Transparent Electronics Markets—2012

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NanoMarkets, LC
PO Box 3840
Glen Allen, VA 23058
Tel: 804-270-4370
Web: www.nanomarkets.net

In the past few years there has been much talk about "transparent electronics," but few, if any, attempts to assess the potential size of this market or whether there are genuine opportunities to be found in it. This new NanoMarkets report fills this gap and provides the first assessment of transparent electronics from a commercial – rather than technological – perspective. The report covers both opportunities at the applications and at the materials level.

The report begins with an examination of the applications that have been proposed to date for transparent electronics. Most of these have yet to be commercialized and in this survey we analyze each of the applications with a view to determining whether they have a real chance of generating new business revenues in the near-to-medium term future. Our assessment in this regard is based on how the sectors to which transparent electronics is being addressed have developed in the past and on NanoMarkets' many years of experience assessing new technologies in the display, solar panel, TFT, and other related technologies.

This report also provides an in-depth assessment of the devices and materials that are likely to be used in transparent electronics. Here again, NanoMarkets is able to bring to the table its long experience of analyzing the market for transparent conductive oxides, a class on which transparent electronics will be highly reliant. The report also includes a revenue forecast and roadmap for transparent electronics for the period: 2012 to 2019.

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Chapter One: Introduction

1.1 Background to this Report

There is nothing intrinsically new about transparent electronic materials. Glass and (more recently) transparent plastic have been used as substrates for displays, solar panels and large-area sensors for years. In addition, a range of transparent conducting materials—notably indium tin oxide (ITO)—has been developed for use in transparent electrodes. And, of course, optoelectronic materials—of which there are many—*must* be transparent to some degree.

Until quite recently the statements above were at best a set of interesting, but unconnected, observations. Over the past decade new transparent electronic *semiconductor* materials—primarily metallic oxides—have appeared and there are now increasing signs that a complete transparent materials set may emerge in the electronics sector. These materials, NanoMarkets believes, will serve as an important enabling factor for new products in the display, smart windows, lighting, solar panel and large-area sensor markets; perhaps other sectors too.

Despite appearing to be very different, these application areas actually have quite a lot in common; in fact they overlap. A smart window could also be a display, lighting or solar panel, for example. And all of the areas mentioned above qualify as large-area electronics in some sense. Finally, displays, smart windows, solar panels, panel lighting and large-area sensors are similar enough that they share a number of important desirable features such a strong aesthetics, efficiency, etc.

While each of these product types has its own requirements, the similarities among them seem sufficient for this entire group of applications and products to benefit in similar ways from a coherent and comprehensive transparent materials set. Such a materials set would serve as a key enabling technology adding features and functions to transparent electronics. In other words, there is an opportunity to develop a more comprehensive and higher performing transparent materials set that could enable transparent electronic products to evolve to a point where they themselves can generate more revenues. This, of course, is also an opportunity in its own right.

1.1.1 Oxides, Organics and Nanotech: Materials for Transparent Electronics

Parts of the electronics suite are already well developed. This is particularly true for transparent conductors, which have received considerable attention over the past few years. This high level of interest, however, has occurred not so much because of transparent electronics in the sense that we are using the term here, but rather because of the need for improved transparent

conductors in the display and solar panel industries more generally. In particular, these industries have looked for ways to get around the lack of flexibility and high cost associated with the industry standard transparent conductor, indium tin oxide. Transparent conductors that have been proposed as an alternative to ITO include transparent conductive oxides other than ITO, conductive polymers and various nanomaterials.

Also, transparent electronic device makers do not have to look far for substrates. Glass substrates, along with substrates made from plastics (PEN and PET) are easy to source. Not all glasses and plastics are up to this task, but transparent substrates suitable for electronics applications have been available from firms such as Corning (glass) and DuPont Teijin (plastics) for many years.

