	0.1–1.5 m	0.1 m without airflow
Decay time (100–10% of initial charge)	3–10 s depending on airflow and operating distance	3–10 s depending on airflow and distance	1–5 s depending on distance	1–20 s depending on airflow and distance	1–20 s depending on airflow and distance
Remaining charge	Varies at low level depending on pulse rate and distance to the ionizer.	Surface charge uniformity	Surface charge uniformity	Surface charge uniformity	Surface charge uniformity
Particle level	Suitable for class 1–100. Works with ambient airflow.	Suitable for class 1–100. Airflow in excess of ambient may stir up particles.	Suitable for class 100–1000. Blower airflow may stir up particles.	Suitable for class 1–1000. No particle production.	Suitable for class 1–1000. No particle production.

Progressive Systems Technology

Fig. 2: A bar-type pulsed-dc air ionizer in this substrate handler greatly reduces electrostatic charges in the cassette.

industry – described by both the U.S. Display Consortium (USDC) and the Japan Production Cost Savings Flat Panel Display Task Force (PCS-FPD) – indicates that the size of glass substrates is likely to more than double again within the next 5 years, at 950 × 1100 mm. As the size of the substrates increases, the amount of static charge also increases proportionally, so the effective area that the air ionizer needs to cover must also increase.

Currently, ionizers are used at a number of points in the array process.

- ***Substrates in cassettes*** – Glass substrates in a cassette have varying levels of charge, depending on how they have been processed and handled. Glass is a particularly easy material to charge because it is an excellent insulator and it retains its charge for long periods of time. Before placing the substrate in a cassette, it may be neutralized by an ionizer. Unfortunately, it gets recharged by separation from the robot arm that puts it into the cassette. The charge on the substrate needs to be eliminated before the next substrate comes into the cassette, otherwise the charge will be retained and subsequently increase with each successive substrate that is added to the cassette. Without ionization, the bottom substrates in a cassette can build up charges in excess of 20 kV. In order to be effective for cassette applications, an air ionizer must have wide area coverage at large distances. It must distribute air ions from the top to the bottom of the cassette. Typically, a bar-type pulsed-dc air ionizer is installed over the robot and the upper part of the entrance to the cassette (Fig. 2).
- ***Stage operations*** – For many of the steps in the array process, the substrate must be positioned and held very accurately on a stage. During separation from the stage after processing, the substrate gets charged when it is pushed up by the elevating pins. ESD occurring from the substrate to the pins and stage can cause damage to the transistors in the driver array, which results in defective product. ESA from the charge makes it harder to separate a substrate from the stage, particularly at the center. The glass can deflect and then bounce on the elevating pins, which in turn obstructs the pick-up robot movement and can cause glass breakage. This problem can only get worse as the industry moves towards larger and thinner glass substrates. In order to solve the charging problem, air ionizers are installed very close to the stage to give very fast discharge time. Ionized air must reach the bottom surface of the substrates, where the charge is

being generated. An air ionizer can reduce the electrostatic charge on the substrate to less than one-sixth the charge without the ionizer present (Fig. 3).

- ***Other array-process problem areas*** – ESD problems that occur in load/unload stations and process chambers are similar to those that occur on stages. These areas are often metal enclosures of minimal size, causing discharges to occur between charged substrates and the chamber walls. There is little space to install corona air ionizers, since ionizer emitter points must be located away from the metal chamber walls to avoid unwanted arcing or loss of ions. As a result, an ionizer must be used that can charge the air or nitrogen gas that is pumped through the chamber. Other current applications of ionizers in the array process are in spin coaters, photolithography steppers, and in chemical-vapor-deposition (CVD) equipment, specifically for substrate separation from the soaking plate. Similar static problems are encountered during the production of the color filter on a second glass substrate, although the emphasis is on particle attraction due to ESA rather than ESD.

Cell-Assembly Process

Cell assembly is a multi-step process in which the array substrate and color-filter substrate are assembled together, cut to the cell size, and filled with the liquid-crystal material. Assembly begins with coating an alignment layer on both the TFT-array substrate and color-filter substrate. The coated surface is then rubbed with a fast-rotating roller puff cloth to orient the liquid-crystal material. Spacers are sprayed on the surface of the substrate, sealing material is printed on, and the two substrates are aligned. After alignment, the panel is cut to a desired cell size, filled with liquid crystal, and sealed. Static problems that occur during the cell assembly include: unwanted attraction of particles, ESD damage, deterioration of the array substrate, and alignment defects from movement of the substrates caused by electrostatic repulsion.

The cell-assembly process environment is usually class 100 up to the panel-alignment stage, and class 1000 thereafter. Prior to panel alignment, air ionizers are installed to neutralize charges on the substrates in the cassettes and on the stages, as described earlier. During alignment, or scribe and break, particles become less of an issue, but array damage can still result from ESD.

Perhaps the most significant static-charge problems occur during the rubbing process. As any science student knows, rubbing glass with a soft cloth is an extremely efficient way to produce an electrostatic charge, so the rubbing stage poses some unique challenges for static control.

As already mentioned, the glass substrate is rubbed to align the liquid crystal in the display in a fixed direction when voltage is subsequently applied. The rubbing process generates very high static charges due to friction between the roller puff cloth and the glass substrate. The cloth also generates a large number of particles. Fan-powered corona ionizers or blow-off nozzles have been used in the past to neutralize the charge, but they tend to stir up particles and increase the contamination of the environment. High humidity is also used during the rubbing process to reduce static-charge generation. Recently, the soft x-ray ionizer was added to the equipment that does the rubbing process. This ionizer is able to rapidly and uniformly discharge the surface of the substrate with direct irradiation without the need for air flow. It also neutralizes the charge on the roller.

Module-Assembly Process

During module assembly, the driver integrated circuits (ICs) are connected to the display and assembled on the control board. Backlights and other components are also added to create a finished and tested panel. The most serious threat from static charge is ESD damage that occurs during the mounting of the driver ICs and final test process. The process environment class varies from 1000 to 10,000, and particle generation from the air ionizer is not considered a problem, so particle generation is not a concern in selecting an appropriate ionizer. On the other hand, the process of assembling backlights and control boards is not automated, so attention should be given to the static charge on personnel who handle the product. Static discharges from gloves and uniforms of personnel can destroy the product during this assembly step.

Air ionizers used during module assembly are fan-powered ionizing blowers. Installation requirements dictate that ionizer airflow must not create voltage differences across the module surface or stir up particles deposited in the process area. Since airflow from a

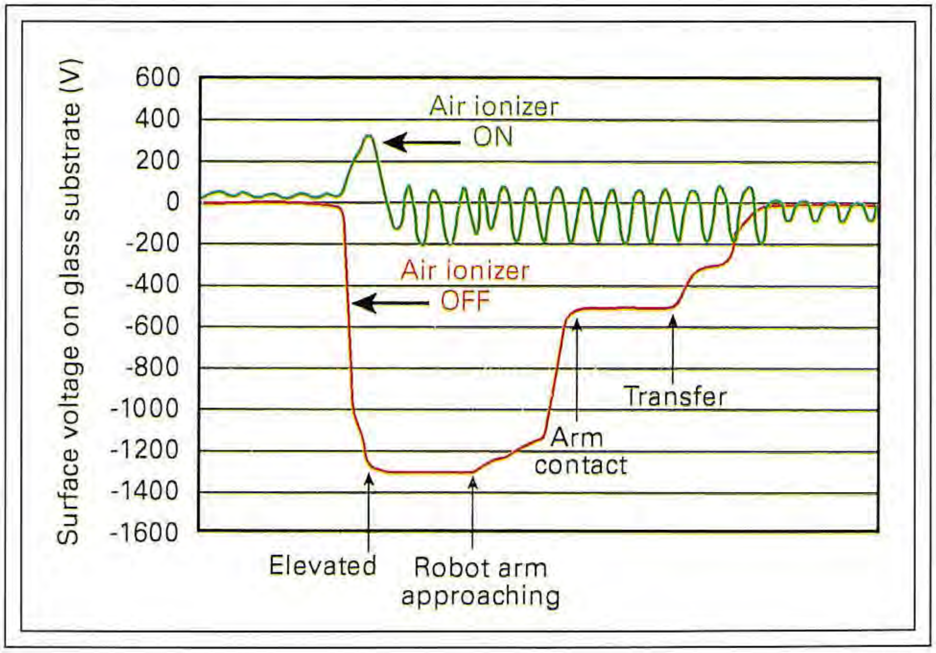

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Fig. 3: *Stage operations can result in handling problems and damage caused by static charges, but an air ionizer can greatly reduce the surface voltage on the glass substrate, which in turn improves handling reliability and production yields.*

benchtop air ionizer can be easily obstructed by tools on the work table, employees responsible for handling glass substrates must be cautious if using benchtop blowers for charge neutralization.

Ionizing blowers should be installed so that their airflow is at a right angle to the substrates (typically from above), which ensures an even distribution of ions over the entire display surface. Airflow parallel to the substrate causes a variance in the charge decay on the glass, depending on the distance from the ionizer, which can result in a voltage differential. Mounting the blower over the work table ensures limited obstruction to the ionized airflow. Ionizing blowers with adjustable airflow are best for such applications, as these can be set to provide sufficient coverage without stirring up particles unnecessarily.

