1.0 Introduction

Electronic displays are one of the fastest-growing worldwide technologies. Once reserved for televisions and computers, and composed of large cathode-ray tubes (CRTs), displays have become ubiquitous and have taken many different forms. Flat-panel displays are overtaking the CRT and are being used in larger quantities for portable computers, a variety of handheld devices, desktop computers and televisions, as well as tiny microdisplays, which are being used in projection televisions, for near-eye applications, where a virtual screen is presented to the viewer. The world of displays is rapidly changing to meet the evolving needs of the electronic-device user.

2.0 Applications

The electronic-display device industry caters mainly for the automation and electronics appliance industries. Characteristic of OEM products, the growth of the display industry is directly linked to the demand trends in end-user markets. Display manufacturers, mainly concentrated in Japan and East Asian countries, account for over 80% of total display production.

The end-user market (which includes televisions, computers, mobile phones and other electronic automation products) is directly linked to the levels of economic development. This end-use market is concentrated in the US and the developed European countries. The Asia-Pacific region, with the highest population and improving standards of living and automation, presents an enormous future market.

During the 1990s, the electronic-display device industry was dominated by CRTs in terms of production volumes of and the number of players. The CRT, being the standard display used in televisions and PC monitors, enjoyed a large market. Although non-CRT displays led the CRT in production-value terms, the unit production was negligible in comparison.

Among the non-CRT displays, also known as flat-panel displays, the liquid-crystal display (LCD) posed an immediate threat to the CRT. With continuous refinement of its features, the LCD was seen as an alternative to CRT. The portable PC segment – the major end-market for the LCD – has also witnessed major growth. As LCDs became more sophisticated, they entered the CRT-
replacement market in desktops. Other display devices include the light-emitting-diode (LED) display, plasma display panel (PDP), microdisplay, light-emitting-polymer (LEP) display and organic light-emitting diodes (OLED) display. These product segments are relatively new, each offering new features that facilitate new product applications.

Within the flat-panel display market, demand has rapidly moved in favour of larger sizes and greater resolution screens (from VGA to SVGA and XGA). The establishment of complex fabrication facilities to manufacture these screens requires a significant amount of capital investment. The cost of constructing a new active-matrix LCD plant has been estimated at between US$350 million and US$600 million during the late nineties.

3.0 The Global Display Industry

Electronic display devices are enjoying impressive growth patterns which are expected to continue for a number of years. The electronic display device market in the United States, for example, is forecast to generate revenues worth US$145.75 billion by 2010 from a figure of $52.5 billion in 2000. Europe holds the largest share with almost 30% of the worldwide market; this is expected to reach US$40 billion by 2010. The major markets for the electronic display devices in Europe are the United Kingdom, Germany, France and Italy.

The industry comprises manufacturers who produce displays for captive use as well as the external market. Large electronics firms have the advantage of synergetic production of the components with end-use products manufactured by them. The industry also has companies that sell the display devices on a private or OEM/ODM (Original Equipment Manufacturer/Original Design Manufacturer) basis to their customers.

3.1 The UK Market

The UK is a key sales region in the European display device industry. While CRT is dominant on account of being the traditional display, regional manufacturers are actively involved in the development of newer displays.

Global Industry Analysts describes itself as a 'publisher of off-the-shelf market research’.¹ In a report it published in June 2004, it estimated the size of the market for electronic displays at US$3.6 billion in 2000 and forecast that it would grow at a rate of 9.6% to US$9 billion by 2010. The market-research company valued the CRT sector at US$1.75 billion in 2000 and forecast that it would grow to US$2.9 billion by 2010. The company estimated the expected compound annual growth rate (CAGR) for the PDP segment – which it forecast would increase by 26% between 2000 and 2010 – would overtake that for the CRT segment.