Developing materials for a complete transparent electronic materials suite could take a number of directions in the future. However, it seems safe to assume that most of the transparent electronic materials that are developed and commercialized by specialty chemical and material firms will be based on metallic oxides. This is apparently the program to get with in the transparent materials space and is where most of the R&D effort and research literature is focused. The popularity of using semiconducting metallic oxides is due to several factors, but it helps that, for the most part, these materials are very inexpensive. In addition, much of what is going on in transparent electronics devices today can be traced back to the thin-film transistor (TFT) research devices created with metal oxides in the early 2000s.

This is not to say that other materials will not find their way into the palette of product/systems designers in the transparent electronics space. The metal oxide paradigm is far from a perfect one. In particular, the absence of widely usable p-type oxide semiconductors at the present time is a real barrier to having a complete oxide-based electronics materials suite.

The search for better metal oxide materials for transparent electronics will continue, and as transparent electronics searches for better materials, it is unlikely to restrict itself to metal oxides. Another obvious direction to seek out a materials infrastructure that can serve as the basis of transparent electronics is in organic electronics. Here some of the materials that are routinely used (e.g., PEDOT) are intrinsically transparent. But organics as electronic materials have some of the same problems that metal oxides do; in particular it is hard to build high-performance TFTs using organic materials; the electron mobilities of both oxide transistors and organic transistors are stunningly low by the standards of conventional silicon microelectronics.

Given all this, it seems reasonable the transparent electronics community will see opportunities in the area of nanomaterials. There is already considerable interest in developing transparent

nanocomposites with enhanced electrical and mechanical properties. A range of transparent coatings based on nanomaterials is also now available. Although not a consistent program to provide a materials suite for transparent electronics, trends in transparent nanomaterials of this kind could help provide enabling materials of various kinds for transparent electronics at some point in the future.

1.1.2 Real-World Transparent Electronic Applications: From the Future and the Past to the Present

Eventually the materials suite used by transparent electronics will stabilize and the role of organic electronics materials and nanomaterials in transparent electronics will become clearer. But as we have explained above, the possible technical directions that these materials are likely to take are fairly well defined; although we should not exclude surprises entirely.

Opportunities in the area of the transparent electronics products themselves can be somewhat difficult to pick out. This is not just because of the diversity of the possible products that can be built within the context of transparent electronics paradigm, but also because both the actual past of transparent electronics so far and the somewhat futuristic prognostications about transparent electronics that have been widely published are a distraction from understanding what can really be achieved in the next few years with transparent electronics:

- **Too cool to succeed:** Transparent electronics suffers, we believe, from the fact that it is so cool that it virtually cries out to be built into highly futuristic scenarios. And this is exactly what has happened. Just a casual look at the literature on transparent electronics—even the formal technical literature—usually reveals quite quickly a slew of references to science fiction movies in which transparent electronics are featured. The favorite in this regard is the Tom Cruise movie "Minority Report," but other movies are also referenced. This is all a lot of fun, but gives a false impression of the current state of the art in transparent electronics and what might be achieved using this technology. Watching Cruise in "Minority Report," it is never quite clear just *why* he is using transparent displays in his work. In other words, these display are props not just in the sense that they are not physically real (they don't actually function). They are also divorced from market realities.

- **Current apps for transparent electronics are quite primitive:** Paradoxically, the other reason why systems opportunities in the transparent electronics space can be difficult to identify is the exact opposite of the over-optimism reported on in the previous bullet point. A quick examination of the current offerings that might reasonably be included

under the heading of "transparent" electronics reveals not products that, with a little tinkering could make it into "Minority Report II," as it were, but rather primitive niche products.

For example, in the display space, if one looks for transparent displays, what one will find are simple passive matrix LED and EL displays which represent a tiny niche within the digital signage business; they are displays with very limited functionality. Similarly, self-tinting smart windows have been around long enough to show that they cannot compete with a conventional window, when a customer is looking for something that enables good natural lighting and attractive views. Or where tinting is critical to the specific application, the difference between tinted and untinted offered by a smart window is just not great enough. Again, we are looking at products and concepts that are out of tune with market realities.

