DISPLAY MATERIALS ISSUE

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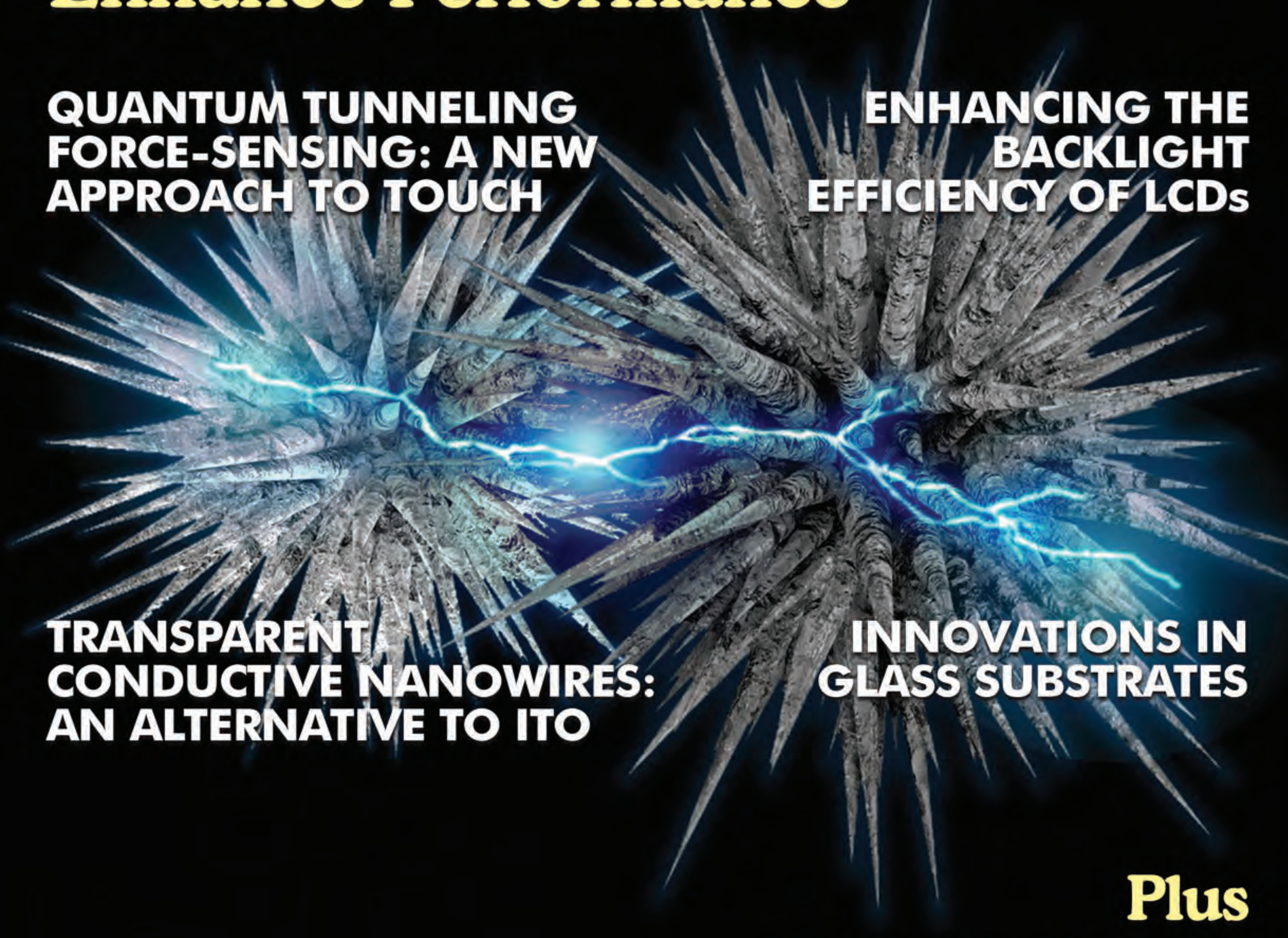
Novel Display Materials Enhance Performance



QUANTUM TUNNELING FORCE-SENSING: A NEW APPROACH TO TOUCH

ENHANCING THE BACKLIGHT EFFICIENCY OF LCDs

TRANSPARENT CONDUCTIVE NANOWIRES: AN ALTERNATIVE TO ITO

INNOVATIONS IN GLASS SUBSTRATES

Plus

LatinDisplay Review

Journal of the SID January Contents

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JANUARY 2012
VOL. 28, NO. 1

ON THE COVER: *This artist rendition depicts two Quantum-Tunnelling-Composite (QTC) particles for which electrons "leap" or tunnel from one particle tip to the next. QTC is made from a polymer that has nanoscale conductive particles, each characterized by a "spikey" surface structure, evenly distributed throughout. The spikes do not actually touch, but when the material has a force applied, such as pressure, the spikes move closer together and a quantum effect occurs in that the electrons leap or tunnel from one spike tip to the next and a current flows until the pressure is removed.*

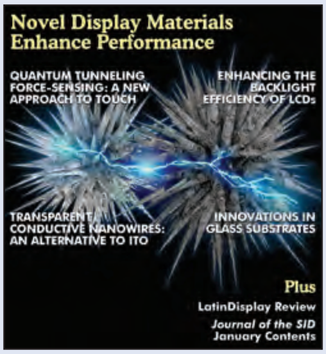

Image: Courtesy of Peratech Ltd.
Cover Design: Acapella Studios, Inc.

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- Electrophorectic Displays for Textbooks
- Touch Technology for e-Readers

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New Year, New Materials

by Stephen Atwood

Happy New Year and welcome to the year two-thousand and twelve. For some of you, the New Year celebrations are still under way. For most of the rest of us, those celebrations are now a memory, or an explanation for some slight memory loss. Either way, we are well into January and there is no turning back from the exciting year ahead.

There are endless predictions about what may happen in the year 2012, based on everything from interpretations of the Mayan calendar to the teachings of New Age gurus. We could be looking at anything from a year of rebirth and renewal, possibly punctuated by a spiritual alignment of the solar system and the reversal of the Sun's magnetic poles, to something dire that involves black holes or asteroids on a galactic scale. I'm not sure I'm buying any of it but I can say it's looking to be a very exciting year for the display industry.

Each year, we choose our issue themes based on our best assessment of the future direction of the industry and the topics we perceive to be most likely to produce new and relevant developments. This year, we're focusing on Novel Displays, Cutting-Edge Technology, TVs in all their forms, and Interactivity. Of course, we continue with our perennial roundup of flexible displays, this year with a focus on e-Reader technology, as well as updates on backlighting technology and LEDs. While 3-D technology will not get its own issue this year, we will keep our eye on the field and expect to have several updates on it in the months to come.

We start off the year with our January issue focused on Display Materials. Our guest editor Ion Bita from Qualcomm MEMS Technologies helped us line up several interesting articles on substrate glass, touch-screen materials, transparent conductive coatings, and diffuser films. We start off with our Display Marketplace feature, "Display Glass: Bigger, Thinner, and Stronger," from analyst and *ID* Contributing Editor Paul Semenza. There was a quite a bit I did not appreciate about glass substrates, but thanks to Paul, I have some new insights about the technology as well as the future of the entire glass supply chain. If you think this is not an exciting marketplace, you should read this article.

Our next feature is a Frontline Technology article titled "Wet Processable Transparent Conductive Materials," written by Michael Spaid from Cambrios. Michael describes the company's new process for producing a transparent coating filled with high-aspect-ratio silver nanowires. The coating, ClearOhm, is an exciting innovation that proves to have real commercial opportunities in touch screens as well as displays. I know from personal experience that developing alternatives to ITO has been a long sought-after goal and one that many different companies have made investments in. It's been a rough road with many technical and business challenges. We wish Cambrios much success and hope you will enjoy reading about its considerable achievement.

In a similar vein, I was also surprised to read about a new type of force-sensing material being applied to touch screens in "Quantum Tunneling Composite Touch-Screen Technology," written by David Lussey from Peratech Limited. This company's invention is a material, dubbed "QTC," that changes its electrical conductivity in proportion to a force applied to it. This same material is also transparent, making it suitable for displays and touch-screen applications. While force-sensing touch concepts are not new, this approach, which essentially mimics the electrical characteristics

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DuPont Licenses OLED Technology to Major Asian TV Manufacturer

In November, DuPont announced that it had signed a licensing agreement for its proprietary solution-based printing technology to be used by a leading Asian manufacturer to make large AMOLED televisions. At press time, DuPont was – at the manufacturer's request – not at liberty to reveal the name of the manufacturer. Since Asian TV makers with a vested interest in OLEDs can be counted on the fingers of one hand, the pool of possible partners is small indeed, with online speculation leaning in the direction of Samsung or LG. Nothing is certain until the partnership is made public, which, according to Bill Feehery, Global Business Director for Dupont, will definitely happen on an as-yet undisclosed date.

DuPont's technology is of particular interest because it allows the OLED materials to be spray-printed on a backplane using a super-fast multi-nozzle technique. The printer, developed by DuPoint in conjunction with Dai Nippon Screen, uses a continuous spray of ink rather than droplets and coats the substrate at rates of 4–5 m/sec. According to DuPont, a Gen 4 OLED display can be printed in about 2 minutes.

The company has been working on this technique for several years. "We've had many iterations," says Feehery. "It wasn't easy." The key challenges were improving the performance of the material, including its color and efficiency, and being able to print at a high yield without mura. The key to scaling up to Gen 4 was using multiple nozzles, notes Feehery.

This announcement would seem to indicate that OLED TVs are inching closer to commercial reality, although "We're only a piece of the OLED puzzle," Feehery is quick to point out. Other developers have had to solve issues such as reliable encapsulation and the ability to make backplanes at a larger size. And this has been happening. Feehery notes that even if DuPont had had the process ready 5 years ago, there would not have been a market for it because the other pieces of the OLED equation were not ready. Are they ready now? We'll have to wait just a bit longer to find out.

For more background on this technology, see the article from DuPont Displays, "Clearing the Road to Mass Production of OLED Television, in the October 2011 issue of *Information Display*.

– Jenny Donelan

Part II of Solid-State-Lighting Update: OLEDs and LEDs in Europe

Part I of our Solid-State-Lighting Update in the October issue of *ID* magazine looked at OLED-based developments from European companies such as BASF, Novaled, and OSRAM, as well as activities conducted by OLED research groups including the OLED100.eu consortium (which recently concluded its research in Q3 '11 on schedule) and the TOPAS (Thousand lumen Organic Phosphorescent devices for Applications in lighting Systems) 2012 research project. Two other companies involved in the European solid-state-lighting push include AIXTRON and Nanaco.

AIXTRON

"The special features of OLED solid-state lighting, such as the potential for free-form and/or transparent-area light sources, appeal to many designers and allow for novel architectural concepts," says Juergen Kreis, Senior Department Manager for Business Development at AIXTRON, a leading provider of deposition equipment to the semiconductor industry. "Also," says Kreis, "the fact that OLEDs already are luminaires and only need a minimum of additional packaging makes this technology especially interesting."

At this moment, he notes, manufacturing costs and the respective pricing of OLED devices are not competitive with other technologies such as inorganic LEDs. Therefore, the OLED-based devices that are currently being produced still serve mostly as proof-of-principle or are designed for niche markets such as high-end interior design.

Says Kreis, "Technically, the so-far-dominant vacuum thermal evaporation (VTE) seems to create some limitations when it comes to scaling up to larger substrate sizes." Some of these challenges, he continues, such as efficient material use, high deposition rates and throughput, avoiding parasitic material deposition in the process chamber, and minimizing thermal stress to the organic material, are being addressed by AIXTRON's OVPD technology. The OVPD system uses AIXTRON's proprietary Close Coupled Showerhead (CCS) technology to ensure homogenous material distribution, uniform film thicknesses, and efficient utilization of the organic materials.

Exposing organic materials to elevated temperatures over a long period of time usually speeds their degradation and can render sensitive materials unusable in processes for larger substrates. In conventional VTE systems, scaled-up solutions also require the scaling up of the respective crucibles, which, in turn, keeps larger amounts of materials at elevated temperatures for a considerable period of time.

AIXTRON's novel STEx source principle addresses this hurdle by enabling on-demand evaporation of materials (bulk material is kept under room temperature), and at the same time providing high deposition rates, which then allows for short cycle times and high throughput.

Says Kreis, "For white OLEDs, efficient blue emitters still are a challenge with respect to lifetime. It should be noted, however, that here (as well as in many other fields) tremendous progress can be seen from the major material makers." Support programs such as those funded by the EU, he notes, will, for the near future, be necessary to help companies endure the incremental investments necessary to make this technology a success.

Nanaco

Quantum dots, semiconductor nanoparticles between 10 and 100 atoms in width, hold promise for solid-state-lighting applications due to their unique electro-optical characteristics. These include the ability to emit light of a very specific wavelength depending on the size of the dot. However, to date the challenges involved in bringing this technology to market include power efficiency, cost to manufacture, and scalability.

One company that is firmly vested in quantum-dot technology for LEDs and other applications, and says that it is currently capable of producing quantum dots on a large scale, is the UK-based Nanaco Technologies. "Nanoco has been working with lighting manufacturers to help them develop LED lighting incorporating its quantum-dot technology," says Nanoco representative Mark Court. Last August, according to Court, the company signed a joint development agreement with one of the world's largest lighting companies (the name

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guest editorial

Advances in Materials for Touch-Panel Applications

by Ion Bita

Welcome to 2012, and a Happy New Year to all of you. We start out with a look at advances in the area of materials for touch panels, a display component that has become a must-have for many of today's mobile devices. With the recent explosion in popularity of these devices, many of which incorporate new types of user interaction, it comes as no surprise that the annual touch-module volume has more than tripled in the last 3 years, exceeding 1 billion units in 2011. About half of that volume represents smartphones alone. As a result of this significant growth and business impact, the touch-panel industry is being further shaped by an aggressive pursuit of opportunities for cost and value-added-based differentiation, a pursuit embodied by strategies for sensor-technology development, integration, and manufacturing. While projected-capacitive-based sensing has lately taken center stage, a variety of other technologies are being used as well, including resistive, electromagnetic resonance, surface acoustic, and a host of optical solutions.

