Markets for Zinc Oxide In Electronics

March 2009

Executive Summary

E.1 Opportunities for ZnO in the Electronics Sector

A casual glance at the zinc oxide (ZnO) industry might suggest strongly that this material is unlikely to produce any new opportunities in the electronics sector. First, ZnO is a very old material; it was used in the Bronze Age for healing wounds. It was later used in the production of brass for many centuries and then went on to become a key ingredient in white paints, porcelain enamels, and rubber manufacture. Many of the ancient applications for ZnO are the same ones that are in existence today and some of the newer ones—as a food supplement, for example—also do not carry the image of new technology.

The same can be said about the few existing applications for ZnO in electronics and optics. These applications are primarily found in three areas. The most mature of these applications is in the form of various anti-static, EMI/RFI shielding and optical coatings, an area in which ZnO has been used for a very long time. There are also two electronic devices, which are well-established in the market, that are based on the electrical properties of ZnO. These are: the varistor (variable resistor) and surface acoustic wave (SAW) devices. The varistor is now widely used in applications ranging from computers to power plants. SAW devices are commonly found in mobile phones and rely on the well-understood piezoelectric capabilities of ZnO, which have been known and understood for a long time.

Together, these three established applications presumably account for a fairly large amount of the annual consumption of ZnO, but they can hardly be considered "opportunities." For the most part, they are mature areas with an established supply chain and near-commoditization of the products themselves. For example, varistors are sourced from small Chinese suppliers, whose profitability is largely based on low-cost labor, or large passive electronic components firms that rely on economies of scale to hold down costs. In ZnO-based SAW devices, the ZnO is only one layer of many. The prospects for these and other older applications in which ZnO is used—precisely because they are mature areas—are tied directly to growth (or lack of it) in the economy, which at the present time is not a good place to be.

Nonetheless, there are a few niche areas worth looking at even in the older applications for ZnO. For example, despite the current recession, the semiconductor industry continues to proceed down the path set by Moore's Law. The result: devices created by this industry are ever more in need of protection from damage by static electricity, etc. ZnO could play an important role in this protection both from enhanced antistatic coatings for bags used to hold electronic components—and more directly—with better/more varistors in circuit boards. There are also specialized coatings using ZnO that are not just garden variety and must meet the demanding requirements of (say) the military or aerospace industry. ZnO is often not the first choice in coatings applications and is chosen because of special requirements in particular applications. It is perhaps worth noting at this point that ZnO devices are capable of withstanding both high levels of radiation and high temperatures. This gives

ZnO significant potential in military, medical and (perhaps) industrial markets where these factors are important. Some believe also that the high thermal resistance of ZnO provides it with an opportunity to increasingly penetrate the high end of the power electronics business where high temperatures are very much the norm and where cooling technology is reaching its limits. ZnO already exists to some extent in this space; however, at the present time SiC is the most common material used in power electronics.

E.1.1 ZnO Means New Opportunities for Device Makers

Beyond the mature uses of ZnO in electronics and newer niche opportunities (such as power electronics, again) that exploit very well-understood properties of ZnO, there appear to be a growing number of new applications for ZnO that can provide genuine opportunities, initially for device makers and then (if and when the markets take off) for materials suppliers and equipment manufacturers. Indeed, some of these newer applications—transparent ZnO transistors, for example—are anything but mature; they are at the edge of commercialization, and may not take off at all.

These very new opportunities may ultimately generate hundreds of millions of dollars for both materials and device suppliers and they may enable billions of dollars in new business for consumer electronics, IT and other systems providers. But like all opportunities of this kind, they come with big risks. Most of the newer applications for ZnO in the electronics sector seem to resonate with major market trends (such as the trend toward cost-efficient lighting or flexible displays), and therefore have a somewhat established demand. However, in many of these applications the ZnO approach often competes with other approaches and in many cases the advantages of ZnO over alternative materials platforms have yet to be proven.

Take the example of ZnO's role as a material for next-generation thin-film transistors (TFTs). Here, ZnO competes with printed silicon and organic TFTs as an alternative to conventional TFTs. ZnO can bring its transparency to the table as an advantage, but there is not yet a market for fully transparent displays (or other forms of transparent electronics) and whether such a market will ever take off is really just speculation. There are other reasons why one might want a transparent TFT short of a full-fledged transparent electronic device. These are also unproven, but there is already good evidence based on laboratory results that ZnO TFTs can perform quite well when compared to existing silicon TFTs in certain environments, and superbly when compared with organic TFTs. ZnO TFTs have been suggested as the basis for a new generation of display backplanes, especially in the context of OLEDs, where it is hoped that they might be able to jump start the AMOLED market, which has never really taken off as forecast but which nonetheless remains the key to OLED market growth.

