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Indium Tin Oxide and Alternative Transparent Conductor Markets

April 2009

Executive Summary

E.1 Opportunity Analysis

The transparent conductor industry is dominated by a single material—indium tin oxide (ITO). Manufacturers of flat-panel displays (the largest users of ITO) have relied on this material for years but have always griped about ITO's inability to meet their requirements. When used as a conductor, ITO is not very conductive, and as a transparent layer, it is not very transparent. Beyond this fundamental shortcoming is the fact that ITO is generally difficult and expensive to apply as a thin film of sufficient quality. Once it is applied, it is brittle, and therefore can easily wear out or crack when used in applications where bending is involved. The price for this mediocre performance is quite high, since ITO is dependent on indium, which has been priced at $350 to $1,000 for the last several years.

ITO's many faults would seem to create a ripe environment for competition—new transparent conductor materials offering improved performance in the areas where ITO falls short, and different methods of using and applying ITO to address these issues.

These things *should* happen, and presumably they will some day, but we are not there yet. Since NanoMarkets issued its first ITO report in 2008, ITO has shown little sign of fading away, and because of the price decline due to the worldwide recession, its end is even further out than we might have previously expected. We did warn in that report, however, that alternatives to ITO would make progress, but only slowly; this has proved to be true, and it probably would have been so even without the recession. However, the ITO market is very large, so that even small inroads into the market by ITO alternatives can lead to substantial revenue opportunities. In addition, some of the new applications that are emerging are only enlarging the challenges that ITO is facing.

E.1.1 New Applications Challenges to ITO: Displays, Lighting, and PV

Touch screens: Touch screens routinely use ITO in the touch subsystem as well as in the LCD frontplane from which they are usually built. Resistive touch screens, which dominate the market, are ripe for an alternative transparent conductor. All one must do to verify this firsthand is walk into a local high-volume retail establishment and attempt to sign on the old, worn-out point-of-purchase display device. ITO cannot stand up to the repeated poking and flexing that is involved with this type of touch screen without deteriorating or cracking.

Capacitive touch screens are a different story. These are emerging as the high-end version of the touch-screen category, especially since the launch of Apple's iPhone, which uses capacitive technology. Capacitive technology offers higher clarity and quality of the display image and since it does not work by poking with (say) a stylus, the capacitive screen can more easily make use of ITO. However, resistive technology is likely to take most of the touch-screen market for some time to come and will be one of the first areas to adopt an ITO substitute in a significant way.

Makers of ITO substitutes see the touch-screen market as a big opportunity; in addition to the business and engineering reasons supporting the adoption of such a technology, the addressable market is already very large. As a result, NanoMarkets expects ITO to lose market share in the resistive touch-screen segment fairly quickly, although, absent some kind of breakthrough in the transparency and conductivity of an alternative, NanoMarkets expects ITO to dominate the capacitive touch-screen market throughout the forecast period.

Flexible displays: Flexible displays would be an attractive market for ITO substitutes, because, like touch-screen displays they also place important physical demands on the transparent conductors that they use. However, despite the impression that one might get from a superficial read of the trade press, there is really no such thing as a fully flexible display on the market today.

There have been demonstrations (in late 2008 an issue of *Esquire* magazine was released with an e-paper display on its front cover), as well as announcements of such displays, but none are commercially available. For instance, the first flexible e-book reader, Readius by Polymer Vision, was scheduled for release in 2008 but now is not expected until later in 2009.

And in terms of flexible OLED displays, these are even further behind. While Samsung has announced that it expects to introduce flexible OLED displays in 2010, flexible OLED displays have far fewer backers than flexible e-paper displays and indeed the term “flexible display” and “e-paper” have become closely related, if not synonymous.

With the plethora of product delays throughout the thin-film electronics industry, NanoMarkets has a healthy skepticism with regard to claims of imminent releases of revolutionary devices. Thus, NanoMarkets doesn’t expect flexible OLED displays to gain a foothold in commercialization until 2011 or later.

Thin-film photovoltaics (TFPV): TFPV stands out as the only one of these five major application areas for transparent conductors in which ITO does not start off as the dominant market leader. Only organic photovoltaics (OPV) and closely related dye-sensitized cell (DSC) PV—the lowest-volume technologies and the furthest from commercialization—use mainly ITO for their transparent conductors. The most recent entries onto the TFPV commercial landscape, CdTe PV and CIGS PV, mainly use alternative TCOs (fluorine-doped tin oxide for CdTe and aluminum-doped zinc oxide for CIGS). And the long-established amorphous silicon (a-Si) PV industry, although it used mainly ITO prior to about 2000, now uses alternative TCOs (AZO and FTO) as much as ITO.