Verifying Air-Ionizer Effectiveness

Once air ionizers are in place, how can we tell whether or not they are effective and adjusted for optimum performance? Measurements to verify the effectiveness of air ionizers can be made with the charged-plate monitor, as defined in the ESD Association Ionization Standard, ANSI EOS/ESD S3.1-1991. However, this test instrument relies on a 150 × 150-mm metal plate, which does not accurately characterize the charge neutralization of a large glass substrate. An alternative measurement method uses an electrostatic-field meter to measure static decay on the actual glass substrate. Monitoring with the field meter in any process will allow the adjustment of the ionizers for optimum neutralization performance, resulting in lower charges on the substrates. By minimizing the charge, the defects and handling problems caused by the static charges will be minimized.

Other Static-Control Measures

Static-charge control is rarely accomplished with a single method; a well-designed static-control program will rely on multiple approaches. Air ionizers can only neutralize a static charge after it has been generated; they can not prevent a static charge from being generated in the first place. Manufacturers can take a number of steps to prevent the creation of static charge.

One fundamental approach is to ground all electrically conductive and static dissipative materials in production equipment. Increased humidity levels can lower static-charge levels on insulators. Equipment can be designed to minimize contact of smooth surfaces or friction between materials, which reduces static-charge generation.

Taking Control

So when we ask, "Can electrostatic-charge generation in TFT-LCD manufacturing be prevented?", the only honest answer is, "No, it can't." At every step in the manufacturing process, the natural physical properties of the equipment, the substrates, and even the manufacturing environment itself produce static charges that have effects that range from the annoying to the catastrophic.

Careful analysis of the manufacturing processes, however, can lead to the selection of effective static-charge-control systems, which can include steps toward both prevention and elimination. Air-ionization units have been proven to be effective at eliminating charges, and different types of ionization units are available for different types of applications. They vary in a number of important ways, including airflow, particle generation, effective range, and installation constraints. By carefully matching the unit's operating characteristics with the needs of a specific process in the manufacturing operation – and instituting appropriate performance monitoring and maintenance procedures – an effective static-charge-elimination system can be created.

The pace of technology change in LCD manufacturing seems to be increasing daily, and as an industry, we must be prepared to meet the new challenges that these changes will present. As we seek to make larger displays with higher resolution and fewer defects at lower cost and in less production time, static-control programs will become increasingly important in TFT-LCD manufacturing. Only through close cooperation between the manufacturers, equipment designers, and air-ionizer suppliers will we be prepared to respond swiftly to the new problems as they arise. ■

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The 15th Annual Flat Information Displays Conference. Contact: Stanford Resources, Inc., Attn: Laura Barretto, P.O. Box 20324, San Jose, CA 95160; 408/448-4440, fax -4445, e-mail: www.stanfordresources.com.
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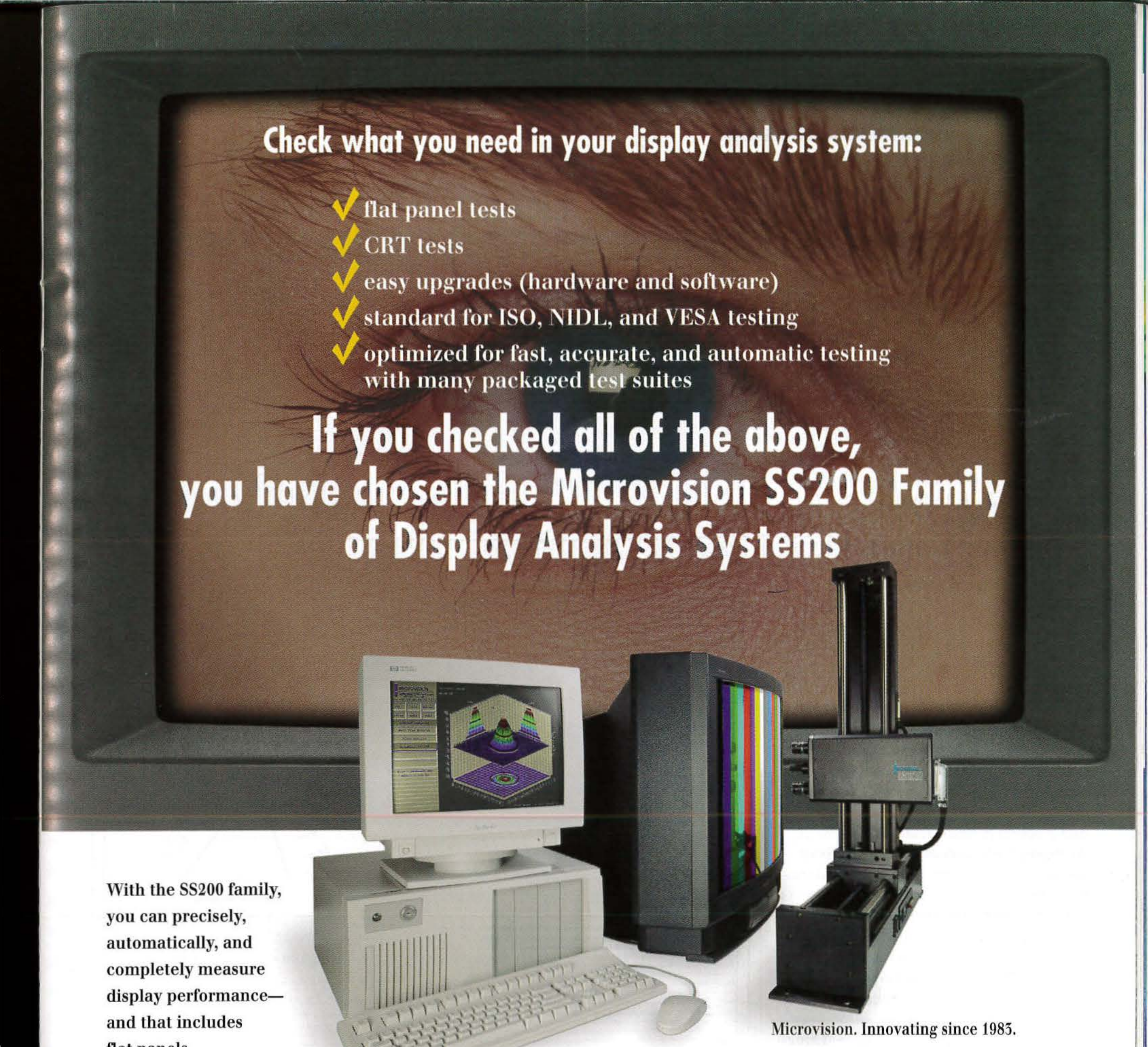
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Continuous-Grain Silicon Makes the HDTV Retro-Projector Sizzle

Continuous-grain silicon puts most of the performance of single-crystal silicon into a TFT material – and brings the "glass chassis" much closer.

by Hisashi Ohtani, Jun Koyama, Toru Mitsuki, Masaaki Hiroki, Shumpei Yamazaki, and Masaya Hijikigawa

MANY INDUSTRY WATCHERS consider polysilicon thin-film-transistor liquid-crystal displays (TFT-LCDs) to be the next generation of display devices. They are already important as a leading technology for making the small LCD light valves used in many data/graphics projectors, and at SID '98 in Anaheim, Toshiba showed that polysilicon displays can be surprisingly large by exhibiting a prototype 13.3-in. low-temperature polysilicon display in an XGA format.

Among the attractions of polysilicon is the ability to fabricate drivers on the panel along with the TFTs, using the same polysilicon material. But the electron mobility of conven-

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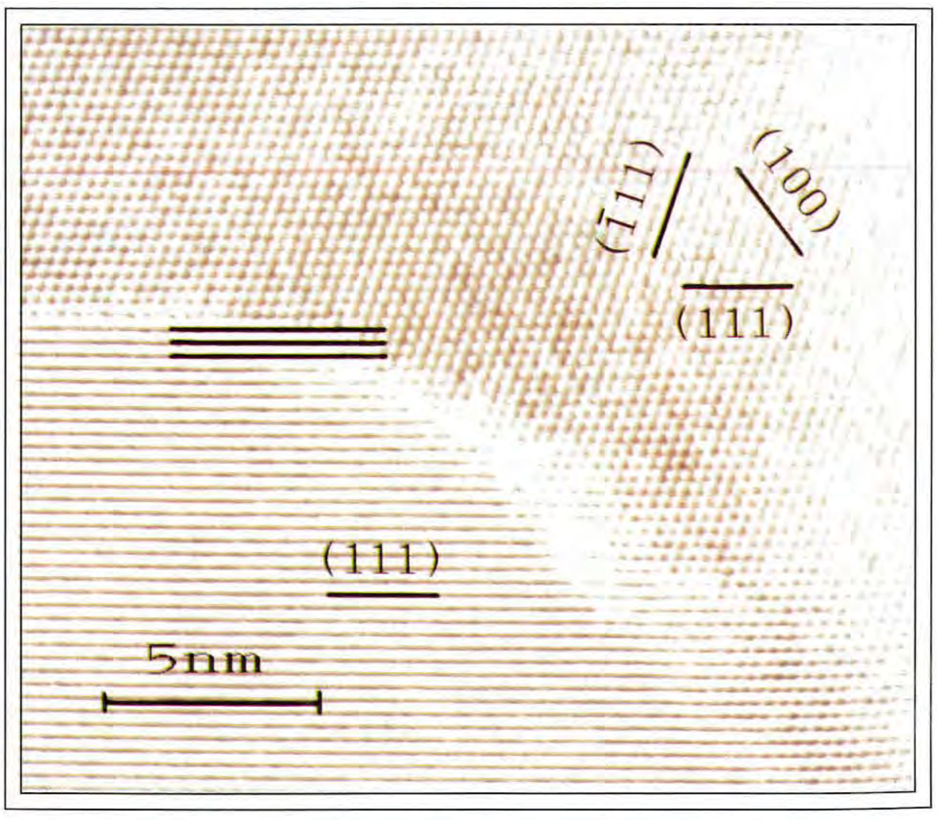

