Opportunities for Nanosilicon: 2009-2016

September 2009

Executive Summary

E.1 Opportunities for Silicon Nanomaterials and Nanostructures

For decades, nanotechnology has promised entirely new applications—and improvements in performance of older ones. Until recently, it was widely believed that the best applications for nanotechnology were the ones only considered in science fiction—molecular-sized machines that automatically manufacture all sorts of sophisticated macro-scale products, for example—but now the more "mundane" applications, such as conductive films and photovoltaics, for instance, appear to be as good an investment, or even better because the technology and the market are much closer to realization.

NanoMarkets believes that nanocrystalline silicon could be the nanomaterials to address challenges facing several of these more "mundane" applications. This material brings with it all of the benefits promised by nanomaterials in general—high surface area-to-volume ratio, which enhances properties including conductivity and charge storage that are active predominantly at the surfaces of particles or crystal grains; quantum effects, a characteristic that has implications for both electronic and optoelectronic applications; and the ability to tune the properties of the nanocrystals by controlling particle size, which is useful in inks for printing processes—in addition to useful characteristics that are particular to nanocrystalline silicon itself.

Nanocrystalline silicon in particular has the greatest potential for near-term returns because it is based on the very material that is the foundation of the electronics industry. In a time when the investment community is extremely risk-averse and very particular about where to invest, the fact that silicon is familiar works to the advantage of nanocrystalline silicon. The companies developing nanocrystalline silicon have observed that investors are comfortable with this material because of its silicon basis, which allows focus on the proposed applications for the material rather than scaring away investors at the sight of the term "nano." In some cases, NanoMarkets believes that commercialization of nanocrystalline silicon is less than one year away, largely because sticking with silicon—even at the nanoscale—eases many of the concerns with implementing a "completely" new material. Other nanomaterials in general suffer more from a longer time horizon for commercialization and the short-term focus of most funding sources.

The applications we cover here are the ones we see as the most profitable within the eight-year scope of this report. Several other applications are possible—nanosilicon lasers and certain biomedical applications, for example—but have little likelihood of achieving the volumes and technical developments required to produce large enough profits within this timeframe. Thus, we focus on the applications that will most likely produce significant revenue streams over the next eight years.

E.1.1 Major Changes from NanoMarkets' 2007 Report

Everyone can agree that the state of the electronics industry—and the entire worldwide economy—in 2009 is much different from what it was in 2007. Focusing specifically on the development of nanocrystalline silicon technology for electronics applications, a number of things have changed.

First is the state of the economy itself. The reduced demand for most electronic products and an increased aversion to risk have made investment in the commercialization of new technologies more difficult than it was in the past, across the board. This has produced a setback for all of the nanocrystalline silicon applications discussed in this report, although development is continuing albeit at a slower pace.

Through the backdrop of the economy and the investment environment, some other important developments have also occurred that affect the outlook for nanocrystalline silicon. The most significant changes have occurred in the areas of photovoltaics and in printed organic electronics (which is expected to compete with printed nanocrystalline silicon in some applications) and these are the areas where this report differs the most from the 2007 report.

The state of the photovoltaic industry is not quite what was expected as of 2007, especially for thin-film PV (TFPV). The growth of TFPV has been a bit more rapid than anticipated—mainly due to First Solar's high rate of growth—but a greater change is that the mix of TFPV technologies and products is much different from what was expected. There is First Solar, of course, which has boosted CdTe PV volume beyond our forecasts from that timeframe. But the one-time darling of the TFPV industry, CIGS PV, has not even come close to what was expected of it. This is true both in general terms—the volume of CIGS PV production—and in terms of the types of products expected of CIGS PV—flexible ones. While good flexibility has been achieved in some cases, barrier film technology is still lagging and the flexible modules remain limited by their sensitivity to moisture.

The low penetration of CIGS PV leaves us largely without a high-volume, high-efficiency TFPV platform to compete with the high end, but bulkier and heavier, crystalline silicon (c-Si) PV products on the market. The CIGS encapsulation issue has also left thin-film silicon with its rather mediocre conversion efficiency as the technology best suited from a practical standpoint to the flexible applications that have always been widely expected from TFPV. Nanocrystalline silicon PV has the potential to help on both fronts. The enhanced properties of silicon nanocrystals as well as quantum effects including multiple exciton generation (MEG) are likely to offer significantly higher conversion efficiencies. And nanocrystalline silicon should suit the flexible product platforms as easily as does current thin-film silicon PV technology.