ITO is not heavily used in the TFPV sector, in part because this sector is very cost-conscious. This area is attracting considerable attention from makers of ITO substitutes for a number of reasons. One such reason is simply that PV is one of the few industries that has continued to experience growth during this recessionary period and so is seen as providing an attractive customer base. Another relates to flexibility. The TFPV industry is heading toward flexibility in higher-end products—a move that may bring about some opportunity for other alternative transparent conductors (besides TCOs). Especially in the pre-commercial fields of OPV and DSC, there is a lot of experimentation going on with flexible transparent conductors.

As such, NanoMarkets expects non-ITO TCOs to remain dominant in the TFPV segment throughout the forecast period. ITO is not expected to make any increase to its fairly low market share; instead, the more flexible alternatives (including polymers, CNTs, and the metal formulations discussed below) will make inroads into this market toward the latter part of the forecast period.

Solid-state lighting: OLED and electroluminescent (EL) lighting both employ ITO as the transparent electrode in most cases. If there is a reason to replace ITO in EL lighting it would be cost, since this type of lighting is used primarily in cost-sensitive areas such as automotive dashboard lighting and low-end signage applications. But EL is a mature technology that most people believe will gradually be replaced by better performing sold-state lighting technologies, so the opportunities are not that great in the long-term for transparent semiconductors of any kind.

The opportunities are much greater, however, in the area of OLED lighting, which is expected to yield higher-performance devices and to eventually become a major part of the general lighting market because of its energy efficiency and potential low cost in the future. OLED lighting is just emerging as a technology, and although ITO is usually used for its transparent electrodes, it is not firmly entrenched because of this early state of development. In addition to the usual drawbacks of ITO—cost and lack of flexibility—OLEDs can suffer aesthetic shortcomings due to ITO's fairly low conductivity. Large OLED panels, such as might be used in lamps, will show a brightness gradient as voltage drops along the length of the panel because of ITO's resistance. This non-uniformity of brightness can be addressed by adding a metal electrode grid, but that too often has aesthetic consequences.

NanoMarkets expects ITO to lose share of the OLED lighting market fairly rapidly. (And, of course, such a market barely exists anyway, so there is no established use of ITO as such.) In its place will be a variety of substitutes: other transparent conducting oxides (TCOs) at the low end, as well as conductive polymers, carbon nanotubes (CNTs), and composites. While the EL lighting market will go into decline toward the end of the forecast period, NanoMarkets expects lower-cost TCOs and polymers such as PEDOT to begin to take some share of what's left of the market, helping to extend its life.

Rigid FPDs: As we discuss below, rigid flat-panel displays (FPDs) are not likely to see early inroads by ITO alternatives. However, even this area, we believe, will not be completely invulnerable to competition by ITO substitutes. The rigid FPD marketplace offers producers of ITO alternatives an opportunity to introduce their products one step at a time: first demonstrate performance on a standard platform (the rigid FPD), then go after the targets with greater payoff.

A couple of firms (e.g., Cambrios) seem to be adopting this strategy and NanoMarkets expects ITO alternatives to claim a small portion of the rigid FPD market fairly soon, albeit claiming an increasing market share at a slow pace. Instead, these products will be used as a jumping-off point into the other markets.

E.1.2 Not Fade Away: Where ITO Will Stay Unchallenged

Our analysis suggests that even by 2016, ITO will still have about 90 percent of the high-end transparent conductor market. (This may make efforts to come up with ITO substitutes seem rather pointless, but the OEM market for ITO is so large, that the 10 percent is worth chasing after.) While this number is an estimate only, scenarios in which ITO's use declines significantly as a share of the market are simply not credible and are not often made even by manufacturers of ITO substitutes, although they are sometimes.

The applications for ITO where NanoMarkets expects ITO to retain its dominance well beyond the time period considered in this report are those in which its use is not hindered by ITO's brittleness and where cost concerns are overridden by a requirement for maximum transparency/conductivity performance. This would include rigid FPDs and high-performance capacitive touch screens, both of which are judged by their visual display quality and do not require bending.