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Fig. 1: *The special structural characteristic of continuous-grain silicon, as shown in this high-resolution transmission-electron-microscope image, is that the edges of the crystalline grains are straight and the atomic bonds at the grain boundaries are smooth. This allows carriers to flow between grains without being trapped at the boundaries.*

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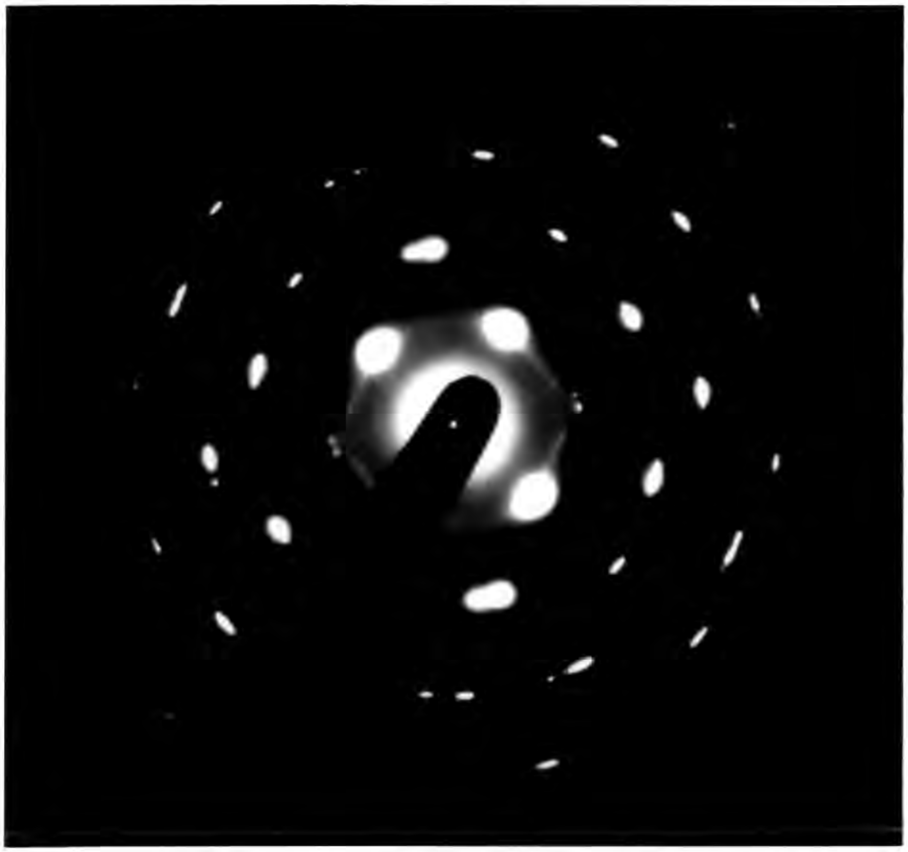

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Fig. 2: This electron-diffraction image of a 1.35-μm-diameter area of a continuous-grain-silicon film shows a distinct <110> diffraction pattern with few spots at irregular positions, even though there were many crystalline grains in the region. This shows that each grain has high crystallinity, that the grains are highly oriented with respect to each other, and that taken together the grains can be treated almost as a single crystal.

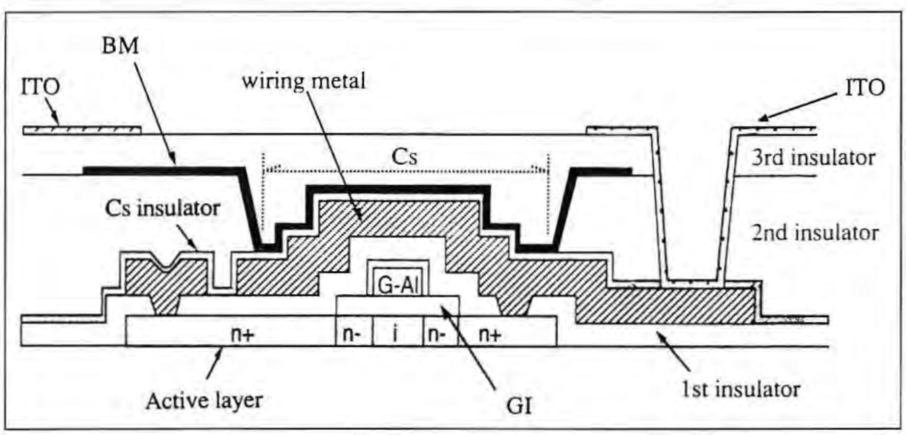

Fig. 3: This schematic cross section of a TFT doesn't look too unusual, except that the active layer is 40 nm of continuous-grain silicon, which is nearly as fast as single-crystal silicon.

Table 1: TFT-LCD Specifications

Display size	2.6 in.
Number of pixels	1280 × 1024
Pixel size	45 × 32 μm
Source-driver frequency	13.6 MHz
Gate-driver frequency	8.4 kHz
Aperture ratio	63%
Contrast ratio	300:1

tional polysilicon materials is too low to fabricate effective monolithic drivers for displays that push into the speed-and-resolution domain required for HDTV or video-rate SXGA. And the mobility is surely too low to fabricate the monolithic microprocessors and monolithic high-speed circuits that would fulfill the dream of making an entire system-on-panel (SOP).

But materials scientists at Semiconductor Energy Laboratory Co., working in cooperation with Sharp Corp., have developed a high-performance type of polysilicon called continuous-grain silicon, which is formed by solid-phase crystallization of an amorphous-silicon film by a novel crystallization technique. According to observation by transmission electron microscopy (TEM), most of the adjacent grains in a continuous-grain silicon have {111} lattices that completely coincide with each other at the boundary, and the atomic bonds at the boundary are smooth (Fig. 1). As a result, carriers can flow without being trapped at grain boundaries, producing excellent electrical characteristics. Remarkably, continuous-grain silicon offers essentially the same performance as single-crystal silicon.

An explanation for this behavior is found in a representative electron-diffraction pattern of a continuous-grain-silicon sample. The typical <110> diffraction pattern looks very much like the pattern for single-crystal silicon despite the fact that there are many grains in the 1.35-μm-diameter region that produced the pattern (Fig. 2).

Continuous-grain-silicon film has been used as the active layer in a pixel TFT design (Fig. 3) for 2.6-in. HDTV panels intended for a rear-projection HDTV receiver. The measured I_D-V_G characteristics of the transistors are excellent, with the field-effect mobility of n-channel TFTs exceeding 300 cm^2/V_s, and the mobility for p-channel TFTs being about 140 cm^2/V_s. S-values are less than 80 mV/dec for both n- and p-channel TFTs, which predicts very fast switching in actual circuits.

TFT materials

Sharp Corp.

Fig. 4: This prototype of a 60-in. HDTV rear-projection receiver uses three 2.6-in. HDTV continuous-grain-silicon TFT-LCD panels.

The pixel size for these panels is 45 μm (H) × 32 μm (V). The pixels have the black matrix on the TFT structure to improve aperture ratio, and the storage capacitor is formed by overlapping the black-matrix and the wiring-metal layers on the TFT. The result is an aperture ratio of 63%.

The 2.6-in. LCD panel contains monolithic drivers. Because of the high performance of the continuous-grain silicon, the panel doesn't need video-signal expansion and only one video signal is input to the data driver. Consequently, a stable LCD image is obtained without periodic unevenness. (Two video lines are connected to the data driver only to perform column inversion, which requires both plus and minus video inputs.)

Table 2: Rear-Projector Specifications

Display size	60-in. diagonal
Number of pixels	1280 × 1024 (1.3 million)
Luminance	960 cd/m^2
Contrast ratio	300:1
Size	1479 × 1447 × 660 mm
Light source	370-W metal-halide lamp

Performance

The panel delivers excellent video performance (Table 1), and has been incorporated in a prototype 60-in. HDTV rear projector (Fig. 4). The projector contains three of the continuous-grain-silicon TFT-LCD panels. The resulting luminance of 960 cd/m^2 and contrast ratio of 300:1 are sufficient for a consumer television receiver (Table 2).

Given the successful development of continuous-grain silicon up to this point, we can expect the application of this technology to digital TV systems. ■


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Manufacturing Cost Structures Provide the Key to the Electronic-Display Market

What display applications can support the manufacturing investments and materials costs for flat-panel displays? Are there any?

by David E. Mentley

THE GLOBAL FLAT-PANEL-DISPLAY (FPD) industry now satisfies a $14 billion electronic-component market, but the economic characteristics of this market defy most conventional analyses. Building the market has come at an investment cost of over $10 billion just for the active-matrix liquid-crystal display (AMLCD) alone, but that is not bad, nor is it troubling. There is no question that there will be a long-term market for electronic displays. But there *is* a question, and it's a serious one: Can end-use demand for display components support such investments?

The growth potential of FPDs is intimately tied to the cost structures of future displays, both cathode-ray tubes (CRTs) and flat panels. Drastic price drops in thin-film-transistor LCD (TFT-LCD) panels for computer applications have brought these issues to the forefront.

Notebooks Justified LCDs

From the point of view of rational financial analysis, the FPD industry could not have arrived where it is today without the convergence of a unique set of circumstances. There is and never has been a larger and more important market for FPDs than the notebook-computer market. This 15–20 million unit market is critically important because the value supplied by an FPD is a significant part of the value of the notebook computer. There is no appropriate substitute for an FPD in a notebook computer.