1.1.3 Three Factors That Can Lead to the Commercial Awakening of Transparent Electronics

Given all this, the big question is can transparent electronics move beyond the fanciful on the one hand and low-performing niche products on the other? In our view, there are four critical aspects of "transparency" that the design and marketing of transparent electronics products needs to focus on for it to become a serious revenue earner. These factors are (1) aesthetics, (2) integration (3) improved economics and (4) (somewhat paradoxically), aspects of transparent materials that are not directly related to transparency:

- Other relevant drivers for transparent electronics may be discovered over time, but these are the ones that seem to matter now.
- As the transparent electronics materials suite that we discussed earlier improves, it seems reasonable to expect an increased ability of transparent electronics to compete over all and any of the three dimensions mentioned above.

Aesthetics: It is intrinsically hard to measure the impact of aesthetics on market response, but important to remember that aesthetics has always been a key factor in marketing glass products; the glass industry having a considerably longer history and deeper understanding of marketing transparent products than the emerging transparent electronics industry.

Aesthetics seems to be key to much of the transparent electronics that has appeared to date. The simple transparent displays that are already available for use in advertising use "transparency" to gain extra attention. And transparent solar panels are being deployed in part

because they look better than large framed solar panels installed in an all-too-visible fashion on a roof.

Integration: *Because transparency enables visual access to multiple layers of a large-area panel it permits an additional level of integration. This is most obvious in the transparent overlay displays that are already being built in prototype by the display industry; but it is also part of the design story in the smart-window concepts that are being dreamed up that combine self-tinting windows, OLEDs and PV.*

Improved economics: Obviously, in the end all of the advantages attributable to PV reduce to improved economics, but in some cases this is more obviously the case. *One example of that is in the PV space again, where transparent solar panels represent an example of building integrated PV in which the cost of building materials and of PV can be distributed over a common substrate, thereby reducing total expenditures.*

Non-transparent aspects of transparent materials: As mentioned above, in the case of transparent conductors, some transparent electronic materials have been developed without truly transparent electronics in mind as an application. However, it is possible that the converse could be true as well; that is that materials that are developed specifically with transparent electronics in mind could find a larger market.

The primary example—perhaps the only example, so far—of this kind of thing relates to the oxide TFTs that are being developed with transparent display backplanes in mind. There is also serious consideration being given to the possibility that these TFTs could be used in OLED displays more generally—that is, in non-transparent OLED displays—on price and performance grounds

Obviously, the business potential for transparent electronics is limited if all the work and all the press releases concerned just materials and research devices. This would suggest that the only market for the new materials would be the R&D community, which is a real market and one that is extremely interested in buying new materials; but in very small quantities.

Fortunately, there are also signs that the transparent electronics market is beginning to move beyond the niche products that are mentioned above. It is particularly gratifying that transparent displays are now moving from being the province of little signage firms to one that interests the likes of Apple, LG, Microsoft and Samsung. And when one digs down a little further it is possible to find interest in designing transparent solar panels from major PV firms.

It would not be a complete surprise to find players in the smart window, sensor and lighting industries also begin to invest substantially in transparent electronics over the next few years.

1.2 Objective and Scope of this Report

Transparent electronics is only just beginning to be discussed as a unified field, both in terms of technical developments and in terms of market opportunities. As we have noted, in the past many of the components of transparent electronics in terms of materials were already there, but no one really talked about "transparent electronics" in a general sense until recently:

- The point of the essay at the beginning of this Chapter is to show that it is reasonable to think of "transparent electronics" both from the market perspective and from the perspective of considering transparent electronics in terms of a unified materials set.
- With this approaching unification of transparent electronics into a single topic, there have been few, if any, attempts to assess the potential size of this market or where the genuine opportunities can be found within it. There are a lot of technical papers in the field of transparent electronics and their number is growing all the time. There are also now (at least) two books devoted to transparent electronics. But again these have a primarily technical orientation. Where they stray into the area of examining the potential of the transparent electronics market, they do not do so in an effective way.