Besides the conventional implementation of these technologies in discrete glass- or film-based touch panels, vertical-integration approaches have become more popular in response to factors including cost and display-module thickness. On one hand, display panel makers can pursue integration of touch functionality in the display panel itself, as with in-cell and on-cell approaches in LC-TFT and OLED displays. On the other hand, touch-panel suppliers can take a different approach for vertical integration by adding display lamination capabilities, with some even pursuing integration of the touch sensor into the cover lens to help display-module suppliers meet the current requirements for reduced module thickness and weight.

We are glad to include in this issue two articles showcasing prime examples of the impact of materials developments on two of the trends discussed above – cost-based and value-added-based differentiation in the touch-panel industry.

The first article is from Cambrios Technologies located in California. Michael Spaid (VP Product Development) provides an overview of the material design, processing, and properties of arguably the first high-volume commercially available wet-processed transparent conductor alternative to ITO, ClearOhm. Given the more advantageous resistance – optical property tradeoffs compared to ITO and low-temperature processing compatible with glass and plastic substrates, as well as a reduced cost structure enabled by the use of roll-to-roll coating processes – ClearOhm materials have been received with great excitement by the touch-panel industry. In fact, just in 2011, these films have been used to produce the projected-capacitive touch module for a leading smartphone device, with significant growth expected in 2012. The basis of the Cambrios approach is the use of silver nanowires to create conductive coatings comprising an interconnected mesh of nanowires, with resistivity and optical properties that can be adjusted by tuning the nanowire diameter, length, and substrate surface coverage. The high electrical conductivity of silver is key to achieving sheet-resistance values comparable to ITO while minimizing optical transmission losses due to the low-area coverage of the nanowires. Further, patterning methods are described and show how these films can be used to fabricate touch panels.

The second article is from Peratech, Ltd., located in the UK. David Lussey (co-founder and CTO) introduces an innovative touch-panel technology based on the

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Display Glass: Bigger, Thinner, and Stronger

Glass substrates are a key building block for flat-panel displays, serving optical, mechanical, and electronic functions. The market has grown along with the display industry, and innovations such as thin substrates and cover glass have served to increase its value.

by Paul Semenza

GLASS SUBSTRATES PLAY A vital role in nearly all electronic displays. For TFT-LCDs, the two sheets of glass provide electronic, optical, and mechanical functionality. One sheet of glass serves as the substrate for the creation of the active matrix – an array of thousands of TFTs, typically silicon-based semiconductor devices, in addition to transparent conductors, typically fabricated from indium tin oxide, to connect these transistors to drive circuitry. These semiconductor processes require pristine surface quality, high temperature resistance, and specific chemistry. Color filters are deposited on the other piece of glass, which also requires a high-quality surface. From a mechanical standpoint, the glass sheets form a space that maintains the liquid-crystal material at a fixed thickness (cell gap), serve as the base for polarizer sheets and other optical films, and provide the mechanical stability for the display panel.

For active-matrix TFT-LCDs, non-alkali glass is used for both layers rather than the alkali substrates found in passive-matrix LCDs since the sodium ions and heavy metals found in alkali glasses can cause problems in the fabrication of TFTs. Such problems include unstable gate voltages and increased current leakage, which affects TFT performance and causes defects. This non-alkali glass must be produced cost effectively at large sizes in thin sheets, with low density to minimize weight, an ability to withstand high temperatures with minimal thermal shrinkage, resistance to harsh chemicals and lateral cracking during scribe and break processes, freedom from bubbles, and a low coefficient of thermal expansion. The non-alkali glass-substrate market was pioneered by Corning, which developed the first a-Si TFT borosilicate glass substrates. There are four major methods for fabricating non-alkali glass substrates.

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Fabrication Methodologies

The float method, pioneered by Pilkington, has been used for architectural and other applications that require lower-quality glass and has been modified for LCDs by Asahi Glass. In the float method, glass is melted and then flowed into a chamber featuring an underlying tin layer. Under the correct pressure and temperature, the glass effectively floats on the surface of the tin. After the glass reaches the desired thickness, it goes into the cooling chamber and is then pulled out from the other end, cleaned, dried, and scribed. This approach is scalable and economical for large substrates but requires polishing (as the process results in planar non-uniformities that adversely affect image quality), which offsets some of the benefits.

An approach that can be implemented separately or in conjunction with the float process is the redraw method. In this approach, the molded glass is reheated, redrawn, and remolded into the desired thickness. This approach is quite flexible because the material properties can easily be reconfigured. It also requires polishing to enhance surface planarity.

A third approach is the down or slot-draw approach in which molten glass is poured into an agitator. The glass is then drawn downward through a platinum orifice or slot with a specified stretching force, then drawn through rollers into a cooling chamber. By changing the orifice or slot, different substrate thicknesses can be produced. This method causes minute surface irregularities derived from the uneven nature of the slot surface edges. As a result, polishing is required. This approach is not as economical as the float method. Nippon Electric Glass has adopted this approach.

A fourth approach, pioneered by Corning, is the fusion method. It is a variant of the down-draw, but bypasses the harmful effects of the orifice. In this approach, over-flowing molten glass flows into a trough-shaped fusion pipe from both sides and is joined into a single sheet as the glass is pulled downward. The substrate surface does not contact metal rollers or guides during film formation. As a result, an improved surface is produced and polishing can be omitted, reducing costs. Thinner glass increases throughput and lowers cost. Fusion tanks do not require as large an investment as do float tanks, resulting in higher utilization and increased flexibility. On the other hand, float tanks can produce substrates that are significantly wider than those from fusion tanks, giving this method an advantage for larger substrates.

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Growing with the Display Market

The market for glass substrates is closely related to the overall TFT-LCD market, particularly the applications that dominate area production of TFT-LCD panels: TVs, desktop monitors, and mobile PCs. Slowing demand for TFT-LCDs in 2011, combined with a sizeable glass inventory left over from 2010, caused a significant reduction in the growth of total demand for glass in 2011 (Fig. 1).

The challenge for glass makers is to anticipate TFT-LCD production investments and make appropriate investments in melting tanks and to moderate production as TFT-LCD factory utilization changes. This must be done for each generation of TFT-LCD fabs, since each requires a different substrate size. While TFT-LCD area production has been growing by roughly 20% per year over the past few years, the financial crisis of 2008 caused a significant disruption in production as TFT-LCD makers temporarily closed some fabs. This led glass makers to shut down their production, and as a result there was a slowdown in capacity growth in 2009 (Fig. 2).

Because re-starting production requires many weeks of increasing the temperature of the melting tanks, a period of glass shortage followed. Glass makers increased capacity dramatically in 2010, and by 2011 were running ahead of demand.

The glass market is characterized by a high degree of concentration, with four companies (including Corning and its joint venture with Samsung) accounting for 95% of production (Fig. 3).

Asahi Glass Company (AGC) has expanded its market share by expanding production in Korea and Taiwan, and Nippon Electric Glass (NEG) has invested heavily in Japan, as well as in Korea via a joint production venture with LG. AvanStrate (formerly NH Techno) is a smaller producer, and LG Chemical, which has licensed technology from Schott, is also developing production. Glass is typically produced close to or even in conjunction with the TFT-LCD fabrication facility that will use it. However, due to the history of the evolution of TFT-LCD production in Japan, combined with the strong presence of Japanese companies in the glass market, there is a higher level of glass production than consumption in Japan; while 37% of glass capacity is in Japan, only about 12% of TFT-LCD capacity is there. Some glass is exported to Korea, which also accounts for 37% of glass production but 48% of TFT-LCD production, and Taiwan, with 25% and 35%, respectively.

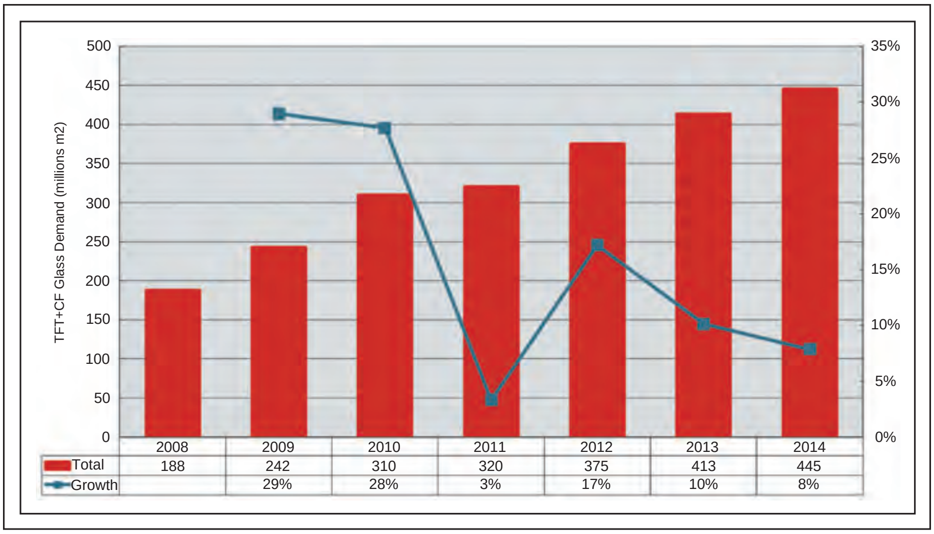

Fig. 1: Demand for glass substrates grew rapidly over the past few years as TFT-LCD manufacturers expanded TV panel production, but market growth slowed in 2011 and is expected to continue to do so. Source: DisplaySearch Quarterly LCD Glass Substrate Report.

The expected growth of TFT-LCD production in China is leading the established glass manufacturers to develop production in that country, starting with finishing or polishing facilities. This growth is also opening up the possibility of Chinese companies entering the market. Three such companies – Irico, Xufei, and CNBM – have installed glass tanks for Gen 4 and 5 substrates; another, a joint venture of the Baoshi group and Dongxu, is called Xuxin.

New Directions for Glass: Thinner and Stronger

There have been many efforts to develop substrates with materials other than glass, including plastic, metal, and other materials. While the goal of developing flexible displays is

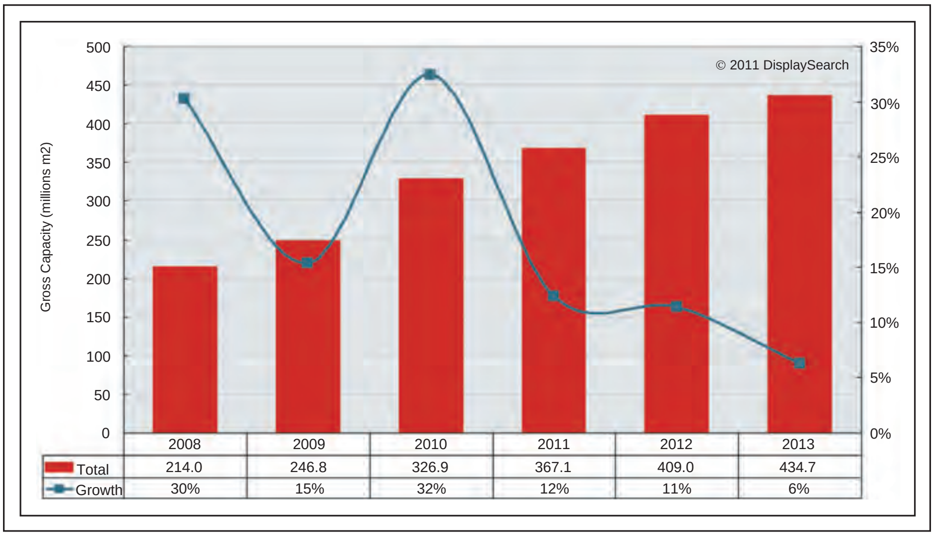

Fig. 2: After slow growth in capacity in response to the global recession, glass production grew rapidly in 2010 and grew faster than demand in 2011, leading to oversupply. Source: DisplaySearch Quarterly LCD Glass Substrate Report.

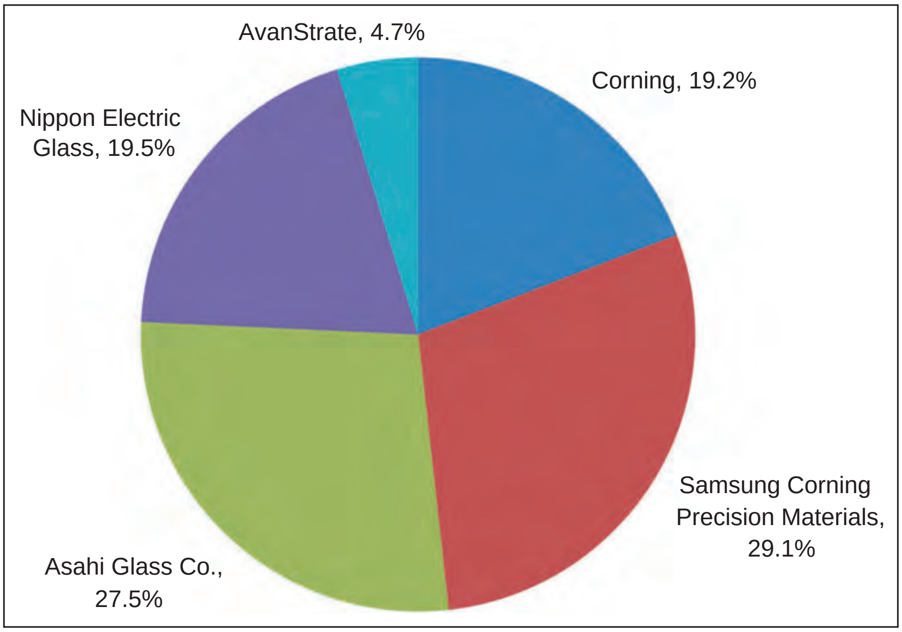

Fig. 3: Corning, along with its joint production venture Samsung Corning Precision (SCP), leads the production of glass substrates (figures are for Q2 '11). Source: DisplaySearch Quarterly LCD Glass Substrate Report.

often mentioned as a key motivator for moving away from glass, there is uncertainty regarding the market for flexible displays. In the near term, lighter weight and resistance to breakage are key benefits offered by such materials.[1] Despite being a mature technology, the form and features of glass continue to evolve. Two of the most important aspects of these developments are thin glass substrates and rugged cover glass.