At this point the investment in ZnO-based semiconductors is minimal when compared with investments in silicon TFTs or even organic TFTs, and the high-tech investment environment is not an encouraging one at the present time. In addition, the missing link that will probably decide how far ZnO electronics can really be pushed in the long-run is the development of a p-type ZnO semiconductor; much the same thing can be said about organic electronics, incidentally. In the past few years, there have been some interesting developments pointing to how p-type ZnO semiconductors might be created and developed. But it is fair to say that there is nothing definitive yet, and even ZnO “enthusiasts” are not certain that there will ever be a ZnO CMOS as it were.

E.1.2 What's So Great About ZnO?

However, if the market for ZnO-based electronics ultimately shapes up, any success that it may have will be based on a list of attractive features/properties of ZnO, some of which have been well understood and exploited for a long time and some of which are just emerging as foci of R&D and commercialization efforts.

ZnO nanostructures in the electronics marketplace: These emerging properties of ZnO include the ability to create interesting nanostructures using ZnO. This ability may create entirely new opportunities for ZnO in some future nanoelectronics, an area where, incidentally, ZnO's role may also be enhanced by the fact that it is a good material for spintronics devices. However, a radical shift to a new nanoelectronics platform looks a little fanciful right now. The semiconductor industry will hold onto the more classical CMOS approaches for a few more nodes along the Moore's Law road, it seems. And even when that road comes to an end, the industry will likely try novel (e.g. 3-D) architectures before it makes a wholesale shift from silicon to nanodevices using spintronics, carbon nanotubes, etc.

Where ZnO nanostructures may make a difference, however, is in enhancing existing electronics applications for ZnO and those that will be developed in the short-to-medium term. While ZnO in the form of nanostructures has the potential to enhance ZnO's role in both conductive and semiconductor applications, most interest for these nanostructures seems to be for new kinds of sensing devices—not surprising, especially for transparent sensing devices. The point here is that nanostructures have very high surface area-to-volume ratios—a property that enhances sensitivity detection.

The applications of these future ZnO sensors are still apparently mostly a topic for the research literature, but they seem to be of some commercial importance during the forecasting period considered in this report and the reader should also note that ZnO already has a long history as a material used in gas sensors. It is perhaps worth noting that the high surface-area-to-volume ratio could also prove an advantage in areas that require enhanced conductivity; we note here that something similar has happened with the use of nanoparticles in metallic conductive inks. However, the reader should also note that *this* nano property is fundamentally different from quantum effects that are usually cited as making materials useful in futuristic nanoelectronics applications; these typically are inherently more complex in nature.

The joys of ZnO: In Exhibit E-1, we summarize the features that give ZnO value as an electronics material and the opportunities they are creating. Most of the newer opportunities analyzed in this report actually stem from three basic facts about ZnO.

Exhibit E-1
ZnO: Incentives for New Wave of Commercialization and Possible Revenue Sources

	Incentive	Challenge	Potential for Generating Revenues
Cost availability and safety	ZnO is a widely used, low-cost material. It is a more well-known material compared with its competitors GaAs, GaN, and ITO. As well, compared with GaAs, ZnO is a safer material.	None	In most applications ZnO looks good against competitive materials on cost and environmental grounds, which will lead to new business. ZnO can plausibly make the claim that it is a "greener" semiconductor.
High-transparency in the visible and near infrared	Opens up the opportunity for ZnO to serve as a possible ITO replacement and in transparent transistors for future "transparent electronics."	ZnO does not exhibit the conductivity associated with ITO (or even other TCOs) and "transparent electronics" remains in the earliest developmental phase.	Future transparent electronics devices would include heads-up displays, dashboards on the mirror, transparent sensors, etc.
Suitability for semiconductor applications	ZnO exhibits good performance as a semiconductor and therefore can be used to fabricate transistors and LEDs. Doping of ZnO to improve conductivity and produce n-type semiconductors is well understood. One unique feature of ZnO TFTs is that they can be transparent.	The quest for ZnO-based p-type semiconductors, which has been spread over several decades, has yet to yield much progress and some informed opinion believe that "ZnO CMOS" will never happen. ZnO semiconductor devices will have to face competitive challenges from a wide range of (often more established) devices.	New devices of many kinds can be built from doped ZnO. The most interesting in terms of revenue generation are likely to be transparent TFTs and LED devices. Such TFTs may, in certain circumstances, prove more suitable than the more established silicon TFTs and the less mature organic TFTs (OTFTs), especially in the context of OLEDs. ZnO LEDs may prove a cost effective alternative to GaN LEDs.
Suitability for contacts/ Electrodes	ZnO has already proved itself a good transparent conductor in various mature applications and this suggests that it might make a good material for contacts/electrodes where transparency is important. There is also a reasonably good opportunity for patterning to enhance the ability of ZnO to serve as contacts/electrodes.	ZnO still has low conductivity when compared with ITO or (more obviously) with many metals.	ZnO has already been shown to provide successful contacts for certain kinds of thin-film PV—notably a-Si and CIGS. These contacts have been shown to enable reasonably high conversion efficiencies for the entire cell. It may be possible to extend this success in the TFPV sector for ZnO electrodes to other applications and ZnO is being seriously considered for OLED contacts.
Interesting UV properties	Can act as both a UV absorber and emitter and can be used to develop solid-state devices that are more reliable than existing UV systems.	Technology depends on advances that address challenges in the ZnO semiconductor industry as a whole, and these are in an early stage of development.	Opportunities ranging from improvements on existing UV coatings to solid-state UV devices. UV devices have growing markets in medicine, water treatment and more generally in environmental applications.