It has been possible to support display costs by the price and cost structure that has developed in the component and system markets. More important, the computer industry provided the incentive in the early 1990s for ambitious display developers to invest billions of dollars in research and production capacity. The free-spending mood of many giant Asian electronics companies also fueled the development engine. The goal was to capture a large part of the billions of dollars of revenue that would flow in the future.

The TV market would not and could not provide this incentive. TV-receiver prices could not support development of an expensive and risky technology, and profits have

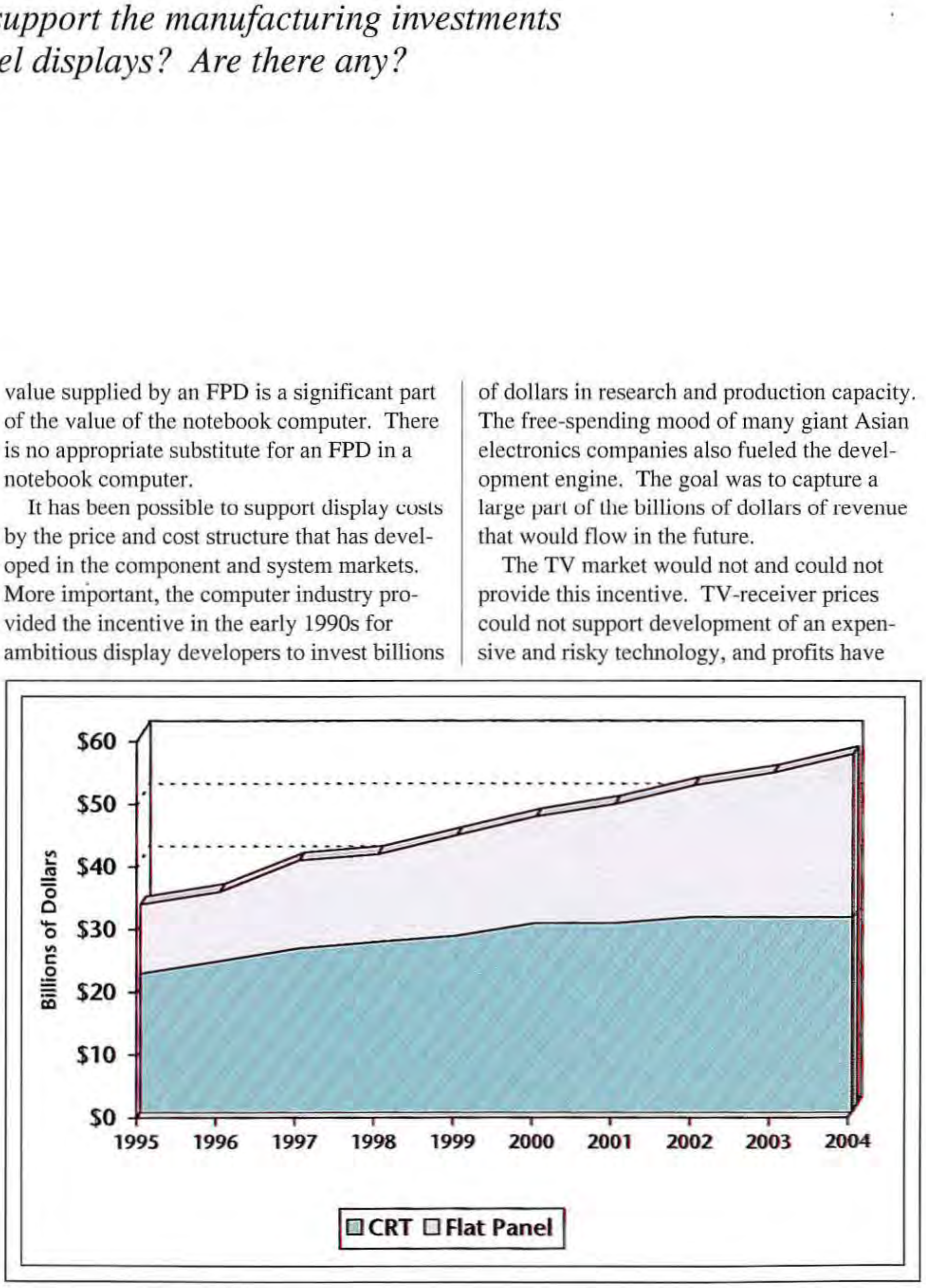

Fig. 1: The global CRT TV and monitor markets were roughly 150 million units ($15 billion) and 86 million units ($12 billion), respectively, in 1998, for a total of $27 billion. This compares with $14 billion for FPDs. (Source: Stanford Resources' Flat Information Displays 1998*)*

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Table 1: Value of LCD Market (millions of dollars)

	1996	1997	1998
Portable Computers	$5079	$7262	$5979
Total, All Applications	$9879	$12,817	$12,253

Source: Stanford Resources, Inc.

been elusive in the TV business. The computer-monitor market could not help either: prices for monitors have dropped steadily and have left manufacturers with erratic profits. Without the notebook-computer market, high-resolution FPDs would have remained very expensive and limited to low-volume military and industrial applications.

But computer manufacturers have gleefully been taking advantage of price competition and are reducing the price premiums that they traditionally paid to LCD manufacturers. As a result, the portable-computer application as a share of the overall demand for LCDs is declining. In one sense, this is not surprising because the industry is heavily reliant on the notebook-computer industry for most of its revenue. Table 1 compares the market value of LCDs for portable computers to the total LCD market for the past few years. In 1996, portable computers represented 51% of the total value of the LCD market; in 1997, they represented 57%. After the "market correction" of 1998, they will fall to 49% of the market.

Intense price pressure has filtered down to every component supplier in the notebook-computer industry. LCD suppliers that focused on making notebook-computer screens were faced with the choice of meeting the demand for irrationally low prices or giving the business to another eager supplier.

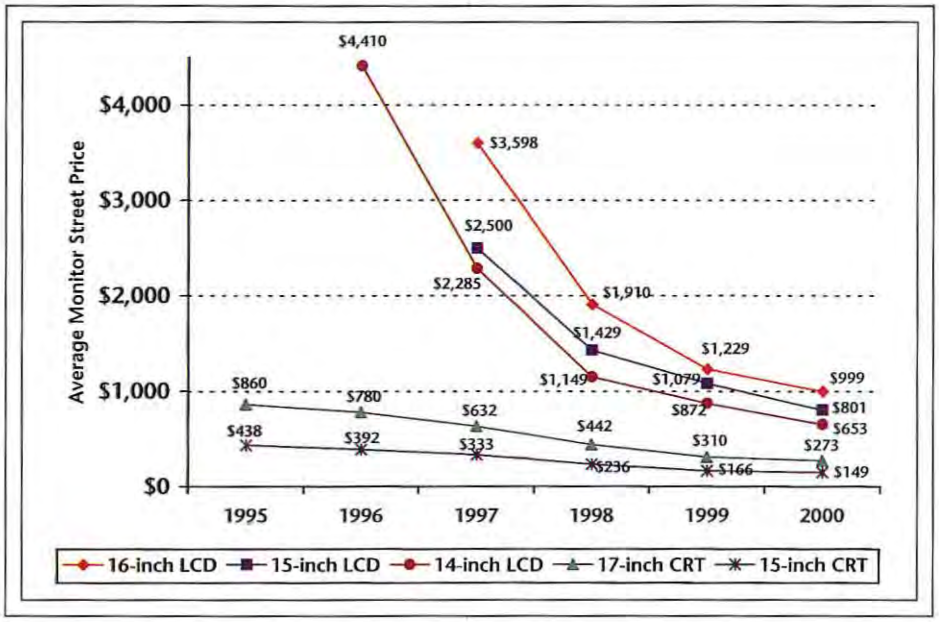

Fig. 2: The average street price of a 17-in. CRT monitor has dropped from $860 in 1995 to $442 in 1998, and will continue dropping to $273 in 2000, which leads to a set of hard questions for LCD monitors. (Source: Stanford Resources' Flat Information Displays 1998*)*

The key problem facing the FPD industry is that no high-value market similar to notebook computers has been identified for the near- or mid-term. This has forced display vendors to search for the next big market, which they have identified as the desktop monitor. While the worldwide desktop-monitor market is much larger than the notebook-computer market in terms of units, the CRT is proving to be a formidable competitor in every conceivable way. CRT-based computer monitors have been increasing in screen size and performance while decreasing in price. CRT monitors are also lasting much longer, reducing the size of the replacement market.

The desktop-monitor market is clearly dominated by the descendant of the color-CRT technology developed in the 1940s in the U.S., Europe, and Japan for television displays. The largest markets for CRTs are now television and monitors, at roughly 150 million and 86 million units, respectively, in 1998. These markets are worth approximately $15 billion and $12 billion (for a total of $27 billion) globally in 1998, which compares with $14 billion for FPDs (Fig. 1).

The average street price of a 17-in. CRT monitor has dropped from $860 in 1995 to $442 in 1998, and will continue dropping to $273 in 2000. The average street-price trends for LCD and CRT monitors lead to a set of hard questions (Fig. 2). First, economically speaking, is the TFT-LCD an appropriate technology to address the desktop-monitor market?

More specifically, can the current materials, overhead, and infrastructure set-up in the LCD industry take the business to the next level? Or are there other FPD technologies that might do the job better and cheaper?