That is not to say that other applications will not continue to use ITO in large proportion. But NanoMarkets expects the applications that require flexibility (touch screens and flexible displays) and ones that are extremely cost-sensitive (lighting and PV applications) to more quickly displace ITO with alternative transparent conductors. It is also reasonable to expect that the type of ITO substitute that will be most significant for each application will depend on the application itself. For instance, rigid applications that are mainly concerned with cost reduction are more likely to switch to less-costly TCOs since they are likely to be similar to ITO in application methods and processing (perhaps even using the same equipment), and flexible displays are more likely to switch to a material touted for its flexibility, such as PEDOT or CNT films. We discuss these materials below.

E.1.3 Alternatives to ITO: TCOs, Polymers, and Nanomaterials

Switching to a non-ITO material immediately introduces a new risk factor, of course. None of the alternatives to ITO comes with the same depth of understanding of its ability to serve as a transparent semiconductor. So, new risks are introduced into the manufacturing process and business process more generally. (There may be new product reliability and lifetime issues that pop up at any level of the value chain.) The usual alternatives that are touted for ITO—as we have already mentioned to some extent—are other transparent conducting oxides, polymers, and nanomaterials of various kinds.

TCOs: TCOs are an obvious direction to take since they guarantee a cost reduction; no other TCO is anywhere near as expensive as ITO. And that cost reduction is more reliably guaranteed than alternative ITO deposition methods—even if alternative TCOs are still deposited inefficiently. As a result, a number of alternative TCOs have found niche markets and in the case where they are used in solar panels, the opportunity has recently moved beyond niche status and is growing at a significant rate even during the recession.

Until the end of 2008, alternative TCOs did not have many advocates who were really pushing the idea. However, a group of Japanese firms has now formed an alliance to promote zinc oxide (ZnO) as an ITO alternative. This group is the Council to Promote Commercialization of Zinc Oxide Film. NanoMarkets is not expecting this to lead to huge new revenues for ZnO, but it certainly helps the cause of TCOs.

Also among TCOs, NanoMarkets is seeing developments in improving etch processes for fluorine-doped tin oxide (FTO). FTO performs similarly to ITO in the plasma display panel (PDP) application, but is not widely used because it is difficult to etch accurately. A promising new etch process has been developed for AGC Flat Glass; if this process improves etch accuracy sufficiently, FTO may begin to make some inroads into the PDP market. However, this needs to be seen in the context of the PDP's future sales prospects, which are not especially good.

Unfortunately, while TCOs undoubtedly get over the high material cost issues associated with ITO, they have identical or worse brittleness issues. In addition, they will never offer the combination of transparency and conductivity offered by ITO. "Never" is a word that one should always be careful to use, but in this case seems appropriate. Work on improved conductivity and transparency for TCOs has been going on for 20 years at least, with no real breakthroughs.

Organic conductive coatings: Organic transparent conductors offer three major advantages over ITO: they are inherently flexible, they can often be easily printed, and they cost only a fraction of the price of ITO. That means that the opportunities are there, and unlike in the case of TCOs, there are major corporate sponsors of this idea, including H.C. Starck and Agfa. It is important to note that these firms are already selling the basic conductive coating for other applications, and are looking for new markets to sell a (slightly altered) version of an existing product. This means that they are thinking in terms of incremental markets and do not need huge opportunities to make their activities profitable.

But the substitution of ITO with organic transparent conductors has not taken off as rapidly as NanoMarkets had expected at the time of publishing our previous report on ITO. At the time, a Fujitsu touch screen made using transparent conductive polymers was being widely discussed. So far, however, this screen, while commercialized, does not seem to have taken off in the marketplace very fast. In addition, the use of organic transparent conductors for OLED lighting by the OLLA team in Europe is still not a revenue generating combination and again—as with TCOs—there is the likelihood that completely matching the optimal transparency and conductivity of ITO is going to be hard, if possible, to achieve.

Of course, the fact that organic transparent conductors could never match ITO in terms of transparency and conductivity was widely understood before such materials started to be used as ITO alternatives. What seems more of an open question is the resilience of this kind of "plastic ITO" when exposed to light in general and UV light in particular. In our research for this report, we came across varying opinions on this issue, ranging from assertions that light-sensitivity made this entire approach a waste of time, to assertions that it wasn't a problem at all. The sources were not entirely unbiased, but the truth or falsity of their claims may have a bearing on how big this part of the transparent conductor market becomes; transparent organic materials may find considerable opportunities in the handheld electronics market where products are generally short-lived but have less of a chance in the television display market, where the opposite is true.