Using thinner glass substrates can enable reduction in the weight of the display and eliminate expensive panel-thinning techniques used for displays in mobile applications. Of equal importance, producing thinner glass allows glass makers to increase output without making investments in new tanks. While most glass substrates produced are 0.7 mm thick for Gen 6 and larger and 0.5 mm for smaller substrates, glass makers have begun producing thinner glass, 0.5 and 0.4 mm, respectively, with 0.3 mm a possibility. One factor limiting adoption of thin glass is that panel makers need to adopt new glass-handling equipment because thinner substrates have less stability.

The trend in thinner glass production has led to the possibility of "flexible" glass. This is glass that is 0.1 mm or even thinner, which allows for a small enough bend radius that it can be shipped in roll form and potentially used in roll-to-roll production. While there is no commercial production of displays using such thin glass, it can also be used in applications such as touch screens and cover glass for OLED encapsulation.

The development of strengthened cover glass has been an important source of growth for the glass industry. Since the introduction of the original iPhone, device manufacturers and consumers have appreciated the benefits of this technology, which is scratch resistant, optically clear, and capable of withstanding high stress levels. In addition, it can integrate a touch sensor and also serve as part of the case and industrial design.

There are different methods for strengthening glass, including physical strengthening, which involves tempering the glass by heating and then rapidly cooling. For the thin glass used in displays, chemical strengthening is typically used. In chemical strengthening, a piece of display-quality glass (typically aluminosilicate, although soda-lime is also used) is immersed in a bath of liquid KNO_3, which has the effect of replacing sodium ions in the glass with larger potassium ions, creating stress in the glass, which needs to be exceeded in order for cracks to form.

Since chemical strengthening makes the glass impossible to cut, it must be cut to shape before strengthening, typically by mechanical or laser-based scribing. Because distinctive shapes and holes are often required, computer numerical control (CNC) is used to control the tool and grind edges smooth, removing flaws, cracks, or chips that can cause breakage under stress. Going beyond flat surfaces, cover-

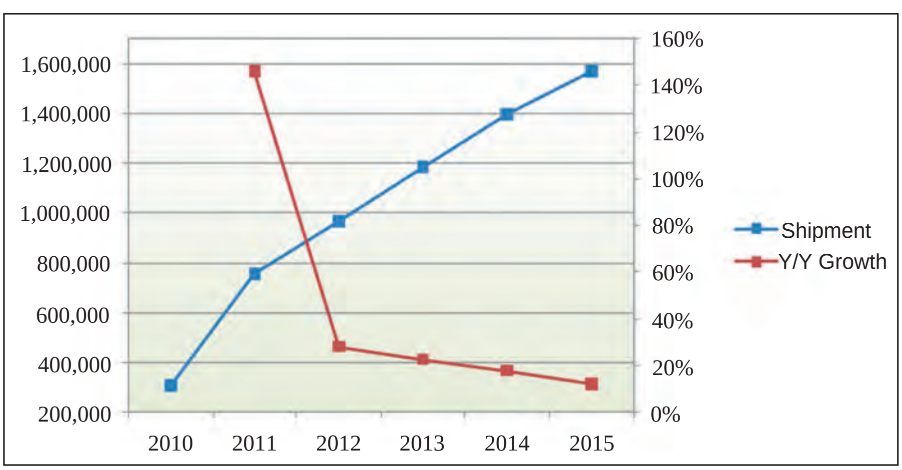

Fig. 4: Growth in smartphones and tablet PCs has provided a boost to the market for strengthened cover glass, which will be in 755 million devices in 2011. Source: DisplaySearch 2011 Cover Glass Technology and Market Forecast Report.

glass makers are developing curved and shaped products. So-called “2.5-D” and “3-D” shapes introduce curvature in one or both axes of the glass surface, enabled through techniques such as hot forming and mold pressing.

In addition to the design and durability improvements enabled by cover glass, it is in most cases required for the use of projected-capacitive touch sensors. Since this is the most prevalent touch technology, cover glass is enjoying rapid growth in smartphones and other mobile devices. In addition, the explosion of tablet PCs, all of which use cover glass – and have much larger areas than phones – has also provided a boost. In 2011, 755 million devices will ship with cover glass, for a Y/Y growth of 146% (Fig. 4). Mobile phones account for 84.4% of the shipments.

The Future of Display Glass

The year 2011 has been a challenging one for glass makers, as demand slowed significantly, and combined with falling prices, led to a drop in revenues in the display glass market. While demand is expected to recover in 2012, it is likely that there will be continued excess capacity. With some of the demand growth coming from new TFT-LCD fabs in China, glass makers will need to make investments in production and/or finishing facilities in China. At the same time, the move towards thinner glass means that more area can be produced from existing tanks. With demand for strengthened cover glass growing, glass makers will need to skillfully manage the timing, location, and product type of their production capacity.

Glass makers also face potential shifts in technology. With the growth of AMOLED displays, the potential exists for elimination of one sheet of glass if AMOLED makers are able to perfect thin-film encapsulation, or even both sheets of glass if this can be combined with the production of AMOLEDs on metal or plastic substrates. Other types of flexible displays are also in production (such as electrophoretic) or envisioned. And there are many types of plastic materials that attempt to compete with cover glass.

Can any of these developments unseat the central role of glass in flat-panel displays? While it may be possible in the long run, it is unlikely during this decade. It is difficult to replicate the combination of optical, electrical, and mechanical properties offered by glass. In the case of backplanes, few materials have the ability to be mass-produced with the pristine surface quality and chemistry that allows high-yield TFT production. For applications such as OLED displays, glass also provides a very high barrier to oxygen and water vapor along with high transmission. Other objections to glass – weight and rigidity – are being addressed by the development of thin glass, though there will be intense competition between glass and other materials if the flexible display (or lighting) markets were to take off. For now, there is no other material that can be produced in the hundreds of millions of square meters per year, at the specifications required, to meet the needs of the flat-panel-display industry.

References

[1]P. Semenza, “Flexible Displays: Still a Lot to Learn,” *Information Display* (February 2011. ■

Wet-Processable Transparent Conductive Materials

A novel wet-processable transparent electrode material exhibits significant performance advantages over ITO. This material has recently achieved mass production in smart phones.

by Michael Spaid

NEARLY ALL DISPLAY DEVICES, including TFT-LCDs, OLEDs, and e-paper, contain one or more layers of a transparent conductive material, most commonly indium tin oxide (ITO). Currently, virtually all applications of ITO for transparent conductors require deposition by a sputtering method in a vacuum chamber. Due to the significant growth of large-area displays, smart phones, and tablet devices that often incorporate projected-capacitive touch sensors, the market for the ITO sputtering targets has become several billion dollars as of 2011, with steady growth expected in the next 10 years.[1] If one considers not just the material cost of ITO, but also the deposition and patterning costs that are necessary to make display devices, it is reasonable to assume that the worldwide cost for creating a useful ITO layer is a significant multiple of the cost of the ITO sputtering targets. While the need for high-quality transparent conductive materials has grown dramatically, desirable alternatives to ITO have not emerged in the marketplace.

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Drawbacks of ITO and Potential Alternatives

There are many factors driving the need for an ITO replacement material from the standpoint of raw-material supply, cost of ownership, and overall performance. Within the last 10 years, the price of ITO has been highly volatile, driven both by the increased consumption of the material as well as the geopolitically sensitive nature of the indium supply chain.[1] In addition to the high cost of the raw materials, capital investments for the vacuum-sputtering equipment necessary to deposit ITO are multiples of the cost of wet-coating tools with equivalent coating capacity. In addition, there are certain performance attributes of ITO that are undesirable, such as its brittleness and tendency to crack – a key factor with regard to making displays on flexible substrates. ITO also has a high refractive index that results in poor light transmission and the need for additional index-matching layers to achieve acceptable optical performance. Finally, high-temperature deposition conditions coupled with post-deposition annealing processes cause significant issues with achieving acceptable optical and electrical properties on plastic films.

In addition to current applications that require high-quality transparent electrodes, emerging applications such as OLED lighting, thin-film photovoltaics, and new types of flexible displays require a higher-performing transparent electrode, driven by both cost and performance. Wet-processed alternatives such as carbon nanotubes and conductive polymers have not been competitive with the optical and electrical properties established by ITO. Graphene has been widely discussed as an alternative; however, its development is in its infancy.[2] In this article, the transparent conductive material produced by the author's company, Cambrios Technologies Corporation, will be described as the first commercially available wet-processed alternative to ITO. Smart phones incorporating ClearOhm* materials have been mass produced since early 2011.[3,4]

Silver Nanowire Technology

ClearOhm conductive material consists of a wet-processable dispersion of high-aspect-ratio silver nanowires. Starting from silver salts, twinned-crystal silver nanowires are grown via the polyol process, a patented method[5] described by Xia.[6] By carefully controlling the process parameters, high-aspect-ratio silver nanowires can be synthesized at high yield, with an average diameter in the low tens of nanometers and an average length in excess of 10 µm. Independent control of nanowire length and diameter is possible, allowing the tailoring of morphology-dependent optical and electrical properties for specific applications. These nanostructures are then purified and formulated into a coatable suspension that is compatible with industry-standard coating methods such as roll-to-roll slot die coating or spin coating.

The transparent conductive layer is created by coating the formulated suspension of nanowires on the surface of a substrate such

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as glass or plastic. Upon drying of the solvent, the nanowires form an interconnected, two-dimensional mesh on the surface. Controlling the sheet resistivity of the layer of interconnected nanowires is accomplished by changing the number density of nanowires on the surface, as is shown in Fig. 1. The electrical properties of the interconnected mesh are well described by the theory of percolation, in which the number density of nanowires required to achieve a continuously conductive path on the substrate scales inversely with the square of their length ($N \sim 1/L^2$). Thus, high-aspect-ratio nanowires are uniquely suited to achieve high electrical conductivity with a minimal amount of metal.

In addition to the efficiency of the mesh structure, a large benefit in material usage relative to sputtered metal oxides arises due to the large difference in electrical conductivity, as silver is 50–100× more conductive than ITO. This difference in conductivity allows the material to cover only a few percent of the surface to achieve equivalent electrical properties. The remaining 95–99% of the surface consists of void space, which to the the first order determines the light transmission of the layer. Comparing material costs, indium tin oxide consists primarily of indium metal (>90% typically), and the price of indium and silver over the past 5 years has been roughly equivalent. Thus, the 50–100× reduction in material utilization due to the higher electrical conductivity of silver directly translates into a similar-fold reduction in material costs relative to ITO sputtering targets.

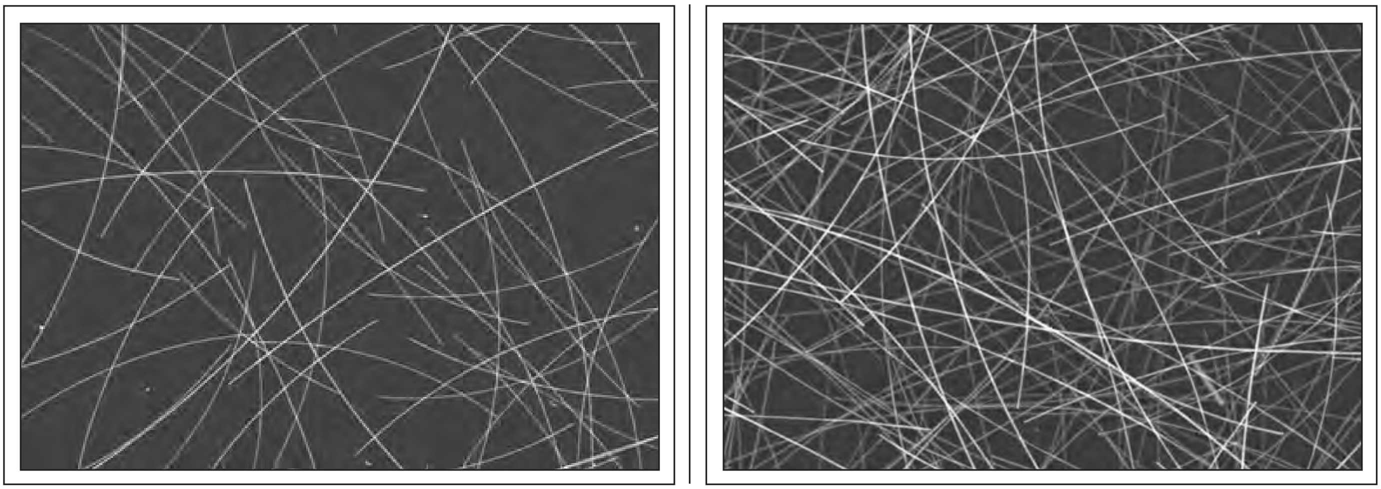
The materials used to create the transparent conductive layer can be scaled efficiently to volumes required to serve entire industries. For example, the estimated market size for ITO-coated plastic film in 2010 was 11 million square meters. The first manufacturing facility at Cambrios was sized to produce enough coating material for 30 million square meters of coated substrates at the relevant sheet resistance for touch panels.