Conversely, it forecast that the LED segment would likely show sluggish growth during this period. It estimated market size at US$126 million in 2000 and forecast that it would reach US$213 million by 2010. The company forecast that the LCD segment, with a value it estimated at US$1.5 billion in 2000, would exhibit a high CAGR of 11% over the period, and reach US$4.3 billion by 2010.²

3.2 Market Drivers

Several driving forces are expected to have an impact on global growth of display materials over the coming years. They include:

- general economic recovery in all regions;
- continued support from government, industry and academia; and
- development of advanced materials

Economic recovery is necessary to keep business and consumers buying. There will certainly be no slow-down in display demand, but the capability to make and sell...
displays must be there. Support from companies, government programs and academic institutions is needed to develop advanced materials. The display-materials industry is economically competitive at this moment, but these driving forces are required to take it forward. Advanced materials will make it possible to manufacture displays that can be used in any product under any environmental condition. This will drive the materials market to new levels of performance.

4.2 Flat-panel Displays

Flat-panel displays (FPDs), initially introduced in the 1970s, are extensively used by the portable-computing and handheld-consumer-electronics industries for numerous applications including compact portable television screens, screens in notebook-size computers and viewfinders in camcorders. FPD technology is also greatly influencing the design and production of industrial, scientific and medical equipment, entertainment delivery, transportation control and a myriad of other systems.

The increasing demand for advanced FPDs for new types of products, and subsequently new market opportunities, has been attributed to their low power consumption as well as their light and thin design. Future FPDs are likely to be cheaper, more efficient, increasingly commonplace and more commercially available in numerous sizes.

The driving forces are expected to be laptop and notebook PCs coupled with new end-user sectors. These include consumers (of mobile phones, pagers, games machines, portable TVs and PDAs); transportation (military, avionics, and automotive); industrial (test equipment, instrument and dashboard displays); and business (medical-device displays, electronic files and portable projection systems).

According to a report from Business Communications Co. Inc., updated in 2003, the value of worldwide shipments of display materials reached $12 billion in 2002. The report estimated that the value of shipments of materials would reach $13.6 billion in 2003 and forecast that they would grow at an average annual growth rate (AAGR) of 10.9% to a total $22.9 billion by 2008.³

4.0 Market Demands and Expectations

Display devices have become a part of everyday life. These devices find applications in electronic gadgets used in daily life, such as digital watches, TVs, computers, mobile phones, PDAs, appliances, camcorder viewfinders and in the automotive sector. The display unit of all these items comes separately and, with the strong demand for this panel, the market is continuing to grow rapidly.

According to a report from Business Communications Co. Inc., updated in 2003, the value of worldwide shipments of display materials reached $12 billion in 2002. The report estimated that the value of shipments of materials would reach $13.6 billion in 2003 and forecast that they would grow at an average annual growth rate (AAGR) of 10.9% to a total $22.9 billion by 2008.³

4.1 Cathode-ray Tubes

CRTs had the largest market share in the electronic-display devices market in 2000. However, they are losing market share to other display devices and are soon expected to be overtaken by the LCD market. LCD prices have fallen in recent years, but the fall is not too drastic when compared to the fall in prices of LCD devices.

CRTs are more efficient than LCDs in terms of response speed, viewing angle, colour and temperature range, and are expected to be dominant in the TV and desktop market in the near future.

In the case of CRT projectors, these provide superior graphics resolution than LCD projectors and are better suited for medical and engineering applications. In the immediate future, CRTs are expected to maintain their dominant position. However, in the long run, the CRT can hold on to its present share only through improvements in the display quality and a reduction in power consumption.

Even though FPD monitors are costlier than their CRT counterparts, they are displacing CRTs in developed countries such as the US, Japan and several European nations. In developed countries, the value of desktop ‘real estate’ is greater than the difference in prices of the LCD and CRT monitors. And since FPDs save a lot of space...
they are preferred over CRTs. FPDs are also considered a status symbol. These factors combined are expected to drive up the demand for FPDs in coming years.

4.3 Liquid-crystal Displays

LCDs are the most widely used display panels, with wide ranging applications such as passive, dot-matrix desktop monitors, dot-matrix mobile-phone displays, full-colour, active-matrix desktop monitors and also the basic, monochrome, passive-matrix character displays used in watches. Among all the FPDs available, the liquid-crystal display is the most viable, and in the past 30 years has helped in the manufacture of many new products.