Carbon nanotubes and other nanomaterials: NanoMarkets still believes what it said in last year's report that the big opportunity for a wholesale replacement of ITO would have to come from the nanomaterials sector, which could mean some kind of carbon nanotube preparation or a completely inorganic nanomaterial. Nanomaterials share advantages of flexibility, printability, and (usually) cost with organics, and also have a lot of yet-to-be-discovered potential because they are not yet completely understood.

It is their immaturity that provides for the potential of this kind of material, but of course, that immaturity carries with it all the risks that are usually associated with new materials and pioneer users. On the other hand, if ITO is ever replaced in a significant way by an entirely different kind of material, nanomaterials are the best bet. Despite the recession, there has been a lot of (mostly) encouraging activity in this space since NanoMarkets' last report, with Cambrios in particular leaving its former under-the-radar image behind it in the past year, a year that saw demonstrations of conductive nanomaterials for e-paper and LCD backplanes. NanoMarkets believes that a significant commercial launch of a display with a nanomaterials-based backplane may not be far off.

While the interest of the makers of organic and TCO replacements for ITO is largely in selling an existing product, the motivation for the makers of nanomaterials is almost the opposite. Often, but not always, the firms that one finds in this area are firms that see ITO substitutes as a stepping off point for other (and sometimes larger) opportunities in the nanomaterials space. ITO substitutes, under this view, represent a *relatively* easy market to break into, although it is far from clear that this is the case.

E.1.4 "Saving" ITO: Materials and Manufacturing Developments

Given the high percentage of the market that we expect ITO to retain even by the end of the forecast period, it is far from clear that ITO needs saving in the usual sense. However, NanoMarkets' strong belief that ITO will continue to dominate the high end of the transparent conductor market is predicated to some extent on the idea that both ITO manufacturing processes and ITO products themselves will improve somewhat in the coming years.

Manufacturing improvements: New methods for applying ITO have been proposed and tried, but for the most part they still do not match the performance achieved through sputtering ITO. Nonetheless, manufacturing improvements still present an opportunity to achieve cost reductions. This opportunity obviously brings value to new manufacturing approaches and the associated materials and equipment. The vacuum deposition methods by which ITO is usually applied are inherently inefficient processes in terms of material usage. Typically, less than 30 percent of a sputtering target gets applied to a substrate; much of the rest is applied to chamber walls. Plus, the vacuum deposition equipment is costly and expensive to maintain. Finally, most sputtering processes require high substrate temperatures, making them unsuitable for temperature-sensitive substrates, such as plastics.

Alternative methods of applying ITO seek to improve on one or more of these problems, and because there is something of a pent-up demand for this kind of technology, successful approaches can expect to start earning revenues fairly fast. New ITO manufacturing technology has the potential to allow manufacturers to continue using ITO—and thereby reducing the need for risk taking at the materials level—while greatly reducing cost, waste, and difficulty of application. NanoMarkets believes that two areas of this kind have a great deal of potential in the next few years.

The first area is the further development of laser annealing methods. These methods have been demonstrated to improve the quality of sputtered films without the high substrate temperatures associated with ordinary curing. If they can be extrapolated to also improve the quality of ITO films deposited by printing, laser annealing may provide a route for increased use of printing in many ITO applications.

The second area of opportunity is the further development of electrostatic spray-assisted vapor deposition (ESAVD). ESAVD requires high temperatures like many of the standard techniques of depositing ITO, but it offers the potential for open atmosphere processing, perhaps leading to the elimination of costly sputtering equipment.

Any analysis of new manufacturing methods for ITO must consider the prospects for *printed* ITO, if only because printed electronics is so much in vogue these days. ITO inks have been around for a while, but have had a niche status. There seem to be few firms really throwing themselves into this area, so NanoMarkets does not expect huge revenues to emerge from the printed ITO sector. However, it is worth noting that printing of ITO with nanoparticle inks is expected to greatly improve efficiency of ITO use (it is applied only where it is needed), thus reducing cost, while also permitting wet coating, which can be done at low temperatures and does not require expensive equipment (as compared to sputtering equipment). And if some important firm really gets behind printed ITO, perhaps we will see significant commercialization of ITO inks.