Exhibit E-1
ZnO: Incentives for New Wave of Commercialization and Possible Revenue Sources

	Incentive	Challenge	Potential for Generating Revenues
Mature manufacturing processes available with interesting ones to come	Proven fabrication methods—notably magnetron sputtering and MOCVD—are clearly able to create thin-film ZnO layers over large areas. This is especially important in the display and PV sectors.	Manufacturing processes for ZnO TFTs and LEDs are at an early phase of development. We do not yet know what role if any ZnO may play in printed electronics.	Manufacturing equipment firms may eventually have opportunities to develop fabrication machinery specially targeted to the ZnO industry or to set up turnkey ZnO fabs. There is some potential to improve on pulsed laser deposition techniques, which will enable more complex patterning and also a possibility for the emergence of solution-based manufacturing of ZnO electronics. Such developments may help to lower the cost of ZnO electronics in the future.
Low-temperature manufacturing approaches available	This means that ZnO electronics can be created on plastic substrates and costs may be lowered.	Often (but not always) low temperature means low performance.	Low-temperature manufacturing approaches—such as sol-gel or even printing—might be employed for flexible displays, sensors, transparent electronics, etc.
ZnO as a nanomaterial	Seems to be easily fabricated into many different kinds of nanostructures. Performance improvements are to be expected because of high surface area-to-volume ratios. In addition, ZnO's ferromagnetic properties make it suitable for use in spintronics.	ZnO nanostructures and spintronics devices seem to have an important potential role in nanoelectronics, but it will be hard to get the semiconductor industry off the silicon CMOS road.	ZnO nanostructures can be used in many of the applications described for regular ZnO and its variants. They would be of especial importance in the short term in contact and sensor applications.
ZnO as an extreme material	ZnO can withstand very high temperatures and is radiation hard.	None	Well suited to new revenues from the medical and military markets as the capabilities of ZnO electronics evolve. In addition, high thermal support may mean new opportunities in power electronics.

The first key property—and one that produces most of the near term opportunities for ZnO—is the relatively high conductivity that makes ZnO an attractive material to consider when one is seeking a transparent conductor for electrodes or large-area coating applications. (Typically this is done when ITO seems unsuitable for some reason or another.) In aggregate terms, ZnO as an electrode material generates large annual revenues. However, at the present time, almost all of those revenues are coming from one—admittedly growing—application. This application is as an electrode material for amorphous silicon (a-Si) photovoltaics (PV). ZnO is also used for CIGS PV, but CIGS itself is currently a small part of the PV market and—although it has considerable potential—likely to remain that way for some time into the future. Applications of ZnO for electrodes for organic PV and OLEDs are quite speculative at the moment and there are better replacement materials for ITO than ZnO—nanomaterials and polymers being obvious examples.

The second key fact about ZnO—which produces opportunities that are a little further off—is the ability of ZnO to serve as a surprisingly useful semiconductor, which can be used to create transistors (and especially transparent TFTs) and for LED-like lighting. A ZnO semiconductor has the potential to create new transparent electronics products of various kinds, but it also has a few more immediate applications, especially in OLED display backplanes and in LEDs. Part of the growing hope that it will be possible to turn ZnO semiconductors into a business is based on the previous success of two other similar, wide band-gap semiconductors—gallium nitride (GaN) for blue/white high-brightness LEDs and silicon carbide (SiC) in power electronics; so there is some history here that new firms entering the ZnO electronics industry will be able to point to, and no doubt they will. There are certainly major challenges though, above all the possibility of creating a stable p-type ZnO semiconductor. Obviously without that there is no "ZnO CMOS" and this could prove a significant limitation to the development of ZnO microelectronics in the marketplace.

The third key fact—and the most obvious—is that ZnO is intrinsically inexpensive, easy to access, safe and stable as a material. It is really because ZnO is so ordinary in the above sense, but apparently has so many extraordinary properties, that ZnO is of growing interest in the electronics materials business. When one lists out all of the properties of ZnO as it is now understood in the electronics context, one is reminded of exotic nanomaterials, but with the added benefit that ZnO nanostructures are apparently easier to create and work with than (say) carbon nanotubes.