The market for liquid-crystal displays will be driven by the growing demand for computer monitors in coming years. The LCD’s share is around 10% of the current monitor market, which is around 100 million units. Some forecasters expect this to grow to 44% by 2006. The major challenge for manufacturers is keeping the price stable.

Even though LCDs are certainly very popular, they cannot be described as an ideal display panel. The liquid-crystal display works on the principle of light-modulation, meaning this technology has limited energy efficiency, restricted viewing angles and imperfect ambient-light viewing quality. The manufacturing costs of large LCDs are also high in comparison with other display technologies.

In newer display technologies, market-research forecasts see the market for OLED-display materials, including chemical compounds and polymers, growing at an average annual rate of 29% until 2008. Forecasters also foresee a market for components for new display technologies, such as MEMS-driven displays and those using carbon nanotubes, experiencing an average annual growth rate of 19% up to 2008.

5.0 Emerging Technologies

Technologically, the long-term outlook for Europe is good. Display makers and materials suppliers located in Europe are either involved in manufacturing or are engaged in joint ventures in other parts of the world. The headquarters of various key display-materials companies are also located in Europe; major ones include Merck (liquid crystal), Schott and Pilkington (glass), and Balzers (thin films). Judging by their production volumes companies, these companies have learned how to sell their products from a European base or operate joint ventures with companies in other regions of the world to their advantage.

The general economic conditions in Europe are not as favourable as they are in the display and other high-tech businesses. Problems adjusting to the Euro and the changing mixes of populations have hampered some of the economic progress of the 1990s. European companies have also been hurt by the large downturn in U.S. stocks over the past three years and the slow-down in tourism brought on by terrorism. Despite this, there are a number of key developments taking place in many display technologies.

5.1 Liquid-crystal Displays

Scientists from Eindhoven University of Technology and Philips have developed a new technique for producing LCDs – which can be ‘painted’ onto a single substrate – known as photo-enforced stratification (PES). This makes possible the development of larger and cheaper LCDs for use in applications as diverse as data displays in clothes and image-changing wall hangings.

The research group has been successful in fabricating a low-resolution LCD on a glass substrate using an isobornyl methacrylate monomer and the commonly used liquid crystal E7. They acknowledge the fact that more R&D is required before it is certain that the technique is a viable alternative to the present LCD production technology. The main challenge is to ensure that the substrate is equipped with the necessary electrodes prior to the application of the PES-LCD components, and also to compensate for lower contrast and brightness because of the presence of polymer boxes.

Growth in LCD and PDP devices is expected to be driven by the boom in PDP and LCD televisions markets. Demand for PDP and LCD televisions has grown in recent years, especially in Japan, Europe and the US due to increase in digital broadcasts and falling prices. According to one forecast, global demand for LCD television may exceed 5 million units by 2006. A fall in the cost of LCD devices has also fuelled the market expansion and, in the future, prices are expected to fall more drastically due to overcapacity and market competition.

CRT monitors contain over five pounds of lead and expose users to radiation. LCDs are better in these
respects. As their prices fall, they are beginning to replace CRTs and many expect their market to increase sharply.

Cash machines are also being transformed with the introduction of new display devices. CRTs have historically been used as standard display devices in these machines, but with the advent of LCDs and other technologies, they are becoming more and more sophisticated. This change is also driving the market for LCDs and other miscellaneous display devices.

5.2 Plasma Display Panels

The plasma display panel (PDP) is based on the principle of emission of light by phosphors. It provides superior colour range, a wider viewing angle and enhanced brightness by comparison with LCD displays. The display panels can be made as high as 60 inches.

The production cost of plasma display panels is very high but key upgrades and developments may help reduce the price. The price of several plasma TVs declined by about 30% in 2000 and is expected to further decline in coming years.

Plasma display panels were initially used for industrial and business-display purposes – at airports, for example, and in conferences. But the use of plasma technology for manufacturing television sets will provide the necessary thrust to the market for plasma display panels. PDPs generated revenues of approximately US$3 billion for the year 2003. One market-research company has predicted they will touch US$6 billion by the year 2006. If the cost of a plasma TV is reduced and the range widened, then the market for the product is likely to improve further.