If printed ITO can demonstrate performance matching that of sputtered ITO, then we can also expect to see a large shift in this direction over time. High-performing, printed ITO would appeal even to the high-end applications where display image quality trumps cost concerns. By using such material, displays could maintain their high visual clarity while simultaneously saving money on two fronts: the cost of ITO could be reduced by as much as 70 percent, according to some sources, due to elimination of the waste from sputtering; and processing could be shifted away from costly vacuum-deposition batch processes and toward inexpensive, continuous roll-to-roll printing processes.

Nonetheless, alternative methods of depositing ITO can only go so far. In terms of cost, even with ITO perfectly applied only where it is needed, it is still an expensive material, because indium is (absent some massive extractive effort) an expensive metal. Hence the need for materials development.

Materials developments: In order for ITO to hold onto its dominant position in the transparent conductor industry, slight changes will be required. One direction in materials development is to mix ITO with other materials. For example, Sigma Technologies offers an ink combining ITO and silver nanoflakes with a conductive polymer binder, which is claimed to be more conductive than conventional nanosilver. Other developments could include: indium oxide and indium zinc oxide (actually Zn-doped indium oxide). The latter was developed by Idemitsu about a decade ago as a material more easily etched than crystalline ITO. The attraction of indium zinc oxide (IZO) is not only that it has better etch characteristics than crystalline ITO but also that it has a lower resistivity than ITO. It can also be deposited on unheated substrates. Two other approaches that still use indium are indium antimony oxide (IAO, but actually antimony-doped indium oxide) and antimony-doped ITO (IATO). These materials exhibit promising transparency and (especially for IATO) resistivity, but they both still contain at least 90 percent indium oxide by weight.

E.2 Key Firms to Watch

Some of the key firms that have been influential in shaping the ITO market in the recent past have been mentioned above. But there are others.

At the level of basic ITO powder production, the industry is dominated by a handful of firms and all of them have almost certainly been hit by the worldwide economic downturn. We note, in particular, that Mitsui Mining and Smelting, one of the world's largest producers of ITO, appears to be suffering as a result of the recent economic crash. According to reports, the company is considering eliminating a division (not the ITO-producing division) but claims that its ITO business is strong and not at risk. As a major ITO supplier, however, the eventual outcome of Mitsui's troubles may have a significant impact on the ITO market.

Higher up the value chain, there are the firms too numerous to mention that produce the many kinds of TCOs, and the two firms—Agfa and H.C. Starck—that are advocates for an organic substitute for ITO. As we have already mentioned, these two firms expect the flexibility of their PEDOT conductive coating to provide an entry for them into the ITO substitute business. As our forecasts below indicate, we don't expect huge revenues to come from such activity, but for these firms, it represents additional revenues for a more or less existing product and it is an approach with some measure of success.

There is the Fujitsu display already mentioned and PEDOT is already in use as a boundary layer in OPV and DSC devices and there seems to be a significant amount of work being done on using PEDOT in OLED displays and lighting that is being promoted by the two principal manufacturers of this material. There is, of course, a natural fit between a plastic conductor and a plastic light, display or solar panel. As we went to press with this report, Agfa had just announced a demonstration of "the world's first large-area OLED tile that does not require ITO … and has printed shunting lines." The OLED uses Agfa's Orgacon PEDOT:PSS formulation for the transparent electrodes and has metal shunting lines (to improve brightness uniformity) that are printed instead of patterned by the usual method of photolithography. The demonstrated OLED is 12 cm × 12 cm, white, and is claimed to be homogeneous in brightness.

Throughout this report, we stress that only nanomaterials really have the potential to beat ITO at its own game in the long run. (They certainly have yet to attain this goal, though.) Several firms and research groups are involved in this area, some of them very small. For a long time, Eikos was the firm that bore the flag in this sector, but it has been very quiet in the past year. By exact contrast, Cambrios, which was very quiet in its early years, has begun announcing alliances. It has developed ClearOhm ink and film, containing conductive metal nanowires, and has teamed up with Sumitomo and Chisso to market it as an ITO substitute, starting first in the conventional LCD market.