Roll-to-Roll Wet-Coating Process

Wet coating as a deposition technology for key layers in consumer-electronic display devices has proven cost effective and robust for the most demanding applications. Examples of wet coatings in TFT-LCDs include the color resists and the color-filter planarization layer, both of which must be deposited defect-free at high yield. On plastic film, scratch-resistant hard coats and optical coatings such as anti-glare and anti-reflection are routinely applied at high yield using high-speed roll-to-roll coating methods. Cambrios' transparent conductive materials can be coated using a variety of industry-standard techniques, including roll-to-roll methods such as slot-die coating on plastic film. For sheet processing, standard wet-coating methods used in the LCD industry for coating color resists and photoresist are applicable, such as slit-coating or spin-coating. Capital equipment costs for equivalent coating capacity are typically 3–5× lower for wet-coating methods relative to vacuum-coating methods.

The Cambrios transparent conductive film is created using roll-to-roll slot-die coating. As shown schematically in Fig. 2, two coating steps are used to produce the transparent conductive layer, with the aqueous dispersion of silver nanowires coated and dried in the first step, followed by the coating of a thin (100–150 nm), transparent, UV-curable polymer layer on top of the nanowire layer. The purpose of the second layer is two-fold: (1) to impart mechanical strength to the coating, including some degree of scratch resistance, and (2) to protect the nanowire layer from direct environmental exposure. All processing steps can be performed at low temperature (<100°C) and are thus compatible with most types of optical-grade plastic film such as polyethylene terephthalate (PET), polycarbonate (PC), triacetyl cellulose (TAC), or cyclic olefin polymer (COP).

Once coated, the film does not need the subsequent 60–90-minute annealing step that is commonly required with coated ITO film to achieve the optimized optical and electrical properties. Contrary to sputter coating of ITO, the throughput of the roll-to-roll wet-coating process is not linked to the amount of conductive material to be deposited. At an



70 Ohms/sq. 9 Ohms/sq.

Fig. 1: Scanning electron microscope (SEM) images of transparent conductive layers show how they are created by an interconnected network of silver nanowires. By controlling the nanowire surface coverage, different sheet resistances can be produced.

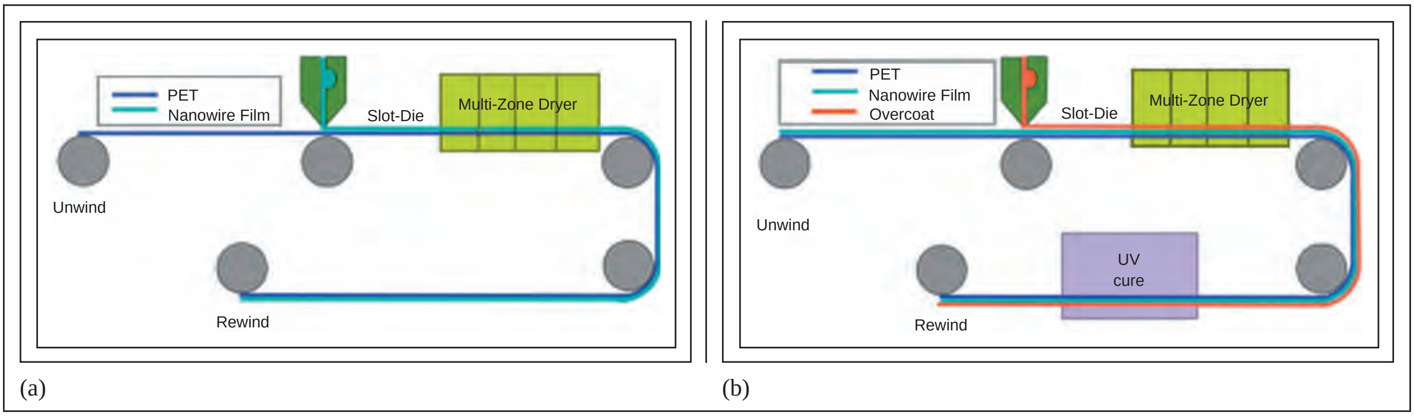


Fig. 2: The roll-to-roll slot-die coating process for creating ClearOhm film: (a) Coating and drying of the nanowire layer is followed by (b) coating, drying, and UV-curing of a clear polymer overcoat layer.

equivalent line speed, it is possible to adjust the roll-to-roll coating parameters to deliver a thicker wet film on the substrate that, in turn, results in a higher density of nanowires (and higher conductivity) in the dry film. Conductivity levels of the coatings can also be adjusted without sacrificing throughput by changing the nanowire concentration in the coating material to create a layer with a higher or lower density of nanowires using the identical wet-film thickness. Whether the conductive coating is at resistivity of 10 or 300 Ω/sq., the throughput remains the same. For sputtered metal oxides, higher conductivity necessitates longer sputtering times, resulting in a reduction in coating throughput.

Optical, Electrical, and Mechanical Properties

Three key optical properties that govern the performance of a transparent conductive layer at a given sheet resistivity are light transmission, color, and haze. A relatively low refractive index (~1.5) is desirable for many applications, as this minimizes reflection losses and optical appearance issues arising from patterned layers on glass or plastic due to differences in refractive index. Since the index of refraction of the transparent conductive materials layer is dominated by the index of the void space, it is possible to tune the refractive index by choosing an overcoat material with the desired index. As with most optical layers that appear in a display stack, the uniformity of the optical properties is critical, and the defect level of coated substrates needs to conform to industry standards.

Figure 3 shows the transmission of ClearOhm PET film as a function of sheet resistivity spanning a range from 10 to 250 Ω/sq. Including reflection losses associated with the PET substrate, the transmission of the film is in excess of 90% at 40 Ω/sq. or >98% for the conductive coating itself. Comparing this to ITO film that includes a multilayer anti-reflection coating, the Cambrios film has equivalent transmission at 50 Ω/sq. as compared to ITO film at a 3× higher sheet resistance. For standard-grade ITO film that does not include anti-reflection coatings, the transmission advantage of this film would be significantly larger. ClearOhm film also provides improvements in reflection, primarily due to its lower effective refractive index. In Fig. 4, the total reflection, or combination of diffuse and specular reflection, is plotted as a function of wavelength for both ClearOhm film and high-quality multilayered ITO film. ClearOhm film has a lower total reflectivity across the entire spectrum, with notable improvements in the blue and red regions of the visible spectrum.

In addition to its high transmission, ClearOhm transparent conductive film exhibits a more neutral color relative to ITO film, as measured by the color indices b* and

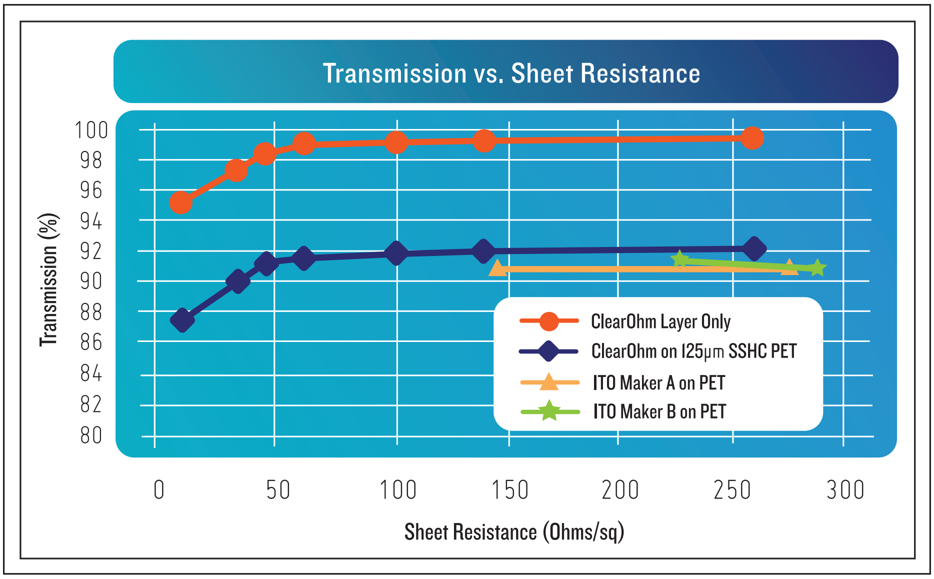


Fig. 3: Transmission vs. sheet resistance of the ClearOhm conductive material layer is shown on 125-μm single-side hard-coated PET film (blue curve) and for the ClearOhm layer by itself (red curve). For reference, commercially available ITO film is shown.

a*, metrics that are derived from the film transmission spectrum. ITO film typically has a yellowish appearance corresponding to b* values of 2.0–2.5 in the resistance range of 150–270 Ω/sq., whereas ClearOhm transparent conductive film is less yellow, with values ranging from 1.0 to 1.5 over a wider resistance range from 80 to 250 Ω/sq.

In most display applications, a high degree of optical clarity is necessary, which, in turn, requires coated substrates to have minimal haze. Transparent conductive materials that are particulate in nature will typically scatter more light than a smooth continuous film, with the amount of light-scattering proportional to the particle surface coverage. However, the level of light scattering can be controlled through careful engineering of the nanowire morphology.[7] For a fixed nanowire length, the amount of light scattering is proportional to the cube of the nanowire diameter, or the scattering cross section of ~d^3. Thus, for applications that demand a minimal amount of light scattering such as displays and touch screens, very thin nanowires should be used. For applications such as thin-film photovoltaics or OLED displays and lighting where a high degree of haze is desirable to allow more efficient light input or output coupling, larger-diameter nanowires are appropriate. Commercially available ClearOhm film for display applications has achieved very low haze with typical values ranging from 0.6 to 0.9%, corresponding to a resistance range of 80–250 Ω/sq. These values are only a few tenths higher than the haze of the optical-grade PET substrate.

Flexible, curved, or 3-D shaped displays and touch screens have been discussed for a number of years; however, the advent of these types of devices has been hindered by a lack of availability of the appropriate materials. Since ITO is a ceramic material, it is inherently brittle and cracks when exposed to a minimal amount of bending or strain. In addition to enabling new types of flexible devices, ClearOhm's flexibility and compatibility with mild strain should enhance manufacturing yields for existing devices manufactured with flexible conductive films. The silver nano-wires in the material are inherently flexible, and conform to surfaces in a manner more similar to well-cooked pasta than rigid beams. Figure 5 compares the flexibility of ClearOhm transparent conductive film and ITO film. In this test, a piece of conductive PET film is rolled

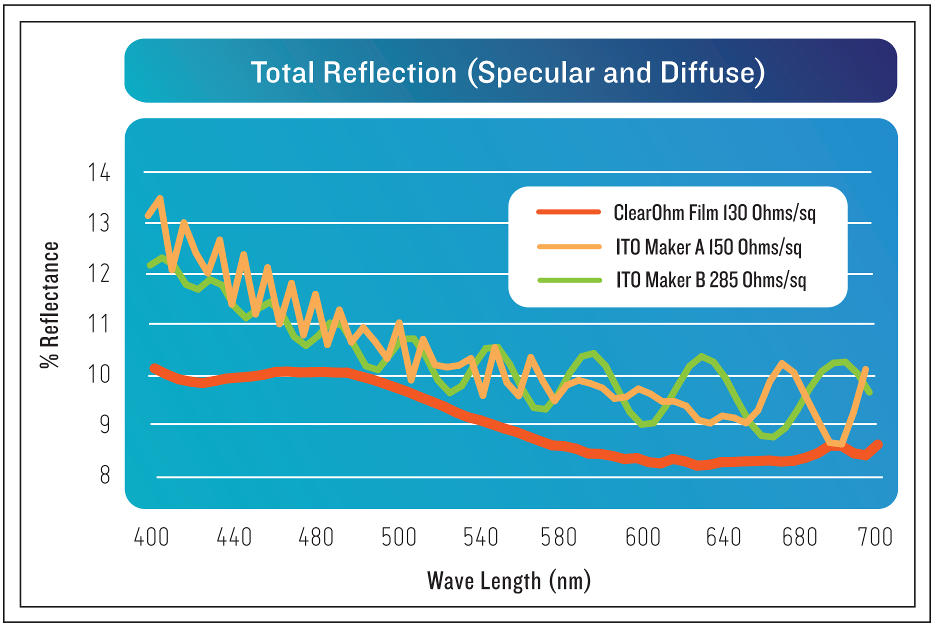


Fig. 4: Shown is the total reflection of multilayered ITO film at 150 and 285 Ω/sq., versus ClearOhm film at 130 Ω/sq. Oscillations in the spectra for ITO are due to the presence of a hard coating layer.