Printed organic electronics has long been considered the emerging technology of choice for all things flexible and low-cost; it was supposed to be just a matter of time—and just a short time—before it reached the proper price and performance points. There were suggestions at the time of our 2007 report on nanocrystalline silicon that organic electronics was beginning to fall short of its expectations; this realization has been reinforced over the past two years. While this is not a good thing for printed electronics in general, it does leave open a door to opportunities for another low-cost printing technology, and nanocrystalline silicon is perhaps the best inorganic option to achieve low cost while also maintaining performance similar to that of conventional silicon devices.

E.1.2 Photovoltaics

NanoMarkets considers photovoltaics to be the most promising opportunity for nanocrystalline silicon in the electronics industry today. For one thing, the addressable market is huge and growing rapidly. While the PV industry has been definitely hit hard by worldwide economic and market conditions, it is still growing overall. Eventually the worldwide economy will begin to grow again and the construction markets that PV depends so heavily on will again start to pick up—in some places sooner than others—resulting in more and better opportunities for PV installations. Granted, the fervor with which the industry grew in the mid-2000s is likely far behind us, but the capacity growth that has resulted from that frenzy will help to keep prices lower—and hence demand reasonable—even if government subsidies and feed-in tariffs start to peter out. While we do not expect PV to return to the growth rates of 2007 and early 2008 for many years, the industry is rife with innovations—some of which are nanosilicon-related—that may help to boost growth rates, at least for portions of the PV market.

Also important is the niche that nanosilicon seems ideally suited to fill. Current amorphous silicon (a-Si) PV cells are rather disappointing in terms of conversion efficiencies as compared to other competing PV technologies—specifically c-Si PV, CIGS PV, and CdTe PV—and tandem cells using Si:Ge or microcrystalline silicon as the second cell are not too much better. But thin-film silicon PV almost certainly has the lowest cost of materials for the long term. With the end of the silicon shortage, the silicon for these cells is cheap compared to some of the materials used for other TFPV cells. Even at the peak of the silicon shortage, the price of silicon was still well below that of indium, for example. Tellurium is also fairly scarce and has had some price volatility with increasing consumption for CdTe PV cells. And c-Si PV cells use as much as 100 times as much silicon as do TF Si PV cells.

But nanosilicon offers the promise of higher conversion efficiencies while still benefiting from silicon's relatively low cost. Tunable nanosilicon particles can contribute to higher-efficiency tandem or multijunction PV cells, and other morphologies—nanorods and nanowires—offer to boost efficiency even further. One of the key developments since NanoMarkets' last report on nanocrystalline silicon has been the changing composition of the photovoltaics industry. CdTe PV has superseded a-Si PV to become the leader in TFPV, while CIGS PV has not made the progress that was widely expected. What this means for the PV industry is that the makeup of the technology mix is different than expected. Instead of a high proportion of the highest-efficiency—among the TFPV technologies—CIGS PV, nearly all TFPV production is split between the lower-efficiency technologies CdTe PV and TF Si PV. While we wait for the higher demonstrated efficiency of CIGS PV to come around in volume, a window of opportunity has been opened for expected—though not yet demonstrated in products—improvements in efficiency such as those anticipated from nanocrystalline silicon.

Along with the low market penetration of CIGS PV, the much sought-after encapsulation solutions that were expected to enable durable flexible CIGS PV applications have also not yet materialized. This leaves a-Si PV as the only currently viable technology for flexible, exposed applications such as some building-integrated PV (BIPV) products. CdTe PV has been dominated almost completely by First Solar, which has focused exclusively on conventional panels and has not made any hint of flexible products.

These developments actually manipulate the market somewhat in favor of nanocrystalline silicon PV. The higher conversion efficiency expected from nanocrystalline silicon can have a greater impact in the market since the bar has set itself lower than anticipated. In addition, the large niches that depend on flexible PV panels, which it was widely thought that CIGS PV would fill, are being filled by flexible TF silicon panels at mediocre efficiency. This presents an early opportunity for nanocrystalline Si PV to enter the fray to offer a higher-performing, moisture-insensitive flexible technology for these applications.