E.1.3 Display-Related Applications for ZnO

The display industry is looking to next-generation technology to restore growth. In the past decade the massive move away from CRTs and toward liquid crystal displays (LCDs) has propelled the display market, but that replacement trend is now coming to an end; there are no CRTs left, except at the low end of the TV market and in a few specialist applications. In addition, the display industry is looking for a new technology that can pull it out of the doldrums created by the current worldwide economic downturn.

This is not an easy task. The last challenger to LCD was plasma, which has never achieved the place in the market that was expected; for one thing, the LCD market keeps catching up with it in terms of performance. The latest rival to LCDs is organic light-emitting diodes (OLEDs), which could potentially compete with LCDs in every area that LCDs are currently used. OLED displays are the only next-generation display technology about which this point can be made; all the others have more specialist applications. The other areas we are talking about here are the overlapping areas of e-paper, flexible displays and touch-screen displays. All or any of these new technologies may turn out to be money spinners, but—at least in their current form—they are likely to target parts of the display market, rather than be wholesale replacements for a dominant display technology.

ZnO may have important roles to play in the OLED display market of the future. It has been proposed both as a material for electrodes and as a material for backplane transistors. However, the future of OLED displays itself is still fairly unclear. On the face of things OLEDs have a lot going for them in the form of vibrant colors, ultra-flatness, (potentially) low-cost manufacturing, the ability to use flexible substrates and a high degree of scalability. Nonetheless, to date, LCDs have managed to keep up with most of what commercially available OLED displays can offer. As a result, OLED displays have had a hard time breaking out of the niche market for MP3 players and cell-phone sub-displays. During 2008, it looked like that breakout was about to occur, with the first real burst of activity in active matrix OLEDs both in cell-phone main displays and in televisions. Although the current poor market environment for consumer electronics may intervene, cell phones and televisions are two huge markets and if OLEDs eventually take off in those sectors—as we expect they will—ZnO will apparently have a large addressable market to chase after.

Given the early stage of OLED market development, it is not surprising that the use of ZnO in OLEDs is a topic that is primarily found in research literature. With regard to electrodes, the material that is primarily under consideration is aluminum-doped ZnO (AZO). NanoMarkets is not aware of any OLED firm with plans to adopt ZnO for anodes in commercial OLEDs, but we believe that such a use is a distinct possibility in the not-too-distant future, especially if the cost of ITO starts to rise again, as may well occur in 2011 and beyond. However, one missing piece of the puzzle that will be needed before ZnO replaces ITO anodes in any significant way is the demonstration that ZnO electrodes are scalable. Even if this proves to be the case, however, unless both OLED displays take off in a big way *and* ZnO becomes widely used for OLED anodes, the opportunity in money terms from this application will not amount to much.

Meanwhile, ZnO is getting more attention as a possible backplane TFT material for OLEDs, and this is both a development that is of strategic importance and one that could lead to significant revenues over the next decade. Today, conventional polycrystalline silicon TFTs are frequently used in backplanes for OLEDs, but suffer from the non-uniformity of their mobility and threshold voltage over large areas. Amorphous silicon TFTs may not be powerful enough to drive large-area active matrix OLED displays. However, certain OLED makers apparently see ZnO TFTs as exhibiting enhanced uniformity of TFT performance and relatively high mobilities. In addition, the fact that ZnO TFTs can be transparent in the visible region lends itself to entirely transparent displays. A number of ZnO variants have been used in the lab for OLED backplanes; indium-gallium-zinc-oxide (a-IGZO) has been especially popular in the research literature on this topic.

NanoMarkets believes that OLEDs using ZnO as an ITO substitute are probably closer to commercialization than ones with ZnO backplanes, but ZnO backplanes are where the money is, since they stand a chance of becoming *the* way of fabricating OLED backplanes. Also, since the OLED market needs AMOLEDs to become commercially successful for it to become truly viable, ZnO is potentially a material of strategic importance for the OLED market as a whole.

Other next-generation display products are not intended to be wholesale replacements for conventional LCD displays and in many cases they may be just LCD displays of a special kind. We are thinking here of e-paper, flexible displays and touch-screen displays. All of these novel kinds of displays seem to represent long-term potential as addressable markets for ZnO and related materials, although at the present time exactly how big the opportunities are for ZnO in these new kinds of displays is far from clear. It is possible that ZnO may find no more than niche applications here.

Within the e-paper space, ZnO could be used in a number of ways in this sector. As usual it is a possible ITO substitute, although the research literature discussions of using ZnO instead of ITO are mostly confined to OLED rather than either e-paper or flexible display applications. In addition, ZnO may not be a great leap forward as a solution to concerns with ITO. Conductive polymers may be a better solution. ZnO TFTs could also easily be used in e-paper backplanes. However, to date, active matrix e-paper has mostly used regular silicon TFTs and is just beginning to use OTFTs. While ZnO transistors could easily surpass the switching performance of OTFTs, OTFTs have exactly the same advantages that we have already met in the context of conductive polymers as an ITO substitute; they can be processed at low temperatures and do not crack on flexible substrates.