This report is deigned to fills the gap in terms of the missing business analysis. Its main objective is to identify and quantify genuine opportunities for transparent electronics devices and systems; that is, opportunities that take transparent electronics beyond the current niche status of most of its current manifestations. At the same time, the opportunities with which this report are concerned are not so futuristic that they are unlikely to attract much investment in an era of high business risk and the likelihood of high long-term discount rates going forward.

Put another way, the goal of this report is to discover applications for transparent electronics that are both likely to be achievable in the next few years and that have a reasonable likelihood of attracting a reasonable level of consumer demand.

It is important for the reader to understand the scope of this report. First, we cover both commercialization of materials for transparent electronics *as well as* devices and commercial products and systems. At this early stage of development of this phase of transparent electronics, this fullness of coverage would seem to be essential, so that the market and technical forces at work are best understood.

We did not really set any limits to the coverage of this report in advance in terms of applications. However, our research suggests that a relatively few areas represent most of what is going on in transparent electronics. Transparent displays are undeniably where much of the focus of transparent electronics is today. Indeed, some people might claim that "transparent electronics" is entirely about displays.

This is not the thinking used in this report. We have also covered transparent solar panels, smart windows and lighting, and large-area sensors:

- With regard to transparent solar panels, we analyze this market as part of the rapidly growing building-integrated PV (BIPV) market.
- With regard to smart windows and lighting our concern has been not to be over broad, since all windows and lighting are transparent by definition. Our primary interest here is with self-tinting smart windows, since this seems to intrinsically involve transparency. Our discussion of lighting is mostly to do with integrating lighting into other transparent electronics products.

This report is international in scope. However, where there geography-specific aspects of the market need to be pointed out, the appropriate comments are made in the text. As with all NanoMarkets reports, this report includes an eight-year market forecasts; in this case a revenue forecast and roadmap for transparent electronics for the period 2012 to 2019.

1.3 Methodology of this Report

A full discussion of the methodology used in this report is provided in Chapter Four where the forecasting methodology in particular is discussed. We note here only that it is based on an assessment of the size and growth of the addressable market for transparent electronics and the likely timetable for market penetration of transparent electronics in all the major market sectors.

Much of the information that is discussed in this report is based on NanoMarkets' ongoing research activities including primary interviews with key executives. Some of the areas that are covered in these interviews include metallic oxide conductors/semiconductors, organic electronics, nanomaterials, next-generation displays, OLEDs, BIPV, smart windows and large-area sensors. All of these areas are critical to transparent electronics in terms of applications and materials suits. However, this report goes beyond the data collected from these sources in that we have assessed that data as it impacts transparent electronics considered as a whole.

Beyond the applications and materials areas that NanoMarkets provides regular coverage for and which are strongly related to transparent electronics, this report has also derived useful information from the usual online sources; trade periodicals, government sources and the like. We have also consulted technical papers that formally concern themselves with transparent electronics; although we note that for the most part, the topic of these papers tends to be confined to transparent semiconducting devices; both discrete devices and thin-film transistor arrays.

1.4 Plan of this Report

This report is divided into four Chapters and an executive summary, which provides a summary of the opportunities that NanoMarkets identifies in the transparent electronics space.

The main interest in Chapter Two is with the materials and to some extent the technology of transparent electronics. It covers the main trends in oxide electronics and also takes a look at how nanomaterials and organic electronic materials may play a role in transparent electronics at some point in the future. In addition, the Chapter looks at special materials requirements and trends for transparent solar panels, smart windows, etc.

Chapter Three is an examination of the markets into which transparent electronics can be sold. In this Chapter we examine conceptually where the kind of transparent electronics that is available now or will be available over the next eight years may find some effective demand. Since few, if any, products of this kind have moved beyond an early stage of development in this regard, this Chapter involves a certain amount of speculation. The primary applications areas that are covered in this report are displays, smart windows and lighting, solar panels and large-area sensors.

Chapter Four provides forecasts of revenue and (where possible) volumes generated in the markets on which this report is focused. As discussed in more depth in the Chapter itself, the basic approach to forecasting is to examine the underlying markets and see how open they would be to transparent electronics and how likely it is for such penetrations to occur. This assessment can then be turned into a forecast of materials.