Table 2: Factory Prices for Popular Displays

	1995	1996	1997	1998
14-in. Notebook-Computer LCD	- - -	- - -	$1050	$560
14-in. Monitor LCD (module)	$1870	$1647	$1308	$607
15-in. Monitor LCD (module)	$2536	$1856	$1500	$710
17-in. Monitor CRT (CDT)	$262	$230	$185	$95
15-in. Monitor CRT (CDT)	$145	$130	$85	$44
19-in. TV CRT (CPT)	$80	$75	$65	$55
27-in. TV CRT (CPT)	$170	$160	$155	$145

Display Cost Structures

The manufacturing cost of FPDs is the most important issue facing the new FPD market, and these manufacturing costs can no longer be examined in a vacuum. They must be scrutinized in light of competition from the CRT and the price/cost/spending patterns that have

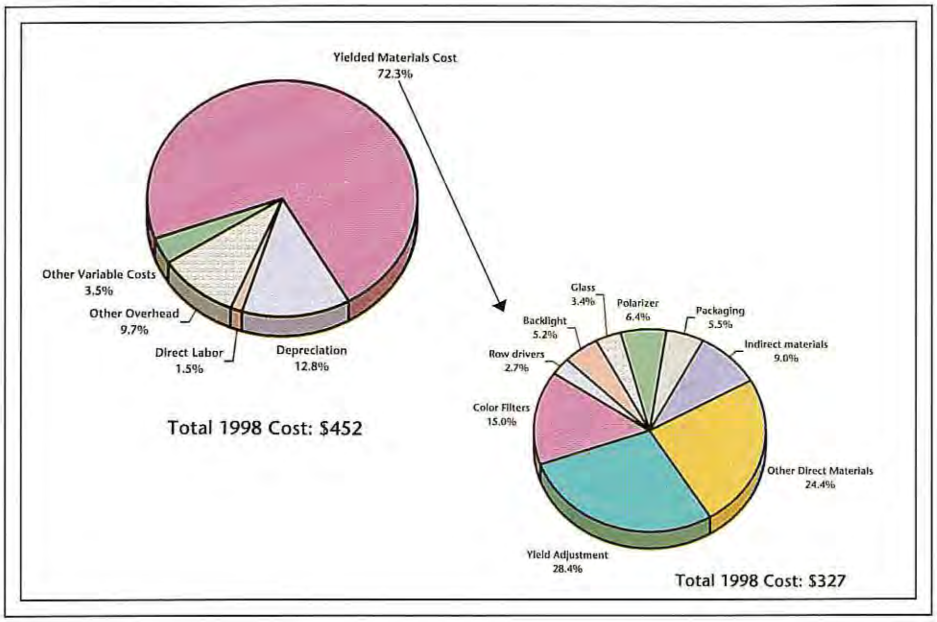

Fig. 3: Yield and throughput are certainly issues, but even for a 15-in. AMLCD monitor module produced in moderate volume, materials account for 72% of the fully burdened cost. (Source: Stanford Resources' Flat Panel Manufacturing Cost Analysis 1998*)*

become ingrained in the marketplace. Is there a chance for the most widely manufactured FPD - the AMLCD - to compete head on with the CRT in all markets? By extrapolating the current cost structures and component cost trends, it becomes clear that some kind of punctuated equilibrium is needed to bring the FPD in line with the CRT.

The AMLCD - as it is currently designed and manufactured - is a good match to the desktop-monitor market in terms of performance and technical specifications. (A 15-in. AMLCD monitor can be compared to a 17-in. CRT monitor for the purposes of analysis.)

CRT costs have been driven down by many decades of manufacturing experience, along with clever engineering and squeezing component suppliers so that the cost of each component approaches the materials cost. The extreme case is the standard (flat, square) 17-in. CRT monitor (Table 2). Current pricing is below $100, with major materials costs accounting for about 62% of this price. Overhead and other variable costs make up the difference, but leave no margin for profit in today's market. This same tube was priced at $262 in 1995. While this is an extreme case of price erosion in a decidedly dysfunctional market, it directly affects the future of the FPD market.

Stanford Resources has a set of interactive cost display models that provide tools for examining current and future manufacturing costs. The TFT-LCD as it is currently manufactured is heavily weighed down by materials costs. Unlike the situation in the early manufacturing days, yield losses and depreciation are not major cost elements in today's high-volume display operations. For new high-information-content large-diagonal AMLCDs, yield and throughput are certainly issues, but even for a 15-in. AMLCD produced in moderate volume, materials account for 72% of the fully burdened cost (Fig. 3).

The major problem with the current AMLCD structure is that it contains an unwieldy number of direct and indirect materials. The five major materials - column drivers, color filters, row drivers, backlight, and glass - account for about two-thirds of the unyielded materials costs. But the packaging, passive and active components, interconnects, sealant, liquid crystal, polarizer, passivation layer, spacers, gases, targets, solvents, photoresist, and others make up another third. AMLCDs are very materials-intensive products.

Extrapolating the costs of a 15-in. 1024 × 768 monitor-grade module to the year 2002 shows that the total cost of goods will decline to $340 (Fig. 4). This extrapolation is made using aggressive year-to-year component price reductions, but with the same set of materials and processes that are in production

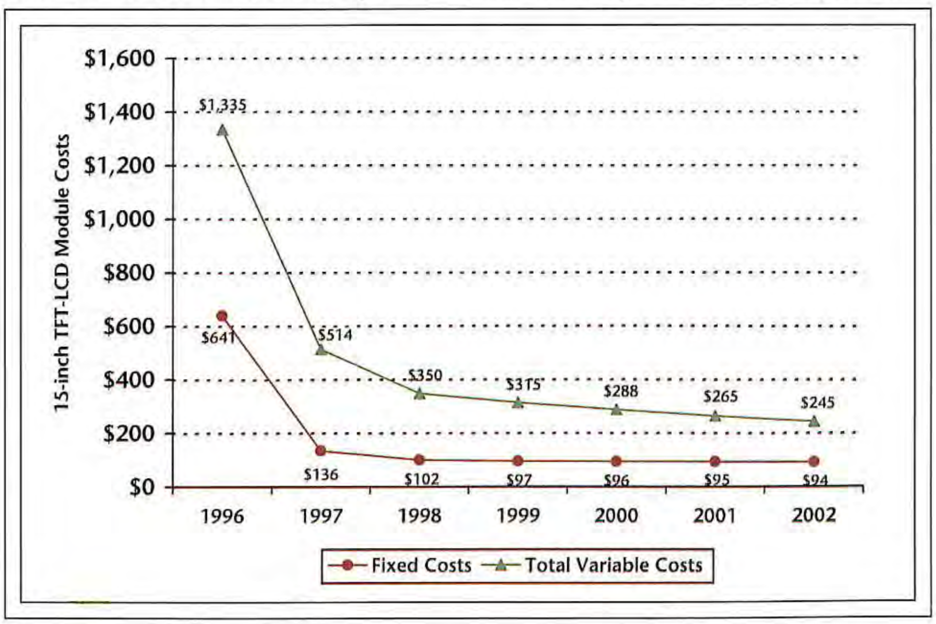

Fig. 4: The total cost of goods of a 15-in. 1024 × 768 monitor-grade module may decline to as little as $340 in 2002, which is still not low enough to make the AMLCD a viable competitor to the CRT in the desktop-monitor market. (Source: Stanford Resources' Flat Panel Manufacturing Cost Analysis 1998*)*

Table 3: Factory Price per Square Inch for Popular Displays

	1995	1996	1997	1998
14-in. Notebook-Computer LCD	- - -	- - -	$11.17	$5.96
14-in. Monitor LCD Module	$19.89	$17.52	$13.91	$6.46
15-in. Monitor LCD Module	$23.48	$17.19	$13.89	$6.57
17-in. Monitor CRT (CDT)	$2.11	$1.85	$1.49	$0.77
15-in. Monitor CRT (CDT)	$1.67	$1.49	$0.98	$0.50
19-in. TV CRT (CPT)	$0.46	$0.43	$0.38	$0.32
27-in. TV CRT (CPT)	$0.49	$0.46	$0.44	$0.41

today. Clearly, this approach will not lead to a viable competitor to the CRT in the desktop-monitor market.

Analysis

Because of the dynamics of the display industry, we must look at costs on the basis of both unit display area and application. The notebook-computer market supported high unit-area prices for high-value FPDs, and unit prices varied only by small amounts. Now that the computer-monitor market is within consideration – and eventually the consumer market – the area and prices must be factored in together. The monitor and television markets will not support the same price per square inch as the notebook-computer market. The consumer market, in turn, will not support the prices that the computer-monitor market provides. Costs must be adjusted accordingly if the FPD market is to continue growing.

Prices of CRT displays for monitors and television are still an order of magnitude less than for the most cost-effective FPD on a unit-area basis. Table 3 shows that the factory price per square inch of a CRT monitor ranges from $0.50 to $0.77 and a TV display ranges from $0.32 to $0.41. In the spirit of convergence of the TV and computer, it is interesting to note that the unit-area price of the 15-in. color display tube (CDT) is approaching the price of a 27-in. color picture tube (CPT).

Meanwhile, the factory price of AMLCDs has dropped from around $14 per square inch in 1997 to $6.50 per square inch. (These are market prices for finished components and may or may not include profit.) Aggressive cost reduction of current materials and processes for AMLCDs will take the unit-area cost to below $4 in 2002. This is still not good enough to address more than the high-performance portion – the top 5–10% – of the entire monitor market.

We would argue that the TFT-LCD is a highly successful technical achievement that competes on nearly every level of performance with the CRT monitor. There is no real competition for the notebook-computer application. For the desktop-monitor market, which is approaching 100 million units per year, the economics are not yet working.