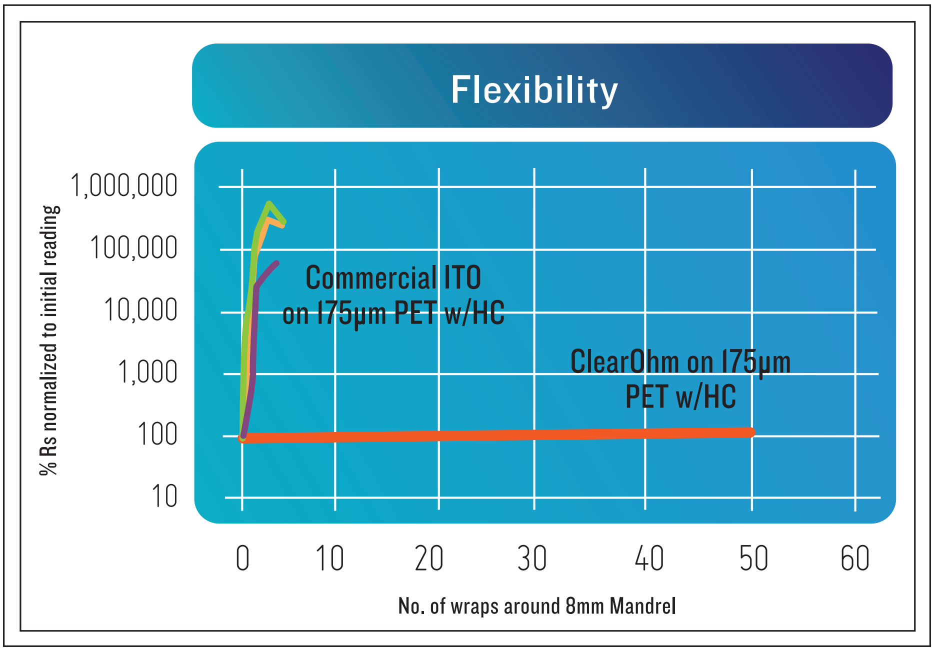


Fig. 5: The flexibility testing results shown above are for conductive films wrapped around an 8-mm mandrel. On the y axis, the percent change in sheet resistance is plotted on a logarithmic scale versus the number of wrap cycles on the x-axis. The starting resistance is normalized to 100%.

around an 8-mm mandrel, subsequently unrolled, and the resistance of the film is compared to its initial value. Within the first few cycles of this process, the ITO-coated PET film cracks, resulting in orders of magnitude increases in sheet resistance. Conversely, the ClearOhm transparent conductive film sheet resistance remains unchanged after 50 wrapping cycles.

Patterning Methods

Transparent conductors based on metal nanowires can be patterned[8,9] into conductive and non-conductive regions as is required for most display devices. Examples of common transparent conductor patterns are the drive and sense lines in a projected-capacitive touch screen or the pixel electrode in an LCD. The most common method to create patterned ITO is lithography with removal of material by wet chemical etching. Etch masks are typically applied by a photo process for high-resolution patterns or by a screen-printing process for low-resolution patterns. Alternatives to wet etching such as laser patterning or other dry-etching methods are much less common, and thus new types of transparent conductive materials should be patternable by wet etching to achieve immediate adoption.

ClearOhm transparent conductive film can be patterned by wet chemical etching using established volume-production processes. After applying the etch mask, the film is exposed to a liquid etchant that penetrates the thin overcoat layer and dissolves the underlying nanowires. The etching time for electrical isolation is dependent on the typical wet-etching parameters, including the etchant chemistry and temperature. The pattern resolution that can be achieved on ClearOhm transparent conductive film by wet etching is the same as with ITO film and is governed by the resolution of the applied etch mask. Figure 6 shows a dark-field micro-scope image of an etched 30-μm line gap that electrically isolates adjacent conductive regions. At this resolution, the pattern created in the transparent conductive film is not visible by the human eye, a key requirement for the patterned layers in a projected-capacitive touch sensor.

In addition to wet-etching processes where the nanowires are completely removed during the etching process, novel methods are possible that exploit the percolative nature of conductive nanowire networks.[9] In the "partial etching" process for the transparent conductive film, nanowires in the etched area are cut into smaller segments, effectively reducing their average length. Due to the strong dependence of electrical percolation on nanowire length, the network can be rendered non-conductive with a minimal amount of material removed.

Figure 7 shows a dark-field microscope image of the resulting pattern created using the partial etching technique. In both the conductive and non-conductive regions, the outlines of the nanowires are clearly visible. However, in the etched area, numerous small breaks in the nanowires that electrically disconnect the network are observed all along their length. Optical properties such as transmission, color, haze, and reflectivity are nearly identical for the conductive and non-conductive regions resulting from the minimal differences in silver nanowire coverage. Patterns that are nearly invisible to the human eye can be produced with this method without the need for additional index-matching layers to minimize the optical differences of the patterned conductor, as is required for ITO film.

Although not described in this article, alternative methods for patterning the ClearOhm layer are possible, including laser-patterning, photosensitive transfer films[10,11] and even direct printing. Direct patterning of the layer via printing represents the most compelling value proposition for cost reduction, by eliminating the numerous process steps and

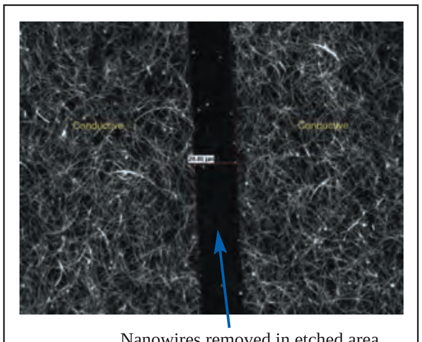


Fig. 6: This dark-field microscope image of a 30-μm gap separating two adjacent conductive regions. The pattern was created by photolithography and wet chemical etching of the transparent conductive film.

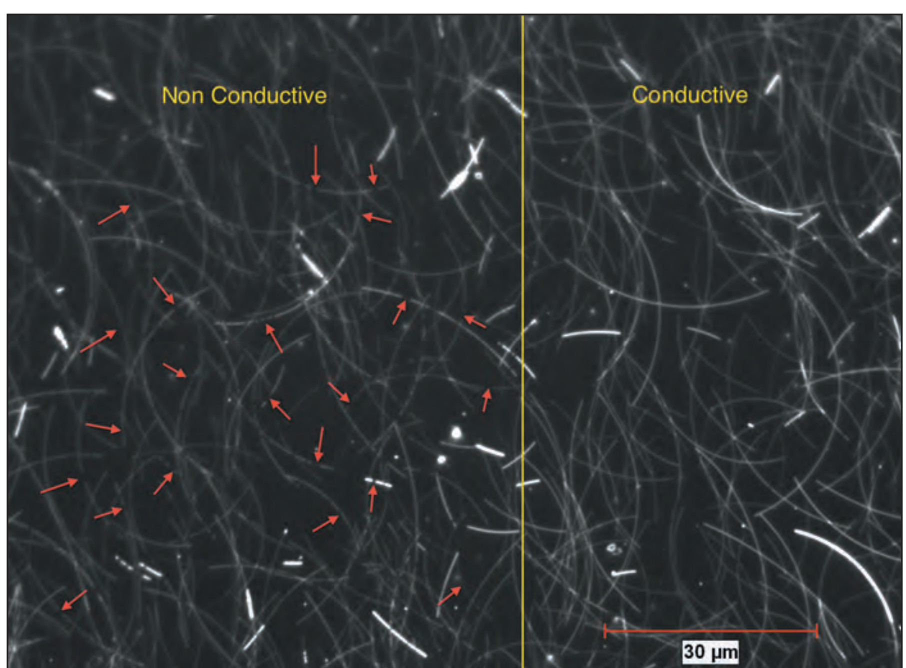


Fig. 7: A dark-field microscope image of ClearOhm film that has been etched using the "partial etching" method. The solid yellow line indicates the border between the conductive and non-conductive region. Red arrows indicate locations of nanowire discontinuities created during the partial etching process.

materials necessary for traditional wet-etching methods. Printable transparent conductive inks have been demonstrated using a variety of printing methods, including ink-jet, screen, gravure, and reverse offset. Future implementations of ClearOhm materials in mass-produced consumer-electronic devices should be able to take advantage of this unique value proposition.

Acknowledgments

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technology preview

Quantum-Tunnelling-Composite Touch-Screen Technology

A new material provides a promising new approach to force sensing that allows transparency and may lend itself to a wide range of touch-screen applications.

by David Lussey

QUANTUM TUNNELLING COMPOSITE (QTC) is a material that is being developed to address some of the ongoing challenges of creating a better touch technology. QTC is made from a polymer that has nanoscale conductive particles, each characterized by a "spikey" surface structure, evenly distributed throughout (Fig. 1). The spikes do not actually touch, but when the material has a force applied, such as pressure, the spikes move closer together and a quantum effect occurs in that the electrons leap or tunnel from one spike tip to the next and a current flows – until the pressure is removed. Thus, QTC provides a change in resistance that is proportional to the pressure applied – from almost infinite resistance when not under force to almost zero when pressed (Fig. 2).

QTC material was discovered in 1996 while the author was trying out different formulas for conductive adhesives. While dismantling one particular experiment, he noticed that the resistance dropped dramatically when he attempted to pull apart two metal strips bound together with one particular formulation.

David Lussey is Chief Technical Officer and co-founder of Peratech Limited, UK. After a 30-year career in the Royal Air Force, he retired as a Specialist Officer and set up a civilian business in 1990, after which he discovered Quantum Tunnelling Composites. He founded Peratech Limited in 1997 to exploit QTCs. He can be reached at david.lussey@peratech.com. QTC and QTC Clear are trademarks of Peratech.

Putting metal particles into a polymer to make a conductive material was not a new concept – what was different was that the metal particles and the adhesive binder had been mixed in a polythene mortar and pestle that imparted low shear forces to the mix. The result was QTC.

Professor David Bloor at Durham University confirmed that conduction was occurring because of a quantum effect – not from the touching of the metal particles. QTC's inventor was able to take out a patent on the manufacturing process to make QTC and founded the company Peratech in 1997. Peratech has continued to research QTC and currently has over 100 QTC patents worldwide. Durham University has a department devoted to investigating the properties of QTC.

In Search of Applications

The first few years of the company's life were spent investigating QTC – how to make it reliably and how changes to the polymer, the conductive materials used, and the size and shape of the particles resulted in QTC materi-

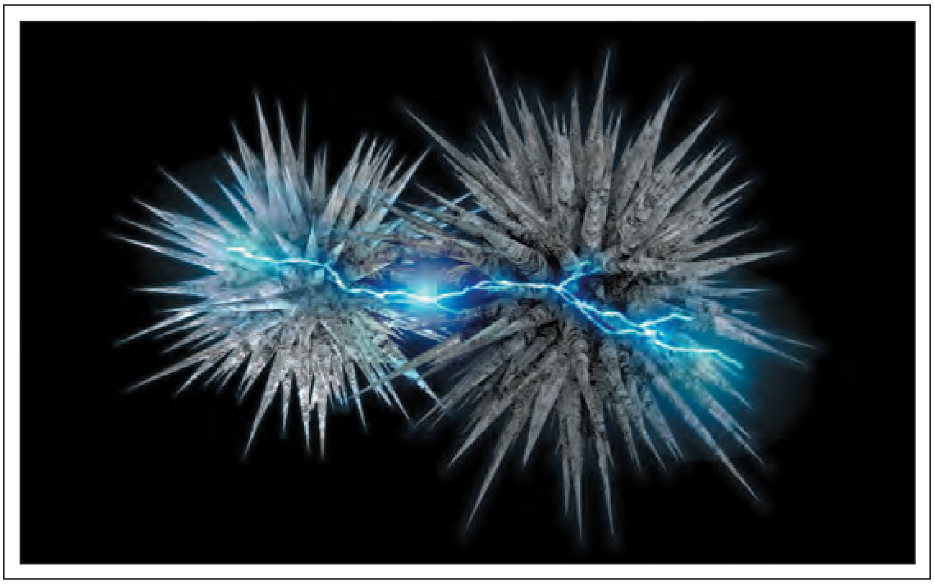

Fig. 1: In this illustration of two QTC particles, the electrons "leap" or tunnel from one particle tip to the next. Source: Peratech, artist's rendering.

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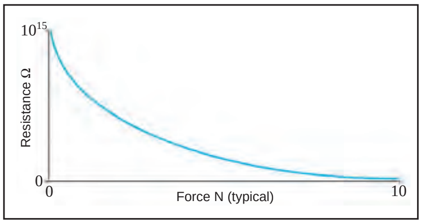

Fig. 2: QTC in bulk form has a very large resistance range and current-handling capability.

als with very different performance characteristics. For example, the overall resistance range can be chosen for the task (Fig. 3), and the sensitivity can range from being so sensitive that a thin film of QTC can act as a microphone to being so insensitive that it takes the weight of a tank to activate it. It can also respond with a smoothly variable change in resistance in the same manner that a conventional variable resistor performs or have a threshold pressure in which it changes from a very high resistance to virtually nothing, just like a switch; in which state it can carry large currents.

When the pressure is removed, the resistance returns to what it was originally – a cycle that can be repeated time and time again. Also, the anisotropic properties of QTC can be controlled to impart functionality to applications such as whiteboards, touch screens, and other large-area devices. Leading whiteboard maker and Peratech licensee Egan Teamboard have pioneered the commercial use of QTC in large-scale applications with the new T3 VRT Interactive Whiteboard.

A key feature of a QTC pressure sensor is that there is no air gap, so there is no possibility of a contaminant getting between two contact points. Similarly, as there is no "make and break" between contact points, there is no possibility of arcing, making the technology interference-free and safe for potentially explosive environments.

One of the first applications for QTC was in clothing in which controls for iPods and similar devices were integrated (Fig. 4). Effectively, a flexible, textile, solid-state switch, the QTC could be washed or dry cleaned, crumpled, and stretched. A number of design wins were achieved with high-end ski brands and suit makers, but the volumes were small.

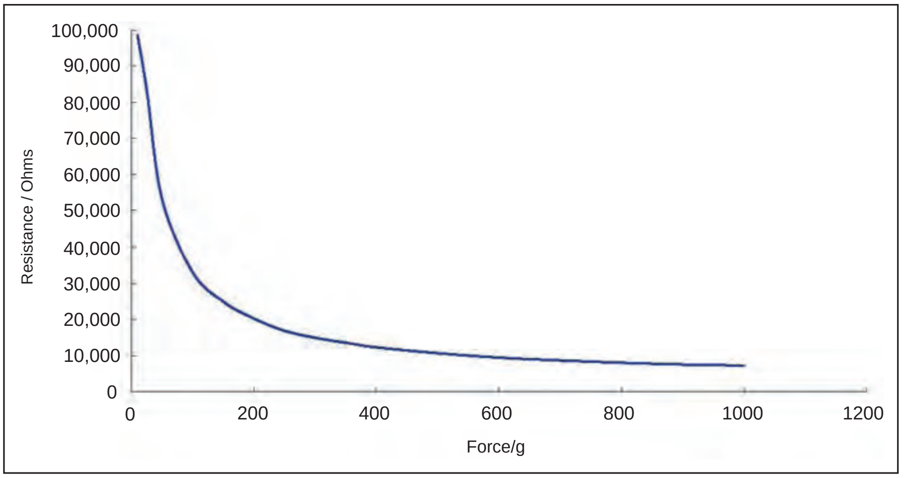

Fig. 3: This is a typical QTC-based ink for touch screens.