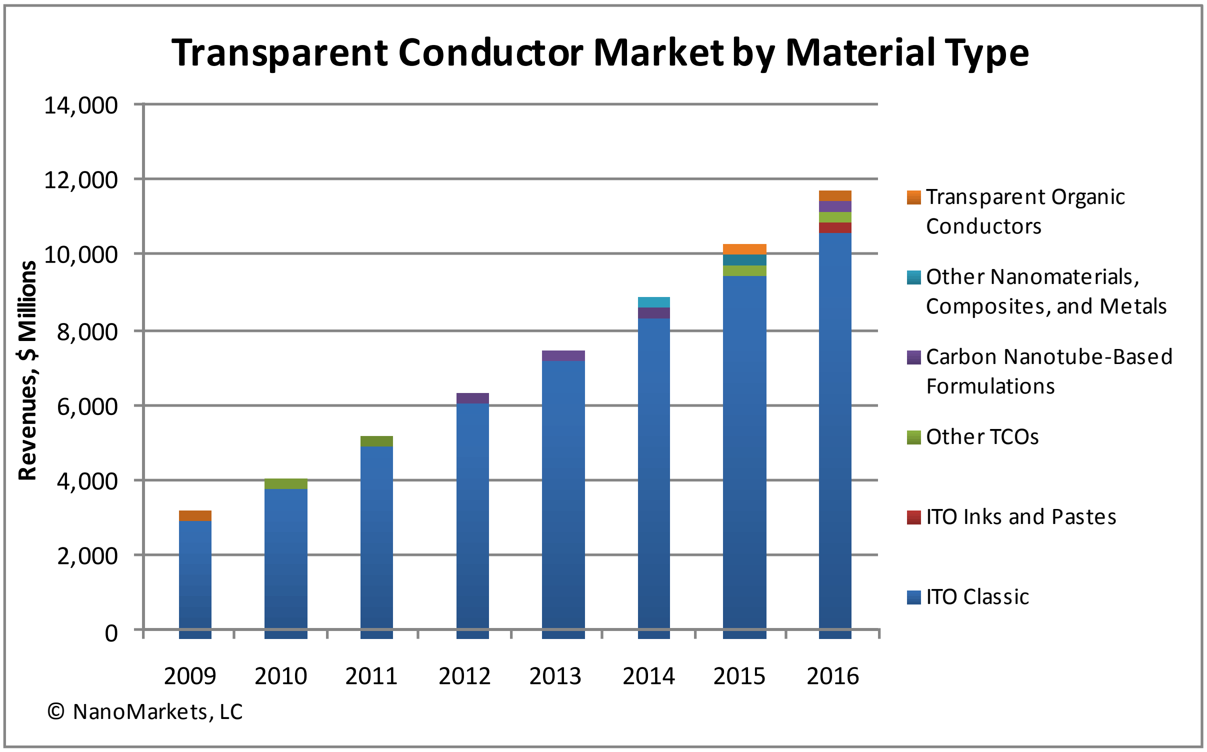
Meanwhile, Unidym, a major developer of CNT films, is actively sampling and marketing them to touch-screen manufacturers as an ITO substitute, and has demonstrated the films in e-paper and LCD applications in cooperation with Samsung. Because of the company's high level of activity, further partnerships leading to commercial products may be coming. Silicon Display Technology is partnering with Unidym to demonstrate applications for CNT coatings in various display products. So far, two kinds of EPD e-paper (monochrome and color) and a full-color conventional LCD have been demonstrated. Using a conventional LCD display may seem like an unusual choice, since much of the anticipated benefit of CNT conductive films is their flexibility. But most of the flexible applications are either as yet nonexistent (flexible OLED displays) or the benefits of flexible conductors will not be apparent on the time scale of a product demonstration (resistive touch screens).