5.3 Microdisplays (micro LCDs)

Microdisplays are very small devices gaining in popularity as head-mounted displays. One of their key advantages is that they help technical workers concentrate on doing skilled jobs that require total concentration whilst receiving instructions at the same time. Several display-technology manufacturers are collaborating with display makers to scale up their technology for further commercial use. Such collaborations are often international in scope, enabling a company that develops the technology to reach the markets of the display manufacturer.

One of Philips’ developments is the DD720 single-panel microdisplay, a 1.18-inch-diagonal active panel using LCOS technology, which is meant for next-generation large-screen television sets. The innovative panel system, apart from offering considerable cost benefits, also boasts an unparalleled contrast capability of 1000:1, a high refresh rate of 180 Hz as well as a high resolution level of 1280 x 768. Development of DD720 comprehensively substantiates the production viability of the LCOS technology, holding out the possibility of economical high-resolution TVs with remarkably thin form factors.

5.4 Light-emitting Polymers

It is widely acknowledged that LEPs have potential in the display market. LEPs generate their own light, eliminating the need for the backlight required in LCD displays. This makes them thinner and lighter, as well as more power-efficient. Additionally, LEP materials are plastics that can be dissolved in solvents that allow deposition using inkjet printing. This provides a potential manufacturing advantage that could significantly change the way displays are produced and open new markets and opportunities for lower-cost displays on flexible substrates that can conform to curved surfaces.

5.5 Carbon Nanotubes

Carbon nanotubes (CNTs) are tubes of carbon atoms of less than 1 nm diameter. They can be thought of as a sheet of graphite (a hexagonal lattice of carbon) rolled into a cylinder. Depending on the way the graphite sheet is rolled, a CNT can be either a metal or a semiconductor.

CNTs have a combination of unique properties that make them highly programmable for a variety of purposes, including flat-panel displays. For displays the most important property is their field-emission characteristics.

A field-emission display relies on electron emitters, arranged in a grid and individually controlled, to generate coloured light. With CNTs, which have a small tip radius and a high aspect ratio, it is possible for electrons emitted by one nanotube to hit the phosphors of just one pixel in the display. The advantages of this type of display over standard LCDs include lower power consumption, higher brightness, a wider viewing angle, faster response rate and a larger operating-temperature range, as well as lower cost.

Because of this potential, in addition to their chemical and mechanical stability, CNTs have attracted serious interest from the giants of the display industry. However, nanotube
displays are technically complex and there have been several problems to overcome such as growth of CNTs at low temperatures and bonding of the nanotubes to the display surface material.

5.6 OLEDs

OLED technology is considered extremely suitable for developing ultra-thin and flexible FPDs from carbon-based compounds. It also makes possible full-colour displays with a viewing quality far superior to that of the other technologies. The positive features that permit OLED displays to communicate more information in a more effective manner are as follows.

- Inherent self-luminosity, which LCDs do not have, helps eliminate the necessity for bulky backlights and polarizing filters when using the black layer
- A thinner and more compact, space-saving screen with a better viewing angle is possible.
- Low power consumption offers considerable advantages for portable applications and helps minimise heat and electronic interference.
- Response time is fast, almost a hundred times quicker than that of LCDs

OLED displays have been hailed as one of the most significant technologies to hit the modern PC market. They are also likely to replace LCDs in small- as well as medium-sized devices such as mobile phones, digital cameras, car instrument panels, PDAs and numerous other consumer-electronics products.

The revolutionary OLED is considered a form of leapfrog technology that offers affordable, reliable, thin-film, full-colour FPDs to consumers. These new displays may usher in full-coloured TV screens made of plastic sheets less than an eighth of an inch thick that can hang from the wall and be rolled up for storage after use.

6.0 Industrial Developments

Examples of some of the companies leading the field in display technologies around the world are now discussed.