In the search for high-volume markets, Peratech also considered mobile phones. One of the main points of failure on a mobile phone is the keypad, as dust or liquids can contaminate the contacts, or the plastic of a collapsible dome switch can lose its resilience and fail to spring back. Peratech, therefore, approached the mobile-phone manufacturers offering to solve this problem for them. However, this was not viewed as a high-priority problem compared to other development challenges. The growing popularity of smartphones was creating a different problem in that the human–machine interface (HMI) was not keeping up with advances in features. A number of phones used a small joystick-like device to navigate a cursor around the screen. However, it was rather crude to have four switches for up, down, left, and right that moved the cursor in the required direction, but only at one speed.

Fig. 4: This ski jacket has QTC switches to control an iPod.

By replacing the on/off switches with QTC sensors, a variable response was now possible. The harder one pushed, the faster the cursor moved, or the faster one scrolled through a list of contacts, or the higher an avatar leapt.

Peratech designed a QTC-based navigation keypad that was licensed by Samsung in 2010 and is currently commercially available in a number of mobile phones. This feature of being able to have a variable response that depended on the amount of pressure applied effectively provided a third dimension of input. The challenge was how to bring this third dimension of input to a touch screen when QTC is a black or gray opaque material.

Peratech's solution was to print a small set of QTC dots 10–20 µm thick around the periphery of the screen (Fig. 5). When pressure is applied to the screen, the dots are compressed against the phone case, enabling this third dimension of input to be achieved. This solution was licensed to Nissha, one of the largest manufacturers of touch screens in the world, to supply mobile-phone manufacturers and mobile-device OEMs and should eventually appear in a shipping product.

Transparency and Touch

Peratech began looking for ways to incorporate its technology as a powerful solution within the touch market. In order to do that, it was necessary to work out a way to employ QTC over the entire area of the screen to give not only pressure sensitivity but also the coordinates of where the pressure was being applied. Developers did this by implementing a solution that used the same structure of well-known resistive touch screens, but replaced that technology's air gap and spacer bumps with an ultra-thin layer of QTC. The challenge was to create a version of QTC that would work at only 6–8 µm thick and at a very low density of particulates, so as to be, for all intents and purposes, transparent. Peratech finally created the right combination of polymer and metal particle size and the resulting film of QTC Clear typically reduces light transmission by less than 1% when applied to a typical touch-screen application. Thus, the structure for the new QTC touch screen is a layer of QTC sandwiched between two layers of conductive material such as silver nanowires or indium tin oxide (ITO), which is, in turn, sandwiched between two transparent sheets of plastic or thin glass. Perimeter conductors are applied in the same way as any other 4-, 5-, or 8-wire resistive touch screen, and the same electrical interface techniques can still be employed.

The top layer of thin glass or plastic can be more rigid than those materials traditionally used for resistive membranes because the QTC can detect tiny deflections of a couple of microns from a force of as little as 5 grams. A harder front surface, such as a sheet of thin glass, also means that traditional problems with resistive technology, such as scratches and top-sheet incursions, can be greatly reduced and that "shaped" screens with compound curves can be produced. One feature of QTC's material is that virtually no current flows unless a force is applied, which is important for battery-operated devices. Just like traditional resistive, this overcomes the power-management challenges of capacitive-based designs that require more energy while searching for a touch event. Lower power consumption in this case also has the advantage of reducing the radiated emissions signature of the screen.

QTC touch screens are also being designed to offer competitively high levels of x-y resolution. As QTC gives a proportional response to touch, the responses from adjacent intersections on an X and Y matrix can be interpolated to provide a highly accurate position. For example, using a 10-bit sampling of the resistance gives 1024 levels of resistance change for the X coordinate and similarly for the Y coordinate, making it ideal for applications in which accuracy is important.

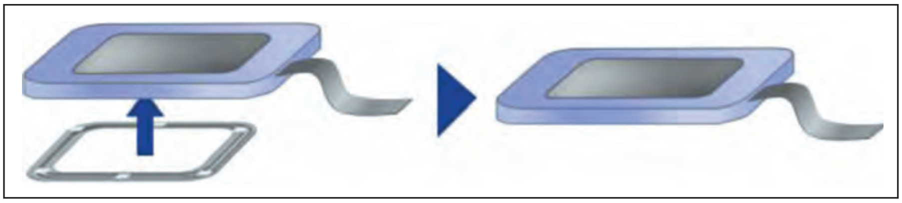

Fig. 5: QTC is added around the periphery of a touch screen.

However, unlike typical resistive solutions, because QTC changes resistance with pressure, this technology provides the opportunity to detect three dimensions of input – x, y, and z. For example, the speed that you scroll through a contact database increases as you press harder. Menu icons can be arranged in three dimensions that you "fly" through to find what you need more quickly. The width of a line being drawn can vary with the pressure applied, which is important for writing characters in some languages.

As the QTC material can be a layer only 6 µm thick, the material costs are minimal and the resulting touch screens should cost the same or less to manufacture than current touch-screen designs, especially as existing resistive or capacitive control electronics can be used. Importantly, QTC touch screens can be made to sizeable dimensions, making possible a wide range of uses from desktop computers to automotive and from in-store displays to interactive control interfaces.

The production of QTC touch screens can be simple, as the QTC material is supplied as an ink that is screen-printed directly onto the electrode layers of one of the substrates. This makes it easy for existing resistive manufacturers to quickly switch from printing spacer dots to printing the QTC layer.

Potential Uses for QTC Touch Screens

QTC touch-screen technology offers the potential to expand touch-screen usage by removing constraints of size, excessive power consumption, system design complexity, and SNR issues. And QTC's ability to respond to very small deformations or pressure changes suggests novel ways of constructing touch screens. For example, the QTC layer could reside behind a thin sheet of metal or similar material – even wood, with small holes to allow light through to create "secret till lit" buttons. This capability would enable a robust interface for applications such as automobile dashboards or consumer-electronic devices such as printers, washing machines, *etc.*, where a glass or plastic screen might be easily broken.

In summation, QTC technology shows considerable promise and has been generating commercial interest. Companies that have been placing patents for the use of QTC in future products include Apple, Nike, Philips, EADS, MasterCard, Samsung, and others. Developers at Peratech believe that new practical uses for this novel material will continue to be discovered. In terms of QTC's use as a platform for touch technology, challenges of scalability and reliability with regard to specific applications are the focus of current work. Peratech has already signed with one major display manufacturer (that it is not at liberty to disclose) and is in search of additional partners.

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Diffuser Films and Optical Performance in LCDs

Diffuser technology is a vital differentiator in the optical performance of LCDs. The authors outline some common approaches for backlighting and film stacks and explain how different types of diffuser films are employed. They also describe how micro-lens diffusers in LCD backlight modules can provide performance that is 10% better than that of bead-filled coated PET diffusers and equivalent to that of coated micro-lens PET diffusers.

by Adel Bastawros, Jian Zhou, Michael J. Davis, Zhe Chen, and Wibowo Harsono

A LIQUID-CRYSTAL DISPLAY (LCD) comprises two primary components for delivering a video image to the viewer: a backlight module (BLM) and a panel. The BLM is the light source that provides necessary illumination for the system, whereas the panel is the addressable light-valve system that converts the video signal into images. Light from the BLM is modulated by the panel so that images are visible to the viewer. Image quality is therefore dependent, in part, on the quality of light generated by the BLM. Common attributes describing image quality that can be linked to the backlight include luminance, viewing angle, image uniformity, and cosmetics (such as point defects).

A BLM relies on a stack of optical films that gathers, redirects, conditions, and delivers the source light – whether from cold-cathode fluorescent lamps (CCFLs) or light-emitting diodes (LEDs) – toward the panel.[1] Attributes of the individual films in the stack dictate the module's ability to meet luminance (brightness) and uniformity requirements of the entire display. The stack design (number, type, and arrangement of films in the stack) varies as a function of lighting configuration (edge-lit or direct-lit), manufacturer, performance, and power-consumption requirements. Figure 1(a) shows an example of a typical or standard film stack for an edge-lit BLM in which the CCFLs are placed proximate to the edges of the light guide.

The first film in the standard stack, or the bottom diffuser, plays the important function of gathering light and redirecting it toward the next film. This functionality is often referred to as "collimation," since the film steers light traveling in all directions toward a preferred direction. In addition, the bottom film diffuses and blends light from different lamps and delivers an even light intensity (or luminance) distribution. This is often referred to as the "hiding power" of the diffuser – the ability of the diffuser film to hide the spatial differences or non-uniformities in light intensities from an array of lamps. These two, often conflicting, requirements of a bottom diffuser drive innovative optical designs of such films. Additional films in the stack (prism and top diffuser films) further steer and condition the light to illuminate the panel.

This article discusses diffuser films that exhibit improved light-redirecting capabilities while retaining hiding power (diffusion). The approach used is to create engineered light-steering elements, or micro-lenses, directly on

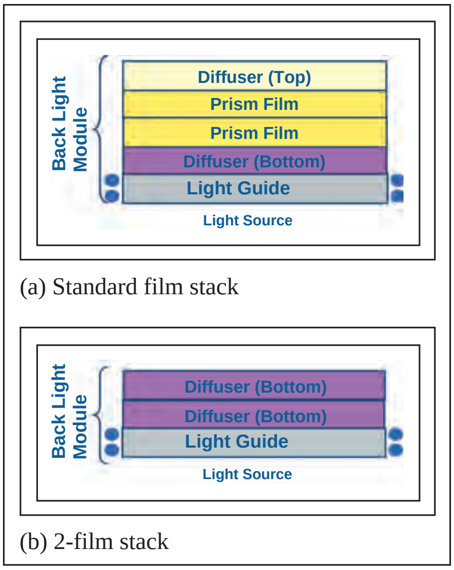

Fig. 1: *The film stacks shown represent cross-sections of an edge-lit BLU configurations, with the lamps (shown as blue dots) placed at the edges of the light guide. The stack shown in (a) uses a legacy bottom diffuser film that requires additional films to steer the light. The stack in (b) uses more modern light-collimating bottom-diffuser films that reduce the need for materials.*

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the film in the same melt calendering process used to make the film. In this process, molten resin is quenched into film as it passes between two cooling rolls. Other approaches used in the industry, as shown in Fig. 2, include the application of bead-filled coatings to produce the collimation effect. More recently, coatings with micro-lens geometries have been introduced (Fig. 3). Such films have the performance needed in LCD applications; however, they both require additional post-processing steps of the optical film (typically bi-axially stretched polyethylene terephthalate or PET film) to accomplish the desired functionality. Both approaches require that the film be made first, then the functional surface in additional coating processes is created. Melt calendering allows for creation of the functional surfaces while making the film itself; no additional steps are required.

It is worth noting that legacy bottom diffuser (BD) films provide diffusion only, so the BLM relies on additional light-redirecting films (such as prismatic films) to steer the light. Use of light-collimating and diffusing films, such as those discussed here, provide additional luminance gain for the module. Moreover, the light-collimation characteristic of such films enables an efficient economic stack comprising only two such films, as shown in Fig. 1(b), thus reducing the cost of the BLM. Such stacks are attractive from a cost versus performance standpoint. Their performance is typically in the 80–90% range of a standard stack. This article's primary focus will be on BLMs that comprise two bottom-diffuser stacks. Standard stack performance will be used throughout as a reference point.

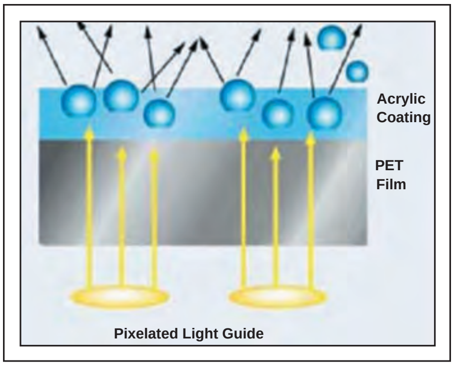

Fig. 2: A bead-filled coated diffuser can be used to produce the light-steering effect.

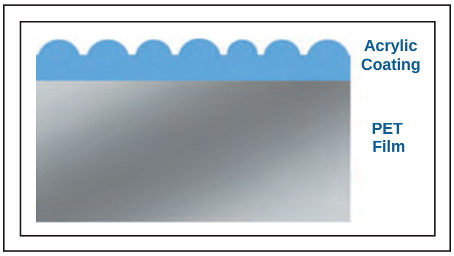

Fig. 3: A coated diffuser with micro-lens geometries is a more recent light-collimation technology.

Optical Films

Light rays traveling through and exiting an optical film follow light-refraction physics. The slope of the surface elements dictates the exit direction of a light ray. Controlling the manner in which light rays exit a surface is therefore possible by controlling the surface slopes. In another research development,[2] the authors identified desirable slope distributions for a surface that are necessary to "turn" light rays in a desirable direction (*e.g.*, toward the viewer). Without light turning, a portion of generated light will be wasted if left to travel in less useful directions, such as away from the panel.