It is unlikely that proponents of ZnO TFTs could make the same claims with complete conviction. However, at least one company, Toppan Printing, has built small, color e-paper displays using sputtered $InGaZnO_4$ (IGZO) TFTs. However, the reader should note that the use of IGZO TFTs was not motivated by the usual considerations of choosing a material to enhance product performance, but rather because the transparency of the IGZO TFTs made it easier to align the necessary color filters. While Toppan Printing's experience may be extensible to future color e-paper architectures, it certainly is not sufficient to predict the ZnO TFTs gaining a large share of the e-paper paper backplane market as it stands today.

Beyond the use of ZnO for TFTs and as an ITO substitute in the e-paper/flexible display area, there are (probably niche) opportunities for the use of ZnO in the frontplanes of e-paper displays. The dominant electrophoretic technology in today's e-paper apparently uses titanium dioxide. But both Xerox and Seiko Epson (and probably others) have patents on electrophoretic displays in which they describe ZnO as being a potential electrophoretic material. ZnO coated titanium particles have also been discussed in the literature. ZnO may also have a role to play in electrochromic displays; it is already used in electrochromic windows.

Finally, the use of IZO and ZnO as possible replacements to ITO in resistive touch-screens has been mentioned in the literature, for example, in patents by Kodak and 3M. The mentions of these materials are usually in the form of one of three or four transparent conductors mentioned as alternatives in the patent. However, the conventional wisdom is that ZnO (or any other TCO for that matter) would not be able to meet the resistivity needs of capacitive touch-screens. Resistive technology still dominates the touch-screen sector, but capacitive technology is becoming more common and has received a major boost in the recent past as the result of the adoption of this technology for the Apple iPhone and some of Apple's iPod products.

E.1.4 Transparent Electronics: Who Really Needs It?

In all of the display applications cited above, ZnO inevitably competes with several other materials in both its semiconductor role and its conductor role. However, the transparent nature of ZnO as an electronic material has suggested to some a future "transparent electronics" sector built around ZnO as the primary material. (GaN is a possible alternative to ZnO in transparent electronics, but is generally considered too expensive for use in large area devices such as displays.)

The problem is that there is really no such thing as a transparent electronics sector at the present time and while the arguments for the emergence of such a sector sound fairly reasonable, they are really very little more than speculation. A lot of the current discussion with regard to transparent electronics centers around heads-up displays, which are transparent displays fabricated or laminated on windshields, windows, eyeglasses and visors. NanoMarkets believes that the most likely applications of this kind to emerge first are in the military and medical professions. This is where they are most likely to receive funding; the military has always been a major funder of novel display technology and medical technology is seen as a good long-term prospect for venture capital funding because of the aging population in industrialized countries. Both the medical and military sectors are ones where split-second life and death decisions must be made and where easier access to information can make these decisions better and faster.

The move of transparent electronics to the consumer sector is harder to predict, because it is not easy to see exactly where the benefits would be. The potential application that gets the most attention in this context is in cars, where the kind of information that is normally found on a dashboard is incorporated into the windshield. Such displays would enable drivers to see information without looking down at the dashboard, which would provide a possible safety boost. However, the advantages are a long way from being proven in this regard. Another possible application for transparent electronics is for displays in the visors of workers that would provide needed information without obstructing their view. What remains unclear is the cost-to-benefits analysis of such a development, and indeed one of the key questions that hangs over the whole of transparent electronics is "who really needs it?"

With this question in mind, discussions about transparent electronics often source the movie "Minority Report" in which transparent displays appear in several scenes. The problem is that in none of these scenes do the displays have any practical functionality that one could not find today in a display bought at Wal-Mart, with the exception that the displays in the movies are voice- or motion-activated, which, of course, has nothing to do with the display per se. It is always possible that transparency alone will be enough to generate some interest in transparent displays. The reader should also note that displays are not the only application area to which transparent electronics might be applied. Other areas that have been suggested for the application of transparent electronics are RFID, smartcards and smart windows.

E.1.5 Lighting-Related Applications for ZnO

Lighting of all kinds is taking new directions toward much more highly efficient systems. The first wave of product change associated with this trend has been the shift from incandescent bulbs to fluorescent lighting, which has accelerated in the past year or so. The next wave was the growing use of HB-LEDs, a now mature technology that has already made significant penetration of certain lighting niches such as flashlights and traffic lights and which is now slowly beginning to grab part of the general illumination market as well. HB-LED lighting promises more attractive white light than fluorescent bulbs and much longer lifetimes, as much as 50,000 hours. (This compares to 15,000 hours for fluorescent lamps.)