E.3 Summary of Market Forecasts

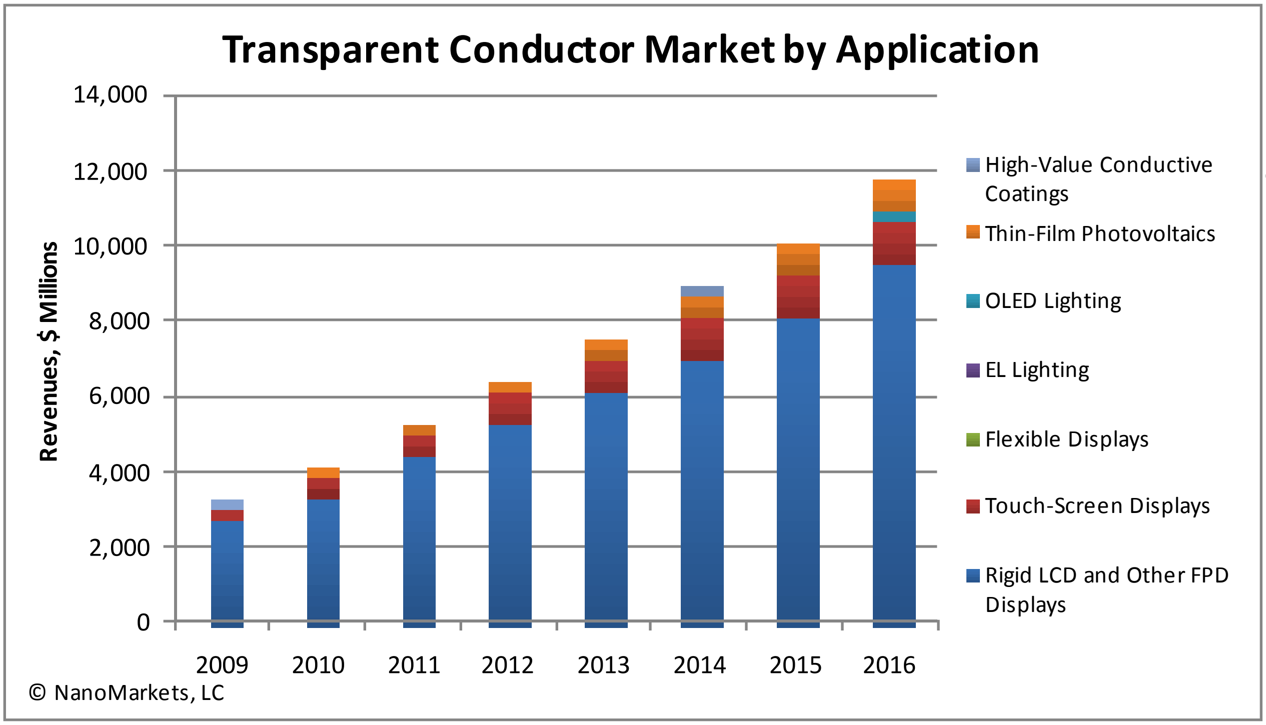
Exhibit E-1 summarizes the forecasts presented in the main body of this report by material type. These forecasts assume that there is some return to economic growth in the next year, and that the worst is behind us. As a result, some of the addressable markets for ITO and its alternatives should resume growth, most probably. (The price of ITO should also return to higher prices.) The combination of these two trends should make for healthy growth in the ITO business as a whole, although one should note that this is, of course, from a low starting point. It is all too easy to imagine alternative scenarios and if a long-lived recession ultimately turns into a depression, it would certainly have a disastrous impact on all the markets considered in this report.

As we have stressed, traditional ITO products will dominate the markets considered here throughout the forecast period for all the reasons discussed above and in the main body of this report. Even by the end of this eight-year period, ITO will account for 90 percent of the transparent conductor market. However, the remaining 10 percent is of a very large market, making the addressable market for non-classic ITO solutions worth pursuing.

We see the key long-term opportunities occurring in the nanomaterials sector and the revenues from this type of technology might start to arrive quite fast in 2010 and beyond. The TCOs sector is likely to remain niche-like in revenue terms for years to come, with TFPV providing much of the opportunity for this type of material. We have also shown low numbers for the polymer sector, but we want to emphasize that this is a real world solution and one success with this technology could propel the market forward to much higher numbers than shown here. The jury is still out on this material.



In Exhibit E-2, we present our forecasts for the ITO/ITO-substitute market broken down by application. Not surprisingly, we see this market as dominated by FPD displays throughout the forecast period. The second ranking application is touch-screen displays, a rapidly growing application that is—as we have seen—also potentially highly dynamic in terms of its choice of materials. The only other significantly sized market at the present time is TFPV, which has rather special requirements for transparent conductors. Finally, there is the high-end general purpose conductive coatings—an area we expect to take a leap forward in the next few years and one where ITO manufacturers are already seeing heightened sales activity. This is because, while ITO has always had a niche use as an antistatic treatment, this niche area is of growing importance to the ITO industry because of the need to protect future generations of integrated chips at the 32-nm node and below.



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