Ray-tracing algorithms utilizing Monte Carlo simulations of light rays traveling through the film were employed for parametric studies of the effects of surface geometry on the direction and intensity of light exiting the film. Figure 4 shows a schematic of the ray-tracing approach used. Light rays reaching the exit surface at an angle larger than the critical angle for film material will undergo total internal reflection (TIR) and will not exit the surface. Such rays will keep bouncing between surfaces of the film (and reflectors in the backlight module) and change their direction until they exit the surface at a desirable angle; hence, the collimation behavior of the film.

The same ray-tracing approach can be used to generate data indicative of an entire BLM's luminance, hiding-power, and viewing-angle characteristics. This is accomplished by performing area assessments so that the effects of spatial differences in the light source and/or film surfaces, observed from different locations at different angles, can be estimated.

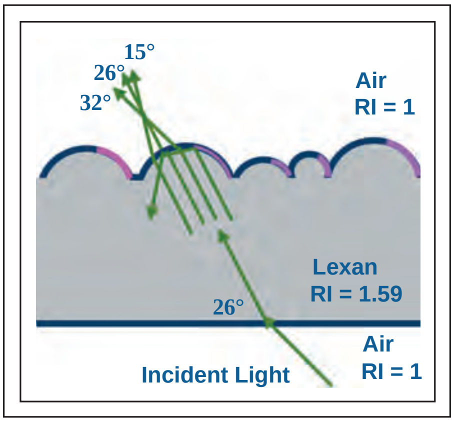

Fig. 4: A ray-tracing approach shows rays exiting within a narrow angle range. TIR causes other rays to bounce and undergo multiple reflections until they exit at the same angle range. (Lexan is a brand of plastic material.)

Micro-Lens Geometries for Diffusers

An optimum BD is one that has light-steering elements, such as micro-lenses, covering the entire exit side of the film. Hemispherical lenses that are closely packed meet the slope distribution requirement[2] for optimum light redirecting. Close packing of micro-lenses in a hexagonal arrangement, as shown in Fig. 5, offers an efficient packing scheme. Throughout the rest of this article, hexagonal packing of similar micro-lenses is used, and the performance of actual films conforming to such geometries is discussed.

An ideal hexagonal micro-lens pattern is one with zero gaps between lenses that are perfect hemispheres and perfectly smooth land areas between the lenses. In contrast, an actual film will have finite gaps between the lenses, distortions to the hemispherical geometry, and possibly some roughness in the land area. To understand the impact of departure from an ideal pattern, the authors ran numerical experiments using the above ray-tracing approach to study the effects of the gap and lens contour. Descriptors for micro-lens geometry were selected based on observations of actual films. The roughness of land areas between cells was not included in the simulation because it is less challenging to obtain smooth surfaces if desired. Figure 5 depicts the different micro-lens contours used in the simulation. Except for an ideal hemispherical geometry (contour a), each contour is divided into three possible sections: a dome, side wall,

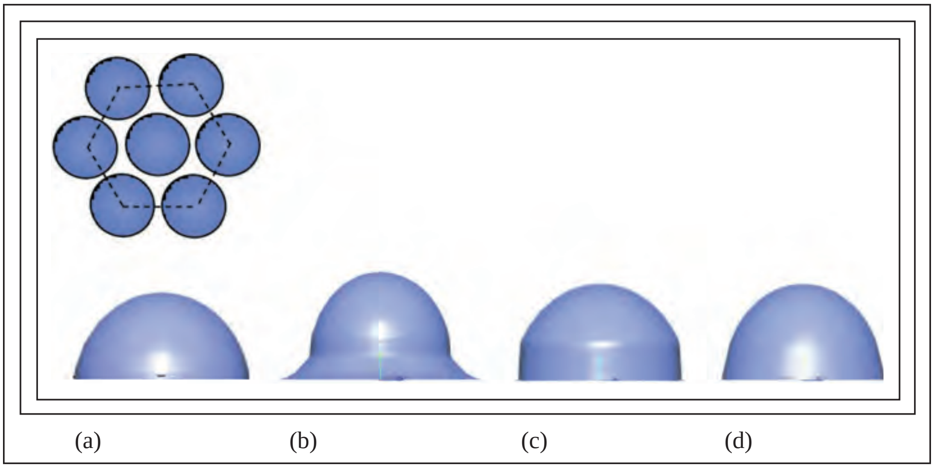

Fig. 5: The following micro-lens contours were used for simulations: (a) ideal hemisphere; (b) micro-lens contour comprising dome, side-wall, and flange sections; (c) micro-lens contour comprising dome and side-wall sections; (d) micro-lens contour comprising a dome only.

Table 1: Ray-tracing luminance predictions for different lens geometries and packing efficiencies show that luminance drops with larger gaps and stronger deviation from hemispherical geometry.

Contour	Gap/Center-to-Center Distance	Luminance (%of Standard Stack)
a	0.00	92.0%
b	0.23	78.0%
c	0.11	85.0%
	0.18	82.1%
d	0.11	86.8%
	0.18	85.0%

and a flange; each having geometric dimensions and weights that were selected based on observations of actual micro-lens films. The dome portion is not necessarily hemispherical.

For simplicity, the performance of different film stacks is presented as the ratio of a standard stack. Performance of the standard stack is therefore used as a reference (100%). This approach eliminates design, light source, and model dependencies and highlights the effect of film geometry selection on performance. The reference (standard) stack used in the current work is shown in Fig. 1(a) and comprises a BD (of the bead-filled coating type), two prismatic films with prism directions crossing each other, and a simple top diffuser. This is a common edge-lit BLM arrangement used in a variety of LCDs. The corresponding two-film-stacked edge-lit BLM configuration is shown in Fig. 1(b).

Numerical experiments were run to predict luminance in a two-film-stacked configuration relative to the standard stack. The four geometries shown in Fig. 5 were used. The gap between the lenses was represented as a ratio of the center-to-center distance. This dimensionless parameter spanned the range 0.0–0.23. Zero represents an ideal hexagonal packing of perfect hemispheres with no gaps (contour a), whereas 0.23 represents a case of distorted lenses (contour b) where the flanges in the contour contribute to the large gap. Intermediate values of 0.11 and 0.18 were associated with contours c and d, respectively. Lenses are always round at the base. For a 0.0 packing efficiency, the lenses will be touching each other at a point. Simulation results for luminance as a percentage of the standard stack are summarized in Table 1 and presented graphically in Fig. 6. As anticipated, the simulation results indicate that larger gaps between the micro-lenses and shape distortions are two key factors affecting luminance level. The results further provide the sensitivity of luminance to such factors and are invaluable for setting practical targets when making actual film. This approach was useful in streamlining experimental work in a cost-effective manner. The following sections discuss the making of micro-lens diffuser film and present actual performance data.

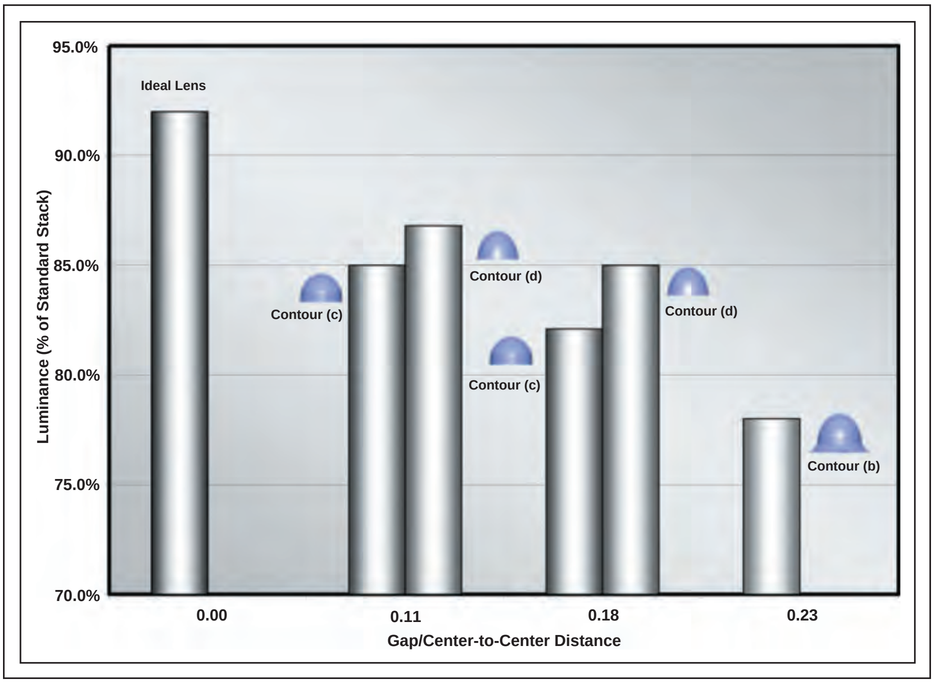

Fig. 6: This chart shows the relative luminance (predicted) change with lens geometry and packing.

Lexan Micro-Lens Films

The authors recently developed monolithic films with a micro-lens surface topography for light management in LCD applications. Sabic's Lexan (a trademark of SABIC Innovative Plastics IP BV) micro-lens films (75–450 µm) are made in a melt-calendering process, in which the molten polycarbonate resin is quenched into film as it passes through the nip of two chill rolls.[3] A negative image of the desired pattern is created on one of the chill rolls,[4] the mastering tool. During calendering, the pattern is replicated to the film under nip forces between the two rolls. Replication of the film occurs at a certain efficiency that is dependent on line design, nip forces, heat management in the calendering stack, and flow characteristics of the polymer. Different calendering lines have different replication behaviors; those need to be fully characterized and suitable process windows need to be identified in order to be able to replicate and control engineered surface features such as the micro-lenses discussed here.

For the purposes of this project, mastering tools with lens designs similar to those of contours b, c, and d were made and used to produce actual film material. Micro-lens sizes of 10–100 µm were also made. The resulting film surfaces are shown in Fig. 7 for contour b, and Fig. 8 for contours c or d (the two contours look very similar under the microscope). The film in Fig. 7 is often referred to as basic lens (BL) diffuser film, whereas that of Fig. 8 is referred to as a "high gain" diffuser because it confines (collimates) the output light into a narrower angular field.

The three films were tested in actual BLMs, and luminance measurements were performed in a two-stack configuration. The resulting performance relative to an actual standard stack is depicted in Fig. 9. The performance of two reference coated diffusers is also shown. These were bead-filled coated PET film (A), as shown in Fig. 2, and coated PET diffuser (B), as shown in Fig. 3.

Measured luminance values for the basic lens, high gain, and coated PET diffusers are summarized in Table 2. Where applicable, predicted values are also included.

Results

Measured luminance for the basic lens diffuser in a two-film stack exceeded that of a commonly used bead-filled coating on a PET film (A); 79% versus 76%. The difference may relate to the maturity of the micro-lenses on the surface of the bead-filled coating. Because such diffusers rely on the beads erupting from the coating surface to form micro-lenses and provide the optical functionality, it is foreseeable that some of the beads may not be sufficiently erupted and will thus form less-efficient lenses. On the other hand, with a basic lens diffuser, all micro-lenses are mature and fully formed. The performance of the basic lens is still lower than that of the coated PET diffuser (B); 79% versus 87%.

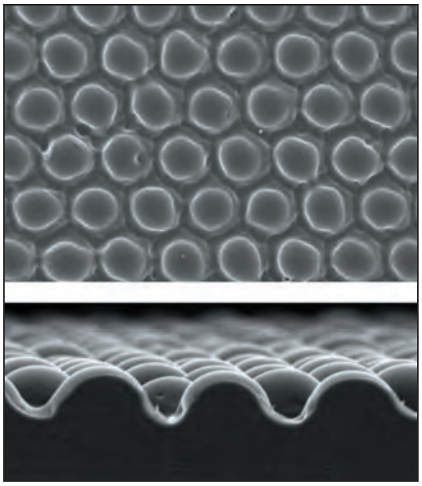

Fig. 7: Scanning electron microscope (SEM) topical and cross-sectional views show actual micro-lens geometry and packing in Lexan basic lens diffuser film.

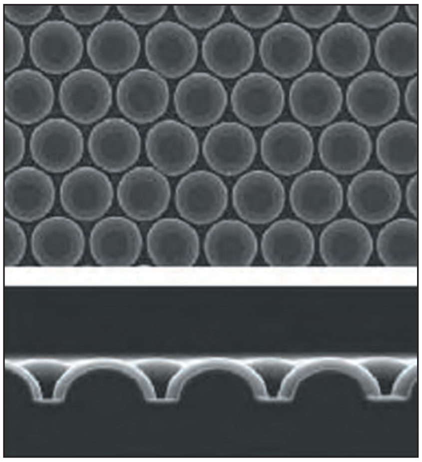

Fig. 8: SEM topical and cross-sectional views of Lexan high-gain diffuser film show micro-lens geometry approaching a hemi-spherical contour and reduced gap between micro-lenses.

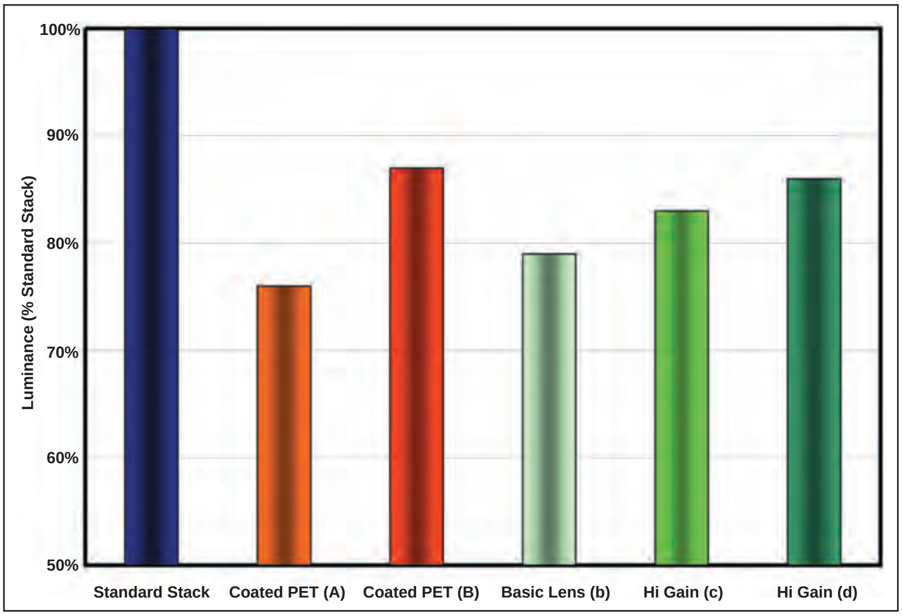

Fig. 9: Measured luminance in two-film-stacked configurations is shown relative to a standard stack (100%).