Prices rarely go up once they are down, and screen sizes for monitors continue to increase. The manufacturing archetype must change if FPDs are to compete directly across all applications. This will involve new architectures, materials, processes, and equipment. ■

A Plasma World

Despite a delayed start, leading members of Japan's PDP community believe that plasma will replace CRT rear projectors – and soon.

by Ken Werner

IN MID-NOVEMBER OF LAST YEAR, I joined my friend and colleague Terutoshi Sato, Editor-in-Chief of *FPD Intelligence* magazine, on a two-day trip to visit executives in the plasma-display-panel (PDP) operations at NEC and Mitsubishi. Our interviews were supplemented by a brief conversation with Tutae Shinoda, Fujitsu's senior PDP designer.

In extensive interviews, the NEC and Mitsubishi executives were straightforward concerning technical challenges, optimistic (perhaps a little too optimistic) about product and marketing opportunities, and quite open in answering the questions Sato and I asked. The interviews provide interesting insights into where PDP technology and the PDP business is likely to go.

Although these comments were made a year ago, technological improvements since then have been evolutionary and product introductions have taken longer than anticipated. As a result, developments during the intervening months do not demand that the reader make too many mental adjustments, and we will provide some helpful comments along the way.

November 17, 1997
Kawasaki, Japan
NEC Color PDP Business Promotion Division

Attending: Michihiro Ota, General Manager (Fig. 1); Yasuo Akatsuka, Chief Manager, Product Development; Yōichi Kadota, Senior Manager; Terutoshi Sato, Editor-in-Chief, *FPD Intelligence*; Ken Werner, Editor, *Information Display.*

Ota: The 42-in. PDP is the main product produced in Kawasaki. We intend to produce 10,000 sets this year. *(Note: Given the slower-than-anticipated ramp-up among all manufacturers, it is unlikely that 10,000 sets were produced by the end of 1997 – KIW.)* NEC is building a factory (NEC Kagoshima) on Kyushu Island to begin producing for the world market in 1998. The factory will produce 10,000 PDPs per month in the future.

NEC is producing a 33-in. panel with a 4:3 aspect ratio and a 42-in. with a 16:9 ratio this year. A 50-in. HDTV is being developed, and will be produced here in Kawasaki starting next year (Fig. 2). *(Note: The 50-in. PDP was introduced that evening at an elegant reception in the penthouse suite of NEC's "Super Tower" headquarters in Tokyo's Shinagawa district. – KIW)*

NEC is planning 40–60-in. panels for next year, and is looking at 100-in. glass for the long term. "My dream - a 100-in. panel," said Ota directly to me in English, bypassing his skillful interpreter, Aston Bridgeman, who is Assistant Manager of NEC's Public Relations Division.

Question: Are there opportunities for American and European companies to provide manufacturing equipment for NEC's PDP manufacturing lines?

Akatsuka: We make some manufacturing equipment in-house, but obtain it mainly from outside companies in Japan.

The process for producing a large high-definition display without defects is challenging. What kind of process should we use to produce this kind of panel with low cost? We need big equipment for PDP manufacturing, so we need a big building for the production line (Fig. 3). We must therefore consider how to design a factory that makes effective use of floor space. This is a consideration for manufacturing-facility design that is unique to PDPs.

Question: Do you have plans to manufacture in the U.S.?

NEC

Fig. 1: *Michihiro Ota, General Manager of NEC's Color PDP Business Promotion Division in Kawasaki, Japan, outlined aspects of NEC's plasma strategy for* Information Display.

Ken Werner is the editor of Information Display Magazine.

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NEC

Fig. 2: *NEC's 50-in. HiVision Plasma TV with capsulated color filters (CCFs) was introduced in Japan in November 1997.*

Ota: There are no plans to manufacture in U.S. But I would like to return to the previous question. Although we are satisfied with our Japanese resources for manufacturing equipment in general, there could be an opportunity in the area of e-beam lithography. We have had low-level contacts with a North American company that might be able to help us, and there is an awareness of possible interest.

Question: What do you see as the most critical technical issues confronting PDP development?

Ota: First is luminous efficiency at decreasing cell size. NEC is working on doubling and tripling the luminance of cells. Second is materials. And third is increasing the low duty factor when the cell is on. NEC Kansai is working very hard on this issue, and I think other companies have not worked so hard on that.

We have two broad objectives: large size with high definition, and economy. Photolithography should help all of these. There will be a great deal of photolithographic development as we move into the future, which will help us get the price of a TV receiver to ¥10,000 per inch by the year 2000.

Question: What about all the capacity going on line? Will product be pushed or capacity not be used?

Ota: We can't afford to have prices plummet, but price does need to decrease. So the market needs to be created and production must be managed. This is not a race to market or an attempt to control the market. After 2000, we see the market for PDP TV becoming a mass market.

Question: Will PDP's competition be CRT rear projection or another technology?

Ota: CRT rear projection *is* a competing technology but does not have the picture quality PDP offers. However, if CRT rear projection has a competitive price it could stay in the running. We will have to wait until after 2000 for the final answer.

Question: What are your strategies for reducing driver cost?

Ota: Drivers account for a considerable part of the cost, so we've been looking for approaches. We are pursuing three main approaches:

1. Reduce the cost of ICs, in part through cooperating with NEC's semiconductor group.
2. Ride the experience curve. Cost will go down as quantity goes up.
3. Bring down driver voltage.

Question: To bring down voltage, must one increase the mechanical precision with which the panel is made?

NEC

Fig. 3: *NEC color PDPs roll down the line at NEC's Tomagawa plant.*

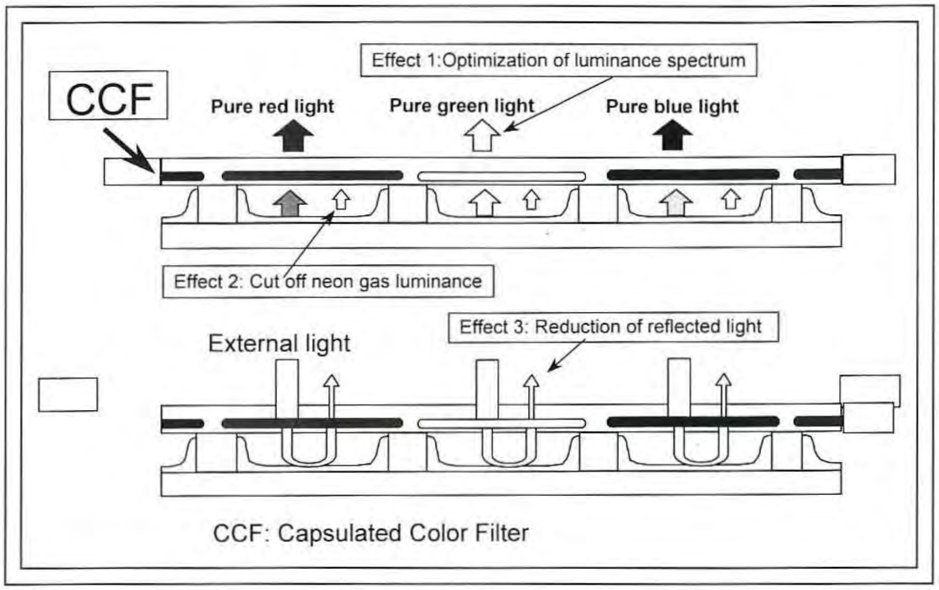

Fig. 4: NEC's capsulated-color-filter (CCF) approach puts a red filter in front of each red sub-pixel, a blue filter in front of each blue sub-pixel, and a green filter in front of each green sub-pixel. The CCF optimizes the spectrum from each sub-pixel, cuts the unwanted luminance from the neon gas in each cell, and reduces reflected light. This results in more vibrant colors and a wider color gamut.

Ota: It comes down to innovating the cell structure and making the cells brighter. This includes innovating with materials, including the gas mixture. Of the possible material innovations, we can talk about gas. Helium, neon, and xenon are now used. The ratios of the gases might change, or we might do away with the helium or add another gas.

Question: What else would you like *Information Display*'s readers to know?

Ota: I believe rear projection will be eliminated from the market. PDP offers superior picture quality. I believe it will be a PDP world. But we must show colors that are as good as a CRT's. That's why we've developed the capsulated color filter (CCF), which is in our current product and will be used in all of our PDP products (Fig. 4).

Sato: Is it any more expensive to use CCF?

Ota: There is no difference. We need to make sure that using new technologies does not add to cost.

Question: What are your current manufacturing yields?

Ota: We are looking for a 100% yield. Yields have come up a lot and are quite high now. They have gone from 50% to close to 80%. We must work on microprocessors to get 100% yield.

Question: What U.S. market size would justify a U.S. assembly plant?

Ota: Thirty to fifty thousand units per month would get us thinking seriously about it. We must look at the logistics [shipping, warehousing] *vs.* the costs of selling from Japan. Storing a lot of 50-in. displays is not a trivial cost. And it's hard to procure materials overseas, although the situation is improving.

Question: Are you primarily interested in module business or a finished-product business?

Ota: We are looking at both the OEM and finished monitor/receiver markets. The module business will be greater in terms of units, but perhaps not in terms of revenues.

Question: Do you see the most popular configuration for monitors and receivers being hang-on-the-wall or stand-on-the-table?

Ota: We're seriously looking at wall-hanging TV. We must make it slim and reduce the weight. Weight is the big concern and we're making major efforts, primarily by getting weight out of the glass. We want to make it light enough to carry around. A TV should not have to be in a fixed location. We should have a TV that we can watch when and how we wish. On the ceiling!

Akatsuka: Make it cable-less.

Question: When will your 50-in. TV be available commercially?