However, on a $/lumen basis HB-LEDs are likely to seem expensive for general illumination applications. The claim made by supporters of HB-LEDs is that when one considers the total cost of ownership, LEDs are said to be more cost effective than incandescent or halogen sources and fairly close to compact fluorescent lamps (CFLs). However, except in the case of very large buildings, upfront costs may prove a bigger determinant of whether or not a new lighting technology is adopted than total cost ownership. Therefore, any technology or manufacturing platform that can provide cost reductions would present an opportunity, especially given that the addressable market for HB-LEDs is huge and public policy favors the rapid introduction of cost effective solid-state lighting.

Today, HB-LEDs are based on a variety of semiconductor materials, but principally various forms of GaAs and GaN. It was the development of blue/green GaN LEDs that enabled white light LEDs to appear and made LEDs suitable for more than just instrument panels. ZnO seems as if it could be a low-cost substitute for GaN; this could mean that ZnO will become a viable commercial solution for lighting within a few years and establish HB-LED lighting at a new cost point. It might also extend the market for LEDs in other ways, enabling the creation of nanoscale light sources for optical data storage, imaging, biological and chemical sensing, and perhaps communications devices. Using the same technology as developed for LEDs, it may also be possible to create solid-state UV sources for medical, water treatment and environmental applications. In addition to various research groups around the world, two commercial firms that have shown interest in ZnO LEDs are Cermet and Sharp.

E.1.6 PV-Related Applications for ZnO

Solar power is another area where ZnO could play a role. There are several new thin-film PV technologies that may use ZnO as an electrode. But in terms of generating revenues, the most important is a-Si PV. This is already in widespread use and remains the largest sector of the thin-film PV (TFPV) market. In addition, ZnO is regularly used as a back electrode. ZnO may be used in similar applications in other types of TFPV, but the revenue potential from these areas would be much smaller. Thus, ZnO seems to be the top-electrode-of-choice for CIGS, but CIGS itself is mostly a PV material of the future and this limits opportunity for ZnO in the short-term. ZnO may also be used for electrode materials in organic PV or dye sensitive cells (DSCs), but it is certainly not in any widespread use for this use at the present time, outside of the lab.

In general, solar power will be adversely impacted by lower fossil fuel costs and in fact the PV industry appears to have significantly dropped its growth expectations since the end of the third quarter of 2008. However, we would expect PV to bounce back in a couple of years when a more inflationary environment begins to make its impact felt and fossil fuel prices begin to rise again, perhaps by large amounts. Indeed, even at the present time, PV looks like a good way to hedge against energy price fluctuations. There is also a strong incentive for electricity companies to support PV as a way to delay building new power plants.

E.1.7 Sensor-Related Applications for ZnO

NanoMarkets believes that the sensor business is set for considerable expansion over the coming decade. It is being driven by important "megatrends" such as the aging population (more need for medical diagnostics), the need for enhanced security, environmental concerns (atmospheric testing) and (possibly) the growth of robotics in the not-too-distant future.

As this list suggests, the sensor business as a whole is highly fragmented and is spread across numerous types of sensors, technologies and industries. Zinc oxide—or indeed any other materials platform—is inevitably a small part of the whole sensor story, no matter how well it succeeds. That said, ZnO (and other metal oxides) has been used in gas sensors for a long time and we expect the gas sensor market to be where ZnO continues to make its impact felt in the future. However, opportunities for ZnO in the gas sensor space will come not just from the general growth in the need for gas sensors but also from a change in the use of ZnO in gas sensors. Instead of the sintered ZnO pellets that are used in the current generation of ZnO gas sensors, we expect these pellets to be replaced by ZnO thin-films and nanostructures, leading to much more sensitive devices.

Most of the rest of the identifiable opportunities for ZnO in the sensor business fall into the UV detectors, motion sensor and biosensor areas. For some motion sensors, ZnO's piezoelectric capabilities can be exploited. For UV detectors, the solid-state technology discussed under LEDs would be used. More futuristically, it has been suggested that the fact that zinc is a neurotransmitter may lead to the use of ZnO in certain kinds of medical sensors.

E.2 Implications for Deposition, Patterning and Printing Equipment Companies

E.2.1 Thin-Film ZnO Manufacturing

Compared with some other new electronic materials, the manufacturing issues for ZnO are fairly settled. Thus, magnetron sputtering is in widespread use for making ZnO thin-films. Also, because this type of sputtering is widely used for glass coatings and in the digital storage industry, it continues to receive very high levels of investment, and therefore continues to improve.

For the most part, firms that manufacture ZnO thin-films seem happy with this approach, although some users in the PV industry have complained about substrate damage. Another process, MOCVD is regularly used in the TFPV sector and appears to address this problem. This might seem to suggest that opportunities for manufacturers of equipment aimed at the ZnO thin-film segment are limited because the industry has little need to break out from magnetron sputtering and MOCVD.

This is probably true in the immediate future, but as the need for more complex ZnO devices arises, new processes may become increasingly attractive. In particular, pulsed laser deposition (PLD) has already been used widely in the lab to create more complex ZnO structures. At its current level of development, however, this process cannot really be extended to commercial device fabrication, as the deposition rates are far too low. There could thus be an opportunity for an improved version of PLD.