What's next: Now that these opportunities have become available, there are a number of ways things might proceed. Innovalight may gain a foothold with its printed nanosilicon PV and may achieve performance matching—or even exceeding—competitive TF Si PV cells. Assuming that Innovalight's technology is as scalable as claimed—and that the expected economies of scale are achieved—nanocrystalline silicon PV may rapidly become the next up-and-coming PV technology.

NanoMarkets sees nanocrystalline silicon PV as the greatest current opportunity for nanocrystalline silicon at the current time. It is likely that PV demand will continue growing as prices come down and the economy eventually gets back to some level of growth. Over the next few years, even though First Solar is likely to continue to lead in the TFPV sector, something will be needed for higher conversion efficiencies at low cost and for flexible applications. Even if CIGS PV gets into high volume and its encapsulation issues are solved, nanocrystalline silicon materials—and, with similar manufacturing processes, overall production costs—are almost certain to be less costly than CIGS materials and there are also likely to be many areas where nanocrystalline silicon PV is more suitable than CIGS PV.

E.1.3 Memories

The nonvolatile memory industry is anxiously seeking options to allow continued scaling of memory arrays beyond what is capable with conventional floating-gate memory technology. While some warn of the "end of Moore's Law," it is not likely that the memory industry will simply sit back and abandon its drive to achieve tighter-packed and faster memories even if the current technology reaches some kind of barrier. Such a barrier may be approaching in the form of the thick gate oxide that is required to insulate conventional silicon floating gates. Nanocrystalline silicon's answer to this problem is to use silicon nanocrystals as the floating gates, making charge retention more robust and reducing the thickness of gate oxide required to prevent leakage.

The memory market is huge and represents a tremendous opportunity for new memory technologies. But there are several new memory technologies and some have already become commercialized. Ferroelectric, ferromagnetic, and ovonic or phase-change memories are all commercialized to at least some extent—ahead of nanocrystalline silicon floating gate memories—and vie to solve the same scaling problem. Even if nanocrystalline floating gate memories make significant penetrations into the nonvolatile memory market, the nanocrystals that are used do not necessarily need to be silicon; metal nanocrystals can also function and there is some suggestion that they could even be faster. Metal gates are becoming accepted in the logic fabs and it is likely that this acceptance will lower the resistance of the memory industry to using nanocrystalline metal floating gates.

What's next: Because of the range of successfully launched alternatives to conventional floating gate memories and the other yet-to-be-launched alternative memory technologies—including within the nanocrystalline floating gate memory regime—NanoMarkets believes penetrations of nanocrystalline silicon into the memory market will be limited. The conventional floating gate memory technology may also surprise us by overcoming barriers to scaling using some other method besides nanocrystalline silicon floating gates or the other memory technologies, thus retaining the lion's share of the nonvolatile memory market. Even so, the memory market is so large that, even at low levels of penetration, the chunk of device-level revenues generated by nanocrystalline silicon floating gate memories is likely to be larger than those of the other categories of nanocrystalline silicon products, excluding photovoltaics. But it should also be noted that the nanocrystalline silicon for the floating gate material makes up a smaller proportion of the total device cost for memories than it does for the other categories of products that nanocrystalline silicon is likely to impact substantially.

E.1.4 TFTs

Most of the companies developing nanocrystalline silicon—especially inks—have some plans for the TFT market. This is understandable because the conventional silicon TFTs used in active matrix displays are rather costly to build and there have been significant efforts to reduce those costs. Some efforts have focused on using amorphous silicon instead of polycrystalline silicon, underscoring the entrenchment of silicon in this industry and the willingness to try other forms of it to pursue lowered costs. Other efforts have switched to organic TFTs, but the performance of these devices is in the best cases only nearly equivalent to—and in most cases much worse than—even amorphous silicon. Nanocrystalline silicon offers a high likelihood of decent performance at lower cost, especially if it is printed.