Mitsubishi

Fig. 5: Mitsubishi is making its 40-in. color PDPs at this facility in Nagaokakyo City, Kyoto.

Akatsuka: The 50-in. TV receiver will go on sale in Japan for the Nagano Olympics, and in the spring of 1998 in the U.S. NEC is looking at PDPs for 30-in. screens and larger. For sizes in the 20s, LCDs look good.

On to Kyoto

The next morning, Sato and I left Tokyo station for Kyoto on the New Tokaido Line. Kyoto, the medieval capital of Japan, is one of the country's most beautiful cities, with over 200 Shinto shrines, 1600 temples, three imperial palaces, nine museums, and innumerable gardens. I saw none of them, as Mitsubishi Electric Corporation's PDP Business Center is in an industrial suburb of Kyoto called Nagaokakyo City.

November 18, 1997
Nagaokakyo City, Kyoto
Mitsubishi Electric Corp.
PDP Business Center

Attending: Kanzou Yoshikawa, Project Manager, Engineering Project Group; Koji Murata, Manager, Sales and Marketing Section; Yutaka Imura, First Group Manager, Development Project Group; Terutoshi Sato, Editor-in-Chief, *FPD Intelligence*; Ken Werner, Editor, *Information Display.*

Yoshikawa: Here in Kyoto we make 40-in. CRTs and much audio and video equipment, including projection CRT sets.

The Mitsubishi team showed Sato and me part of the PDP plant (Fig. 5). In a demonstration area, there was a photomicrograph of the barrier ribs, which were made with a nine-step screen-printing process. The contours were very smooth, with the width constant to ±10%. The black matrix was applied to the front panel. We were told that photolithography was to be used on the forthcoming HDTV panel.

Sato: Will you use sandblasting?

Murata: A sandblasting machine is useful for high-quality images on a PDP, but there are only a few in our factory. We are trying many methods for PDP process technology now. *(Note: The following statements from the Mitsubishi team were made mostly by Koji Murata, who seemed to be the team member most comfortable with spoken English. The comments were sometimes made after a brief consultation with his colleagues.)*

Mitsubishi is making a 40-in. 4:3 PDP now (November 1997) (Fig. 6), and we will be making a 46-in. 16:9 HDTV (summer 1998).

Mitsubishi

Fig. 6: Mitsubishi was making this 40-in. 4:3 PDP in November 1997. An updated model, the Leonardo, is now commercially available in North America.

We will focus on the domestic (Japanese) TV market first. Our current display is 480 lines, corresponding to NTSC.

Yoshikawa: And we are currently developing a 40-in. XGA monitor.

Murata: We are planning the assembly of 40-in. panels into TV sets in the U.S. the beginning of next year in Georgia and California. Everything is moving more slowly in plasma than was anticipated a year ago. *(Note: And it continued to move more slowly than anticipated for all manufacturers. However, an updated model of Mitsubishi's 40-in. 4:3 PDP, the Leonardo, is now commercially available in North America.)*

The current price for a 40-in. set is about ¥1,000,000, so we are focusing on industrial presentation monitors for conference rooms and public information displays first. A substantial consumer market is 2–3 years off.

Displays with 55-in. glass can be made now but not for mass production. Sixty inches is probably the maximum in this century. It is not possible to do more.

Question: In what ways do you intend to lower the price of PDPs?

Murata: We need to increase the luminous efficiency from the 1.0–1.5 lm/W it is today. We must go to 2–3 lm/W within a couple of years to lower power consumption. This can be done in 2–3 years. At the same time, we must lower the driving voltage for lower driver cost.

Question: What approaches can you take to increase the efficiency?

Murata: Many things can be done, including increasing the optical opening to the cell and improving the phosphor itself. "Phosphor and phosphor and phosphor" will be a problem.

Magnesium oxide is also an area of interest. MgO deposition time is not a major problem. MgO printing is being investigated but I don't think it will save much cost.

Question: Is Mitsubishi interested primarily in manufacturing for its own end-user products or in producing modules for OEMs as Fujitsu does?

Murata: We are focusing on our own-brand business first. Mitsubishi's position in TV in the U.S. is very good, and we think our own-brand PDP TV will fit in well. Korean makers have proposed technical cooperation, but we're not agreeing to do that yet.

Question: Since Mitsubishi will be approaching the large-screen TV market with both CRT projection TVs and PDP direct-view TVs, how do you see the market dividing between them? Perhaps by size in the 46–52-in. range?

Murata: Viewing angle is limited, and there are issues with depth, weight, and phosphors with projection TV. PDP is much better in those areas. We don't know how it will break down yet.

Yoshikawa: These two technologies will conflict to a certain extent.

Question: So you don't see plasma wiping out projection TV?

Yoshikawa: I hope so.

A Brief Conversation in Nagoya

Atypically for a Japanese city, Nagoya has broad streets that run in straight lines and meet at right angles. This is a result of American firebombing in World War II that virtually destroyed the old city and required it to be rebuilt from scratch. With great delicacy, this tragic period of the city's history is mentioned only fleetingly and indirectly in tourist literature prepared by the local tourism authority. Nagoya is now a vibrant and modern commercial center.

Sato and I travelled by train to Nagoya from Kyoto to attend the Fourth International Display Workshops (IDW). On the afternoon of the following day, I found myself in a coffee-break conversation with Tutae Shinoda, the designer of Fujitsu's original color PDP, and Roger Stewart of Sarnoff Corp.

November 19, 1997
IDW in Nagoya
Conversation with Tutae Shinoda, Research Fellow, Peripheral Systems Laboratories, Fujitsu Laboratories, Ltd., Akashi, Japan.

(Note: In the late summer of 1998, Fujitsu was widely reported to be manufacturing about 7000 color PDPs per month, far more than any other manufacturer. Many of these panels were being shipped to OEMs such as QFTV, Clarity Visual Systems, and CTX Opto for integration into monitors bearing the OEMs' logos.)

Question: Do you think that PDPs will be the dominant large-screen display? Do you feel that plasma-addressed liquid crystal (PALC) will offer serious competition?

Shinoda: The hardest part of making a PDP is the barrier ribs. PALC must do much the same and then add an LCD. I hear that it's difficult and slow to fill an LCD that large, so I don't see how PALC can compete on price and viewing angle.

The image quality of PDP is much better than CRT rear projection and somewhat better than LCD rear projection because mirrors, lenses, and the cover plate degrade the image.

Question: What about PDP's motion artifacts?

Shinoda: PDP motion artifacts are mostly solved. The only real problem *vs.* rear-projection TV is luminous efficiency. A 7- in. CRT puts out 130 ANSI lumens. The new LCD projectors are putting out about 1000 lm so they can widen viewing angle and decrease screen gain relative to CRT projectors. CRT projectors will go away in 2–4 years. ■

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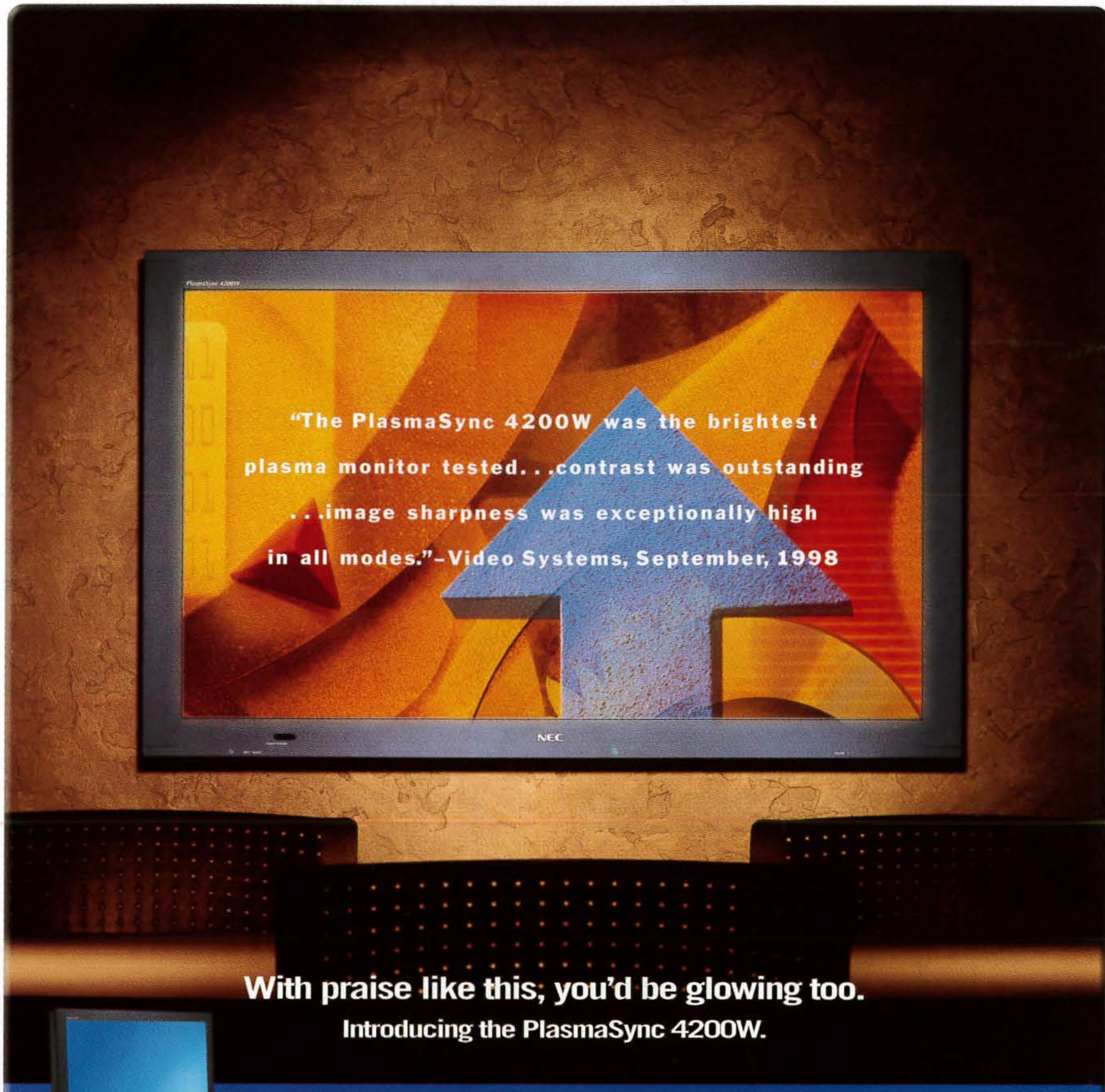
"The PlasmaSync 4200W was the brightest
plasma monitor tested. . .contrast was outstanding
. . .image sharpness was exceptionally high
in all modes."-Video Systems, September, 1998
NEC
With praise like this, you'd be glowing too.
Introducing the PlasmaSync 4200W.
Boardroom visitors, airport travelers, industry experts—there's no telling who the new PlasmaSync™ 4200W will impress next. Thanks to our unique Capsulated Color Filter™ technology, the 42-inch, 16:9 screen produces vibrant, realistic colors, fine detail and excellent contrast. The PlasmaSync 4200W gives you the flexibility you need, too—it's equally at home with computer, conventional video and HD video sources. Finally, we've fit all this performance in a cabinet that's just 3.5-inches deep—40% thinner than its main competitor. Call today to demo the PlasmaSync 4200W, or its equally impressive sibling, the 33-inch PlasmaSync 3300. Because while the PlasmaSync 4200W may look good in print, you haven't seen anything until you've experienced it in living color.
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continued from page 4