As sophisticated ZnO electronics appears on the scene, the cost of manufacturing is likely to play a greater role and this may lead to consideration being given to new manufacturing modes for ZnO thin-films. Approaches that have been considered in that regard are evaporation, spray pyrolysis, sol-gel, electrochemical deposition and even printing.

E.2.2 Single-Crystal ZnO Manufacturing

Single-crystal ZnO is little more than a niche business at the present, but will have to expand if ZnO devices are going to find a sizeable market. At present, this part of the ZnO business consists of a handful of firms and several lab material distributors. It is possible that some of these smaller firms could grow considerably as ZnO electronics takes off.

It also seems likely that new and better processes will be developed and/or that one of the three or four processes that are used now—these include hydrothermal growth, oxidation of Zn vapor, and growth of crystals from melts/salts—will become dominant. In some ways, ZnO wafer firms may follow a similar path to the GaN industry, which began a similar evolution more than a decade ago.

E.3 Firms to Watch

Firms that are involved in zinc mining or in creating bulk zinc oxide seem to have little interest in ZnO electronics at the present time, as far as we can tell. This is understandable, since our analysis suggests that there is little likelihood that the new developments in and applications for ZnO electronics will lead to a surge in demand for ZnO in the near term. Perhaps as ZnO starts to get more play in the trade press as an opportunity, some of the bulk ZnO firms will decide to participate in the ZnO electronics business through partnerships or by creating high value-added products—wafers, etc.—that are specifically targeted to ZnO electronics. For now, it is not surprising that corporate interest in this area begins further up the value chain; more specifically with firms that specialize in ZnO films and single-crystal ZnO.

E.3.1 ZnO Thin-Film Companies

As far as the film companies are concerned, a notable event took place in the fall of 2008 when seven companies in the Japanese electronics sector formed the Council to Promote Commercialization of Zinc Oxide Film, aiming to boost the use of zinc oxide conductive film as a substitute for ITO. The companies involved in this organization are shown in Exhibit E-2. One firm that isn't on the list in E-2 but seems a fit with this group is Idemitsu, which developed IZO about a decade ago as a way to address difficulties associated with finding suitable ways to etch crystalline ITO.

Exhibit E-2
Council to Promote Commercialization of Zinc Oxide Film

Company	Activity
Nippon Kodoshi	Manufactures battery components
Tosa Denshi	Assembles electronics components
ZNO Lab	A research firm founded by Kochi University of Technology
Yamazaki Giken	Manufactures slicer equipment
Heiwagenshi	Makes paper and film
Hakusei Tech	Produces ZnO
Henmi Slide Rule	Manufacturers semiconductor industry equipment

While ZnO films are hardly, if ever, printed at the present time, the current widespread interest in printed electronics (PE) suggests to us that some functional ink firms may take a look at ZnO; Five Star Technologies has already created customized ZnO dispersions. Degussa is a major player in the printed electronics space. As far as we are aware, Degussa has not printed ZnO, but it *has* done work on the use of ZnO as a UV protecting material on PET for packaging, which has an obvious connection to coating ZnO on PET substrates for applications more closely related to electronics.

E.3.2 ZnO Single-Crystal Companies

In another part of the ZnO value chain, there is a handful of firms that specialize in supplying single-crystal ZnO. These include: Cermet, Nanovation, ZN Technology, Mineral Ltd., Tokyo Denpa and ZnOrdic. Although not stressed by the company publicly, Cermet in particular seems to be interested in exploring the opportunities available from ZnO electronics.

E.3.3 Device Firms

There are several firms and types of firms that could emerge as major manufacturers of ZnO electronic devices. As we have already mentioned, the firms pursuing ZnO TFTs include some better-known Japanese and Korean electronics firms. Taking the IGZO route are Toppan Printing, LG Electronics and Canon. Firms using "pure" ZnO include Sharp and Casio. Research groups at ETRI (Korea), Samsung (Korea), ITRI (Taiwan) and a few U.S. academic researchers are also looking at ZnO TFTs. Sharp is known to be interested in the ZnO LED area too.

We would also expect device firms for whom working with ZnO is already a major part of their business to take an interest ZnO electronics. The most obvious companies to list here are the varistor companies. A complete listing of these companies would be very long and include many almost-unknown Chinese chip companies. There are a few varistor firms that stand out though. One of these is clearly Amotech, which has captured about one-third of the market. But there are other big—and fairly diversified—electronics firms that sell varistors and therefore would be expected to have some in-house experience in working with ZnO as an electrical material (albeit for passive devices). Apart from Amotech, some big names in varistors include Murata, Panasonic Electronic Devices, TDK, and Vishay.