6.1 Cambridge Display Technology

Cambridge Display Technology (CDT) announced that it has dramatically improved the life performance of display devices based on LEP technology. CDT has achieved more than 11,000 hours of operation, or almost a year and a half continuously, for its blue polymer research devices. According to a publication (March 2003) from the Minerals, Metals, & Materials Society, the company's research is directly transferable to red, green, white and other polymer material colours. The company focused on the blue material because this is vital to achieve full colour capability for mainstream display applications such as televisions and PCs along with the rising market for mobile multimedia-enabled mobile phones and personal digital assistants (PDAs).

Over the past year, CDT has more than tripled the lifetime of its blue research devices. The longer operating life is due to advances in LEP material formulation, improved deposition processes for the polymer and other materials, and innovative device structures. Even though longer lifetimes for the material are still required for most applications, CDT's results are a significant milestone toward the commercialisation of LEP technology.

6.2 Motorola

Motorola Labs has announced a new display technology based on its carbon nanotechnology research. Dubbed ‘nano-emissive display’ (NED), the technology enables manufacturers to design large flat-panel displays that exceed the image-quality characteristics of plasma and LCDs at a lower cost.

Motorola has developed a process to grow CNTs at low temperatures. This capability is important because the materials with which they must bond, such as glass or a transistor array, is heat sensitive. In addition, Motorola has devised a method to place individual CNTs precisely on a surface, while controlling their length and diameter. Controlled placement was achieved by a combination of the highly selective adsorption of single-walled CNTs (SWNTs) onto open regions of amino-functionalised silicon dioxide in a polymethyl methacrylate (PMMA) resist.

The ability to place CNTs directly on a substrate while controlling their spacing, length and diameter makes possible high-quality images with optimised electron emissions, brightness, colour purity and resolution on flat-panel displays. Other attempts in this field utilised a ‘paste’ or ‘print’ method of applying CNTs, which have so far been unable to provide the same level of image quality or the potential cost savings of Motorola's NED process.

Motorola Labs is currently undertaking research to integrate these nanotechnology advances into key
applications, including large flat-panel displays. According to the company, NEDs could enable low-cost, flat-panel wall-mounted television, as well as much larger displays such as billboards.

Motorola is currently in discussion with electronics manufacturers in Europe and Asia to license the technology for commercialisation. The company is confident that the market is ripe for a disruptive technology, such as carbon nanotubes, that provides a CRT-quality image at a cost which is significantly lower than current plasma and LCD offerings.

6.3 Philips

After seven years of research, the Philips Research team based in New York has developed single-panel LCOS (liquid crystal on silicon), which they have named ‘engaze’. The display comprises a thin layer of liquid-crystal material placed between two substrates which are coated with a thin polyamide alignment layer rubbed in a direction that complies with the surface alignment of the LC.

The level of resolution that can be achieved in the engaze technology is unprecedented. A LCOS panel developed by Philips has pixels as small as 10 microns, a level that is substantially below the level of resolution of near-eye optics and cannot be matched by the common projection-lens technology.

6.4 Xerox Research Centre

Scientists at the Xerox Research Centre of Canada have invented an OLED display that tolerates temperatures up to 100 °C for 10,000 hours – ten times greater than existing OLED standards. This ability to tolerate heat offers opportunities in the automobile and avionics industries.

6.5 LG Philips

LG Philips LCD has successfully employed the latest technology to significantly enhance the brightness of thin-film-transistor liquid-crystal display (TFT-LCD) monitors. The provision of direct-type, external-electrode fluorescent lamp (EEFL) in LCDs improves the brightness by more than 60% over existing models, a major improvement for LCD monitor users.

Though some LCD and component makers had earlier succeeded in developing EEFL technology, they failed to adapt it successfully to products because of persistent heat and noise problems. The Korean-Dutch collaboration is convinced that it has successfully adapted the technology ahead of any global competitor, enabling them to offer new products earlier, hitting the market within two years. The new EEFL technology reduces the weight of the LCD by 50%, reduces the parts required and streamlines the structure of the backlight unit.

6.6 Extreme Devices Inc.

Extreme Devices Inc., a Texas based start-up, is engaged in developing a pioneering technology that will herald the introduction of cold-emission electron guns for extensive use in the large-television and computer-monitor markets.