Table 2: Measured and predicted luminance is compared.

	Measured Luminance	Predicted Luminance
Standard Stack	100%	100%
Basic Lens (b)	79%	78%
Hi Gain (c)	83%	82%
Hi Gain (d)	86%	87%
Coated PET (A)	76%	—
Coated PET (B)	87%	—

In the latter, the micro-lenses are created in the coating in a micro-replication process that is capable of creating mature and controlled micro-lenses. Other than cost and processing disadvantages, these coated diffusers have the desired performance. The luminance level of the basic lens diffuser may be explained by the shape distortions and spacing between the lenses. Modeling results indicated that luminance will be negatively impacted when the shape departs from a hemisphere and when the spacing between the micro-lenses increases. These characteristics are, however, beneficial in providing an added degree of diffusion and are advantageous in applications requiring higher degrees of hiding power.

High-gain diffusers are suited for applications requiring maximum luminance over a narrower field of view. Control of the cell contour and packing density was assessed numerically and implanted in the film-making operation. Luminance increased from 79% (for basic lens) to 83% and 86% for films (c) and (d), respectively. High-gain diffusers (d) are equivalent in performance to coated PET (B) and are 10 percentage points better than bead-filled coated PET diffusers (A).

It is worth noting that luminance predictions were in good agreement with measured values, as shown in Table 2. This observation provided confidence in the simulation approach and validated the simulation tool for further design changes and additional parametric studies. Identification of geometric attributes of a diffuser film surface for desired functionality is thus possible. However, working back these attributes to a mastering tool and a calendering process window to impart desired surface on a Lexan film can be challenging. Often, a number of tooling iterations and thorough characterization of the calendering process are required before realizing target geometry.

The work discussed in this article used a two-stack edge-lit configuration as an example to demonstrate the performance of Lexan micro-lensed diffusers. Similar trends are observed when other designs or stacks are considered. For example, the relative performance in a two-stack "direct-lit" configuration was found to be identical to the trend observed in the current project.

To summarize, the optical performance of PC micro-lens diffusers in backlight modules of LCD applications was shown to be 10% better than bead-filled coated PET diffusers and equivalent to coated micro-lens PET diffusers. Effects of lens geometry and packing on luminance were identified, and improvements of 4% and 7% over a basic lens design were realized. In a field where minimizing the thickness, weight, and power requirements of LCD modules is an ongoing mission, every opportunity for improvements in light efficiency is to be regarded with serious interest.

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LatinDisplay 2011: Displays in the Southern Hemisphere

by Alaide P. Mammana and Victor P. Mammana

LatinDisplay, the premier Latin American event for displays and related technologies, serves the dual purpose of promoting display technology and developing the display industry in South America and in Brazil in particular. The most recent LatinDisplay ran in tandem with the Brazilian Congress on Applications of Vacuum Science and Industry (CBRAVIC), an organization that addresses vacuum and plasma science and technology. All these technologies will be represented in a future industrial park in Brazil that will incorporate the entire display supply chain. LatinDisplay took place at the Federal University of Itajubá in Minas Gerais, Brazil, in August of 2011, and included a scientific and technical symposium, a business opportunities event, an exhibition, and the popular DisplayEscola (school for displays).

Scientific and Technical Symposium Highlights

A total of 19 invited lectures and 195 contributed papers were presented at the Symposium. Munisamy Anandan, SID President and CEO of Organic Lighting, offered a description of a new technology for backlighting systems that employ UV LEDs that dispense with color filters. The latest advances in active matrix for LCDs and OLED displays were described by Tolis Voutsas, SID Vice President of the Americas and Director of the Materials and Devices Applications Laboratory of Sharp Labs of America. He compared different amorphous semiconductor technologies and noted that indium/gallium/zinc (IGZO) was a promising material for the next generation of thin-film transistors (TFTs) for active-matrix displays. Shigeo Mikoshiba, Past-President of SID and Professor at the University of Electro-Communications, Tokyo, Japan, focused on plasma-display panels (PDPs) and their principles of operation, manufacturing processes, and advantages and disadvantages when compared to other display technologies, especially LCDs.

Reflective displays and flexible displays were both highlighted topics at LatinDisplay 2011. Michael McCreary, Vice President of Research and Advanced Development and Global Deputy Chief Technical Officer of E Ink, described recent developments in micro-encapsulated electrophoretic display technology for consumer products and signage applications. Si-Ty Lam, a scientist at HP Labs in Palo Alto, CA, presented recent results obtained with color reflective displays on an array of TFTs (AMTFT backplane).

Other presentations included a lecture on 3-D displays by Adi Abileah, Chief Scientist at Planar Systems, who introduced the principles of stereoscopy and different methods of producing images with depth, and also discussed the strengths and weaknesses of different 3-D systems. Daniel den Engelsen, a visiting scientist at ABINFO and CTI and a visiting professor at the University of Nanjing, China, and Brunel University, England, discussed perspectives and trends in what he called "a revolution in the lighting industry," thanks to the advent of solid-state lamps based on LEDs and also OLED lamps or lamp sheets. His market analysis included exceptional opportunities for Brazilian participation. Gregory J. Exarhos, Associate Director of the Chemical and Materials Sciences Division of the Pacific Northwest National Laboratory, EUA, and Past-President of the American Vacuum Society (AVS), described conjugate property films and how to enhance their performance through design, including transparent and conductive oxide films.

The Brazilian Association of Information Technology (ABINFO) awarded Luis Aguirre from the University of Cordoba, Argentina, with a cash prize and a certificate for "Best Poster of LatinDisplay 2011/CBRAVIC 2011" for his work on "Pattern formation induced by electrical instabilities in nematic liquid crystals with positive dielectric anisotropy."

Meetings, Field Visits, DisplayEscola, and Exhibition

Two round-table discussions on the Brazilian Industrial Policy for Displays were among LatinDisplay's featured events. The discussions focused on an initiative designed to support different companies that are part of the display production chain and to attract foreign groups to manufacture displays in partnership with Brazilian companies. Both government and display experts participated, and together they sought to identify the most urgent plans of action.

As part of the event, there was a program of visits to companies and laboratories in the region of Itajubá, as well as to the business incubator at the University of Itajubá. At the manufacturer Nitere, visitors could view the processes developed by that company to make rugged touch screens, and in the Microelectronics Laboratory of the University of Itajubá, they learned about integrated-circuit design for medical applications.

DisplayEscola, now in its 14th edition, presented courses on plasma displays, backlight units for LCDs, display measurements, and lighting. The school remains the only initiative in the Southern Hemisphere for training in displays and related technologies.

At the exhibition (Fig. 1), companies and institutions exhibited state-of-the-art touch screens; the latest generation of vacuum pumps, detectors, and sensors; instruments and equipment for laboratories; and other display-related technologies.

LatinDisplay 2011 / XXXII CBRAVIC was organized by the Latin American Chapter of the Society for Information Display (SID),

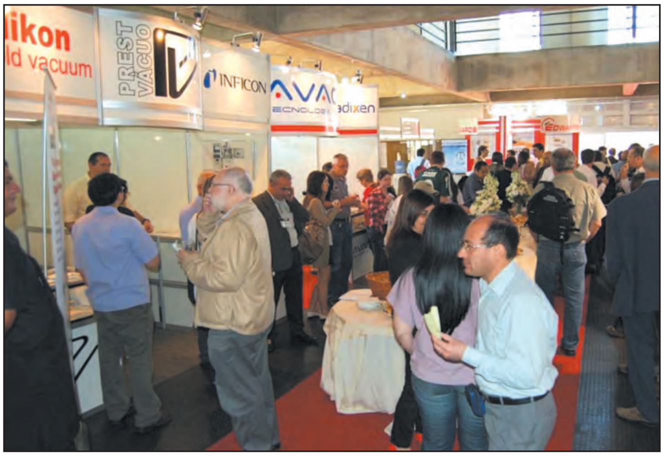

Fig. 1: A well-attended exhibition was just one component of last August's LatinDisplay.

continued from page 3

Associação Brasileira de Informática (ABINFO), and the University of Itajubá, MG Brazil. As an event of the Brazilian Network on Displays (BrDisplay), LatinDisplay 2011 is central to supporting the implementation of the Brazilian Industrial Policy proposed by the Federal Government for displays and related technologies. The event was sponsored by the Brazilian Government, with funding from ABDI (Brazilian Agency for the Industrial Development), CNPq (National Research Council), CAPES/Ministry of Education, and FAPEMIG (Foundation for Research of Minas Gerais State).

More information can be found at http://www.abinfo.com.br/ld2011.

Alaide P. Mammana *is the Director of the Latin American SID Chapter and* ***Victor P. Mammana*** *is the Director of the Renato Archer Center of Information Technology (CTI) and the Chairman of the Latin American SID Chapter. They can be reached at alaide.mammana@ uol.com.br and victor.mammana@cti.gov.br, respectively.* ■

can not be divulged) with the aim of creating LED lighting with superior color performance.

Nanoco believes that its quantum-dot technology has the potential to bolster the widespread use of solid-state lighting in commercial, residential, and other settings and is therefore a key area of Nanoco's R&D activities. According to Court, the company has already developed a range of trial units that combine the company's red quantum dots with blue LEDs to create a "warm" white light with a high color-rendering index.

When blue light from an LED passes through red quantum dots, the light is re-emitted as red light. Similarly, green quantum dots can be combined with a blue LED to achieve green light. A blue LED with red and green quantum dots produces what appears to the human eye as white light. This white light can be in an almost infinitely variable range of shades, dependent on the particular size and combination of red and green quantum dots.

According to Court, Nanoco can control the size of the quantum dots to control the shade of light emitted and should therefore be able to develop LED lighting with the required characteristics for the home, office, and elsewhere. Nanoco is also working with the liquid-crystal-display (LCD) industry to combine quantum dots with LEDs for TV backlighting applications.

– Jenny Donelan

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editorial

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of a simple resistive touch screen, may be a game changer. We thought the artist's rendition of the quantum tunneling effect was so eye catching that we decided to put it on the cover of this issue.

In this month's regular feature, Making Displays Work for You, we feature an article on improving light efficiency in LCD backlights titled "High-Gain Diffuser Film Enhances Optical Performance for LCDs." Authors Adel Bastawros and colleagues from SABIC Innovative Plastics discuss all the details of making their micro-lenses and in the process show how there are still valuable incremental improvements to be found in this area. In a time when every fractional watt of power efficiency is cherished, you can use these materials right now to improve your own designs.

As always, we also bring you a regular monthly dose of industry news and SID news, the latter this month a review of the LatinDisplay 2011 Conference, where a number of our well-respected colleagues gave presentations and networked with new SID members in a rapidly emerging display marketplace.

One item not featured in our Industry News section deserves mention. The news came to us just before press time that mobile technology company Qualcomm had just acquired a Massachusetts startup company named Pixtronix. You may or may not have heard of Pixtronix and its Digital Micro Shutter MEMS display technology. Qualcomm, of course, has been working on its own MEMS displays trade named mirasol for several years – as we have reported in *ID* magazine many times. Qualcomm is just on the verge of commercialization and has made significant investments in manufacturing capability to bring the mirasol displays to market. At press time, neither company would comment about the strategy behind the acquisition, leaving industry analysts speculating about the future of the two similar but different display technologies and what Qualcomm might be contemplating. Hopefully we will have more to report next month. Meanwhile, we extend a hearty congratulations to the team at Pixtronix for its hard work and what looks like a fairly lucrative payday for everyone including the investors. We're sure the rest of the story will reveal itself before too long. ■

guest editorial

continued from page 4

use of a transparent Quantum Tunneling Composite (QTC) force-sensitive material, QTC Clear. The basis of this approach is a composite employing conductive metal nanoparticles dispersed throughout a clear elastomeric matrix, with a composition tailored to enable significant conductivity changes when the material is compressed. The particle concentration is adjusted so that at rest the composite is insulating, but when pressure is applied the conductivity along the compression direction increases orders of magnitude. The local deformation reduces the interparticle distance and consequently increases conductivity via electron tunneling, or hopping across the nanoparticles. Naturally, due to the sensitivity of the resistance to pressure, this remarkable material should find applications in a new generation of resistive touch panels by replacing the conventional air gap, thus eliminating the optical drawbacks of conventional resistive touch panels. Moreover, the sensitivity of the response to various touch pressures enables a third dimension of sensing besides the (x,y) location, which is another reason for the excitement around the opportunities for user interactions enabled by this new material.

I enjoyed working on these stories about new materials developments, and I hope you learn as much from reading them as much as I did.

***Ion Bita** is Staff Engineering Manager at Qualcomm MEMS Technologies. He can be reached at ibita@qualcomm.com.* *The opinions expressed in this article are a personal reflection of the current state and trends in the industry and not necessarily the views of Qualcomm, Inc. or Qualcomm MEMS Technologies, Inc.* ■

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The following papers appear in the January 2012 (Vol. 20/1) issue of *JSID*. For a preview of the papers go to sid.org/jsid.html.

Contributed Papers

Special Section on Papers Based on Presentations from the 2011 SID Symposium

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