Sunday drive or for a shortcut to the hardware store are now high-traffic routes that the new residents use to get to work and to their newly created shopping malls.

For those living a few more miles away, all is still serene and the change is hardly apparent. In fact, these folks may see the newly constructed and now more convenient shopping opportunities as a nice and as yet unobtrusive benefit.

For those on the older and more urban side, the changes are also less immediately noticeable. Their little space on this planet was already nicely defined, although now their parcels seem to have acquired considerable additional value, with the accompanying increases in property taxes. What was once perhaps an area of modest lakefront summer cottages has now become property worthy of the eager attention of millionaires. And now with each change of ownership, there is extensive upgrading or at least incremental improvement. The increasing value of the land demands it.

After my adrenaline-producing encounter with the dump trucks, the rest of my day seemed peaceful by comparison. Sending e-mails and returning phone calls seldom has the "instant thrill" of staring into the headlights of an oncoming truck. And although that truck didn't leave a physical impression on me or my car, it did end up giving me something to think about.

During one of my phone calls to the East Coast, the person on the other end, knowing of my frequent travels, asked where I was calling from. He said that he couldn't tell from the quality of the sound if it was long distance or local. How about that? A major technology change has gradually taken place and we've hardly noticed. It wasn't too many years ago that we could tell immediately if the call sounded local or long distance. Sometimes, it took several tries to communicate at all. Now, I can only tell (most of the time) when calling to some of the countries in Eastern Europe or occasionally some parts of the Far East.

Out of curiosity, I looked up the data. Fiber optics now carries over 90% of transcontinental calls in the U.S., as compared to only 10% a decade ago. Yet, it was not much over a decade ago that everyone was talking and writing about the improvements that fiber optics was "someday soon" going to bring to telephone communications. However, there were also plenty of discussions about fiber connectors not being compatible with the harsh and dirty field environment of underground utilities and installation by unskilled workers not being possible. How could we expect these workers to use clean-room techniques while working in muddy trenches? The cost and difficulty of handling the optical fibers themselves were also major issues. But the benefits that were predicted in sound quality and bandwidth were also rather impressive. So, quietly and almost imperceptibly, the problems were solved and the work went on. Costs came down. The manufacturers worked with the installers and came up with interconnect technologies compatible with outdoor environments. Costs came down some more. The fiber manufacturers figured out how to make cable compatible with the underground installation rigors and rough handling. Reliability and installation ease improved. The incremental improvements and cumulative experience all added up to create the new telephone network that we have today. There was that initial "wave of change," followed by a decade of continuously improving implementation and the development of manufacturing technology.

If this model of a ***change wave,*** followed by a period of ***continuous improvement,*** represents the fundamental process of technology insertion into society, then there is much that we can learn about how any new technology gets to market and who eventually creates the successful businesses exploiting it. This model would suggest that ***the eventual benefits accrue to those who are best attuned to developing cost-effective manufacturing techniques and who understand and implement the processes of continuous improvement instead of to those who stake their future success on making the early technology demonstrations.***

Let's look at a few other examples.

- Good-quality VCRs are currently selling for just under $100. These are machines with full capability, including a remote control. It wasn't all that many years ago that the concept of a consumer VCR was thought to be virtually impossible. The precision required to fabricate the read and write heads and the tape transport mechanism were thought to be only possible in professional-grade machines costing in the vicinity of $100,000. The first consumer machines were, however, in the $1000 range. Gradually, and again almost imperceptibly, the costs came down while quality improved.
- Ink-jet printers, in the beginning, were of just barely adequate print quality for writing business letters and could only do monochrome. And the best color printers or copiers, using even the most sophisticated technology of the day, could do no better than a few colors with a "baked-on" look at a cost of many thousands of dollars for the printer and several dollars for each copy produced. Today's ink jets are approaching photographic quality in full color and are selling for well under $500. However, this

didn't happen without years of sustained effort. Industry leader Hewlett-Packard, for example, has spent over 15 years in ink development and currently employs about 100 chemists to continue the improvements and drive manufacturing costs down even further.

- Where are desktop- and laptop-computer prices going? Down. Performance levels are maturing and the day of the $200 computer (including display) that runs at 200 MHz is less than five years away. There won't be a need for too many GHz+ CPUs but there sure will be a lot of inexpensive 200–400-MHz ones.

In our own corner of the world, the display business is also driven by these same fundamental economic forces. Everyone would like that full-color sunlight-readable display for less than $10 per diagonal inch, or less than $20 each for full-color mini-displays. In our business, too, any new technology introduction is like the ***wave of change***, followed by the decades-long process of driving down manufacturing costs and achieving market recognition. The original technology innovation is only the entry ticket. The business growth and profitability comes from the ability to meet consumers' seemingly unrealistic expectations for ever-lower-priced products. In the display business, the CRT, with its one hundred years of development history, is continuing to set the price targets. The other technologies must present unique performance advantages ***and*** come close – or perhaps even do better – in manufacturing cost in order to succeed.

LCD technology has evolved as the strongest challenger to the CRT. LCDs achieved this competitive viability only because of the introduction and subsequent popularity of laptop computers. The laptop computer allowed LCD technology to enter a volume market, even though in the beginning it was a display with marginal performance. However, LCDs facilitated the presentation of images that were good enough for the commercialization of the laptop computer to be attempted. For all the inadequacies, there was no other way to do it. Not having any alternatives gave LC technology a way to get cost-effective volume manufacturing established.

A similar but not quite as favorable situation exists today for plasma panels. They are the only large hang-on-the-wall displays. Rear projectors are somewhat viable competitors, but up to now haven't had the brightness or image quality, and they are considerably bulkier. How much more will consumers be willing to pay for plasma's thinness and better image quality compared to rear or front projectors, which have recently begun to show significant improvements?

With this as our experience base, can we look ahead and assess the potential success of new or still-to-be-invented display technologies? What about the oft-heard concept of "leapfrog" technologies? Without abusing our land-development analogy too terribly, it seems to me that the leapfrog concept would have a parallel to the land speculators who buy up large chunks of remote country property and promise to build vibrant new cities miles from anywhere. It may sound great in the sales brochures, but without the ability to rely on an existing support base and to allow the continuous improvements to happen in support of the new developments, financial failure is the typical outcome.

I would conclude that there are three fundamentals that must guide any new display business. ***First, if the business is based on a new technology, then we must be clear about what unique problem this new approach is going to solve that can't be solved with any of the existing display technologies. Second, how much more are customers going to be asked to pay for this promised improvement, and are they likely to be willing to do that? Finally, does the technology have the future potential for continuing manufacturing improvements and cost reductions to meet customers' never-exceeded expectations for lower-cost and higher-performance displays?***

New display technologies are what many of us spend our careers developing. I'm sure that I have about as much fun doing this as any of the rest of you. However, every new display technology can't and shouldn't be converted into a sustainable business. Variety is good in displays, but a high price is seldom one of the desirable parameters. Some years ago, a colleague and I were grousing about a competitor who we thought was over-promoting a technology. After considerable wasted energy, my colleague finally came up with the "ultimate" curse that we could wish on our competitor, which then of course made us both feel much better: "May they get a really big order for the product they are promoting." We knew that since they hadn't paid much attention to manufacturing that would surely drive them into financial ruin. As it turned out, we didn't have to wait for that to happen. They managed to run out of Other People's Money (OPM) before that volume order ever materialized.

Should you wish to share any of your new-technology product development or manufacturing experiences with me, you may do so by e-mail at silzars@ibm.net, by fax at 425/557-8983, by telephone at 425/557-8850, or by the well-established post office at 22513 S.E. 47th Place, Issaquah, WA 98029. ■

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