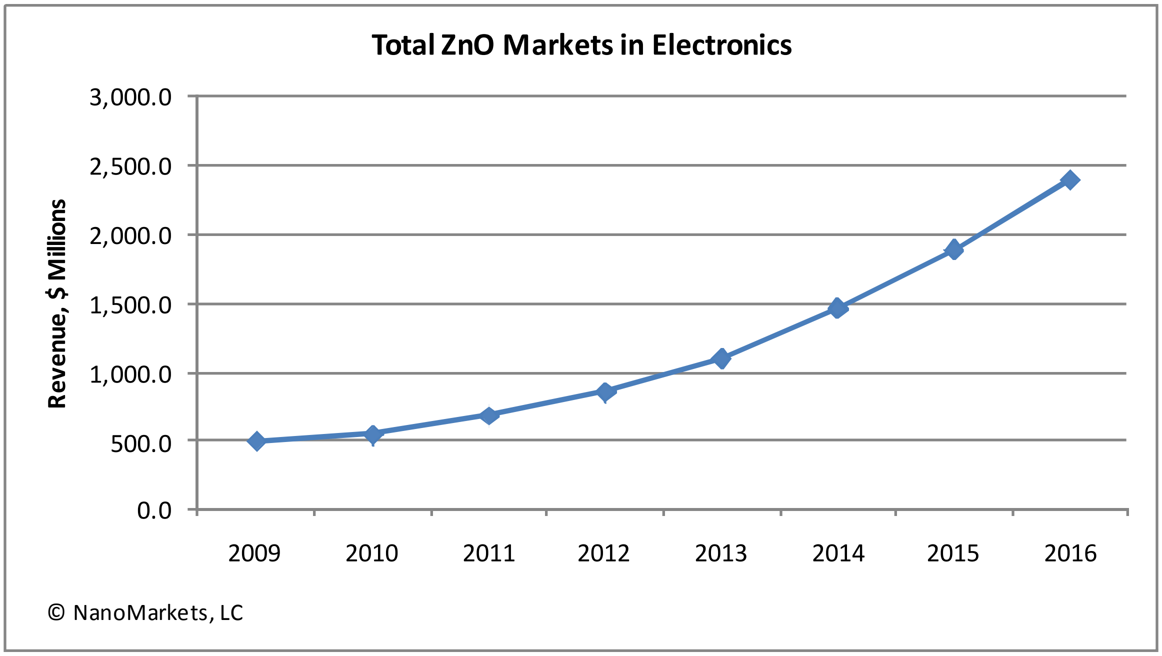
Some firms from the HB-LED and power electronics will also most likely take an interest in ZnO electronics and will likely think of ZnO as a novel material for some of their existing applications markets. NanoMarkets expects that as the more complex end of ZnO electronics begins to develop—we are talking about ZnO transistors, LEDs, sensors and spintronics devices—start-up companies will begin to emerge to produce these devices. Some of these firms already seem to exist but in very early stages of development at the moment. These companies' business models and strategic thinking are likely to be similar to the firms that emerged to support the development of GaN devices a decade or two ago.

E.4 Summary of Eight-Year Market Forecasts

The opportunities available for ZnO electronics can be categorized in a number of ways. One way is to categorize them by the main type of functionality that they exploit. For example, ZnO LEDs are based on ZnO's semiconducting properties. Secondly, ZnO opportunities can be classified according to time frame; ZnO varistors are very much a product that can be classified as mature, while ZnO TFTs for OLED display backplanes are devices that are a few years away from commercial implementation, and transparent electronics in the way we define it really falls into the category of "who knows."

Finally, another way of looking at the opportunities associated with ZnO electronics is to consider the potential size of the opportunity. One way to do this is to consider how big the addressable market is and how key ZnO is to penetrating that market. In this report, we have taken the view that there are really three classes of opportunities that emerge from this analysis. First, there are the big opportunities in which inherently large addressable markets are attacked by products that are distinctly ZnO-centered in nature. An example here would be a new class of low-cost HB-LED made from ZnO, which could quickly make inroads into the already large HB-LED and SSL market. Then there are opportunities in which ZnO competes with many other types of materials, but where there is a good chance that ZnO could come to dominate a niche market, which is not inherently large, but where ZnO is clearly the material of choice. An example here is the use of ZnO as a contact material for a-Si and CIGS photovoltaics. Finally, there are the opportunities for ZnO electronics in which ZnO is used from time to time, but where ZnO doesn't have a compelling advantage over other materials, of which there are usually many. The use of ZnO as an ITO replacement is a good example here.

There is admittedly some fuzziness to this classification. What seems like a niche today may be a huge market tomorrow. However, we believe that this classification is useful, especially in terms of breaking out what parts of ZnO electronics could conceivably produce large revenues at some point in the future. With this in mind, we have used this classification as an important input to our forecasts presented in Chapter Four of this report and summarized at the end of this chapter. In Exhibit E-3, we summarize NanoMarkets' expectations of the electronics applications, both stable and emerging, into which ZnO is being (or is likely to be) sold.



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