Instead of adopting the prevalent hot-electron emission technology, Extreme Devices employs a proprietary approach in which synthetic diamond tips, assembled in a chip-like device, fire electrons. The procedure is compact, eliminates warm-up time and costs less than the hot electron emission technology.

The basics of this new technology are equally applicable to a broad variety of products, ranging from X-ray units to magnetrons in microwave ovens. The immediate opportunities lie in CRTs, which can also be applied to vacuum microelectronics. Other large markets that may stand to benefit are power amplifiers and microwave circuits such as amplifiers used in mobile base stations or in TV and radio broadcasting.

6.7 NEC

NEC is shortly to begin using the SoundVu technology of audio technology developer NXT in its new LCD monitor which will serve as a distributed-mode loudspeaker. It is claimed that the integration of the SoundVu technology greatly improves the sound quality by manipulating exciters positioned on the edge of the acrylic protection screen of the monitor. The technology also helps eliminate the need for extra speakers and effectively locks the sound to moving images.

6.8 Sanken Electric Co.

Sanken Electric Co. has developed a silicon wafer-bonding technique that enables light-emitting diodes to provide high power output. Red and yellow LEDs employing a process that bonds a silicon wafer onto the
LED epitaxial layer have proved to be about 100 times brighter than Sanken's existing products.

6.9 Aixtron

Aixtron is a leading manufacturer of equipment for semiconductor epitaxy and holds an exclusive licence from Universal Display Corp. to sell and produce equipment for manufacturing OLEDs and other devices using the organic vapour-phase deposition (OVPD) process. Development of Aixtron's second-generation OVPD tool began in 2002 as part of a joint development program with Universal Display Corp., where a first-generation pre-production OVPD system is installed. The second-generation tool will be suitable for glass sizes of up to 370 by 470 millimetres.

In May 2003, Aixtron AG announced that it would jointly beta-test Aixtron's second-generation OVPD equipment for manufacturing displays with RTDisplay Corporation. The intention was to qualify the equipment for mass production of OLED devices.

The OVPD process was originally developed at Princeton University. In conventional processes, the organic molecules are evaporated at high temperature and pressure. The OVPD process uses a carrier-gas stream in a hot-walled reactor at very low pressures. The main advantages are high organic material deposition efficiency, high uniformity of thickness and doping, and the capability of depositing in a single chamber all the layers required for full-colour displays. Patterning of all organic layers and pixels for full-colour display production is achieved with an in-situ shadow-mask alignment system. These features are expected to reduce the cost and increase the throughput of the OLED production process.

7.0 Conclusion

CRT makers will continue to make improvements in their products in an effort to compete with flat-panel displays. And new technologies, such as organic displays, will proliferate, making devices thinner and less costly to operate. A return to some kind of economic stability, continued backing from government, industry, and academia, and development of advanced materials are the key items needed for industry competitiveness in the display materials industry. With these conditions met, it is likely that there will be unprecedented growth in materials for a wide variety of displays.

Development for many of these new display technologies is ongoing, but, inevitably, some will never reach the mass market or even command their own niche markets. Certainly, there has never been a more intensive period of R&D into display technologies than now. From these efforts, new markets and applications will emerge to alter the future design of electronics forever.

8.0 Sources Of Further Information

Society for Information Display
www.sid.org

Optical Systems for the Digital Age
www.osda.org.uk

UK Consortium for Photonics and Optics
www.ukcpo.org.uk

DTI Basic Technologies for Industrial Applications (BTIA) Programme
www.basictechnologies.gov.uk

British Liquid Crystal Society
http://www-g.eng.cam.ac.uk/photronics/blcs

Communications and Mobile Information Technology
www.comit.uk.com

Electronics and Photonics Packaging and Interconnection
www.eppic-faraday.com

Engineering and Physical Sciences Research Council
www.epsrc.ac.uk

LINK Information Storage and Displays Programme
www.linkisd.org.uk

Computing Suppliers Federation (Displays and Projection industry group)
www.csf.org.uk

9.0 Sources Of Further Information