There are two major markets for nanocrystalline silicon TFTs—active matrix display backplanes and RFID devices—and they have largely different needs from their TFTs and the materials from which they are built. For RFID devices—particularly passive RFID devices—cost is king. While performance improvements in RFID devices may offer some benefits at the high end, the general consensus—shared by NanoMarkets—is that the major opportunities for market growth lie at the low end. As the cost of RFID gets lower and lower, more and more types of products can absorb the cost of including them within packaging or even on or within the item itself. On the other hand, while costs are certainly important in the display industry, the TFT materials make up only a very small proportion of the overall cost and hence the products are better able to absorb the cost of higher-performance TFTs, especially since competition is based largely on both quality and performance.

The implications of widespread adoption of low-cost RFID at the item level are enormous. One futuristic scenario would be for stores, other businesses, and consumers to instantly determine stocks and the age of individual items in inventories without having to manipulate each item by hand. This could be especially valuable for perishable items such as foods. NanoMarkets does not propose that such a scenario is right around the corner, but various steps in that direction—for instance, remotely readable, unique item labeling—is likely to be commonplace within the next several years.

Most of the attention on development of low-cost TFTs for RFID has been focused on organic TFTs. The thinking is that these OTFTs—and the organic materials used in them—are likely to become very low in cost like other plastics plus the devices are easily printable, allowing additional cost benefits, and easily applied to flexible substrates. But printed nanocrystalline silicon offers its own advantages, some of which are similar to those of OTFTs—the low cost of the materials and the deposition methods—and some that are different, like the similarities to the existing silicon technology being used now for higher-end devices, the higher performance levels expected, and their greater tolerance of moisture and air exposure. NanoMarkets believes that there will be a mix of printed TFT technologies used in the RFID industry and that nanocrystalline silicon will have a significant place, starting with devices that require higher performance along with low price or that can be used in moist environments without degradation.

For displays, TFT development is likely to continue to focus on performance as much as cost. For this reason, NanoMarkets believes that conventional silicon materials—and conventional deposition methods—will be more persistent in the manufacture of display backplanes. Some printed nanocrystalline silicon TFTs will almost certainly be adopted within the next couple of years, but these will most likely remain at the low end of the display market for quite some time. Other materials for TFTs, like organics or zinc oxide, are likely to also fill some niches such as where transparency or extreme flexibility are required.

What's next: The cost of TFTs for RFID is currently constrained by the materials and the cost of the wafer- and fab-based manufacturing processes. Fab equipment itself is a relatively small portion of the cost of current devices because they are made in fully depreciated fabs, but the other fab-related costs are relatively difficult to reduce significantly. Yet new devices will compete mainly on the basis of cost. Both OTFTs and printed nanocrystalline silicon TFTs will have to compete with smaller margins than available for the other applications discussed in this report. Nanocrystalline silicon inks and printing processes can almost certainly achieve low enough costs to compete with wafer-based RFID devices; the questions are how their costs will compare to those of OTFT-based RFID and how low the prevailing prices for RFID can go.

E.1.5 Lighting

Nanocrystalline silicon lighting is not broken out separately in our forecasts, it is instead included in the "Other" category because it is not clear when or if someone will step up to the plate to push this promising technology toward commercialization. There are reasons for and against undertaking these efforts. On the down side, nanosilicon lighting—if so pushed into commercialization—would be entering the marketplace in the midst of the expected steep growth in OLED lighting. On the other hand, nanosilicon lighting is likely to find some niches, and maybe even a majority of applications, in which it is a better performer than OLED.

What's next: NanoMarkets believes that if a company does eventually begin to take steps toward commercializing nanocrystalline silicon lighting, it is most likely to be a nanocrystalline silicon PV player. In addition to nanocrystalline silicon experience, such a player would also have experience with the deposition of the other layers that are similar between lighting and PV and with the wide-area manufacturing processes in general. Much of the same equipment could be used and it could represent a relatively small investment compared to a new startup, and therefore less of a risk. Perhaps Innovalight will return to developing nanosilicon lighting after establishing itself in volume producing nanosilicon PV. Regardless of what company may eventually undertake this effort first, it is likely to be relatively easy for that company to take a leadership position in the industry because the field is currently vacant.

E.1.6 Applications and Opportunities for Silicon Quantum Dots and Other Nanostructures

While the nanocrystalline silicon technologies that are closest to commercialization either rely on continuous films of nanocrystalline silicon or random arrangements of quantum dot structures, ordered quantum dot structures and other nanostructures also offer promise for performance improvements or other benefits. The silicon nanocrystals in nanocrystalline floating gate memories are perhaps the closest manifestation of quantum dot-like materials that is near commercial production. But they are essentially for discrete charge storage within the floating gates.

Silicon quantum dots have the greatest potential for novel performance benefits where light—absorption or emission—is involved. Among mainstream, high-volume applications this means PV cells and solid-state lighting. Such devices that are currently near commercialization generally do not capitalize on the quantum effects of quantum dots; rather they use continuous nanocrystalline silicon films essentially as a conventional silicon film but with greater ease of deposition, or perhaps modestly enhanced performance due to particle size and surface area. Future development of these structures within devices will depend on the prior development of commercial nanocrystalline silicon devices. That is, once nanocrystalline silicon achieves significant volumes of commercial production, the development work on enhancing the performance of the devices—including by taking advantage of their quantum properties—will begin. Based on the types of nanocrystalline devices that are currently in development, nanocrystalline silicon PV cells will almost certainly benefit from quantum effects ahead of nanosilicon lighting.

Silicon nanowire structures and other nanostructures also offer the promise of performance and cost improvements. In photovoltaics, tall, narrow nanostructures—including vertical nanowires—would provide a substantial depth for the absorption of light while limiting the likelihood of leakage or quenching of the excitons thus generated. For both photovoltaics and TFTs, nanowires could potentially be built in coaxial, multilayered structures that would equate to partial assembly of the devices before the silicon nanowires are even applied to the substrate, offering the possibility of reduced costs.

E.2 Manufacturing and Materials Issues and Opportunities

Especially at the nano size, materials and the manufacturing processes used to make and deposit them go hand in hand. The manufacturing processes for nanocrystalline silicon intimately affect the materials characteristics and, conversely, the materials exert a strong influence on the manufacturing processes. As with any new technology, there are development issues with the manufacturing of nanocrystalline silicon materials and with the manufacturing of devices using them. Where these are most apparent are in the use of nanocrystalline silicon inks, which still do not perform as well as conventional silicon films, especially if they are not sintered after application. At least part of the problem is the formation of a native oxide layer on the surfaces of the nanoparticles. Such a layer forms on exposure to air, water, or other oxidizers that may be present in ink formulations.

The issue of film performance without sintering is a common one in inorganic printed electronics; it is a major reason that printed electronics has not grown as rapidly as was once expected. Part of the appeal of printing has been the potential of applying electronic materials to a wider variety of substrates—especially flexible ones—and without the high-cost conditions that are required. Until printed nanocrystalline silicon films can achieve reasonable performance without high-temperature—or other harsh conditions—post-processing, their appeal on flexible substrates will remain limited. It is important to note, though, that printed nanocrystalline silicon on high-temperature substrates such as glass can still be much more economical than the conventional deposition methods, even though sintering is necessary. Regardless of the development of low-temperature cure—or no-cure—nanocrystalline silicon inks, printed nanocrystalline silicon will likely find several niches within the TFT and photovoltaics industries.

Another issue, and also an opportunity, with nanocrystalline silicon materials hand in hand with manufacturing is the self-assembly of quantum dot arrays and of other nanostructures to align on the substrate without extraordinary efforts such as manual placement of individual nanocrystals.

E.2.1 Opportunities for Equipment Manufacturers

The manufacturing processes used to form and deposit nanocrystalline silicon—whether in a single step or in multiple steps—intimately depend on the process equipment used. One important realization about the equipment needed for making nanocrystalline silicon films is in many cases very similar, or even identical to, the equipment used for conventional silicon thin films. This lends itself to a relatively easy opportunity to make equipment more appealing to new segments of the industry. Existing equipment lines for conventional silicon deposition could be optimized for nanocrystalline silicon deposition with minimal changes and then targeted for the nanocrystalline silicon industry.

Printing equipment will also be needed as printed nanocrystalline silicon becomes commercialized and grows in volume. The development of such equipment is already ongoing but there will certainly be opportunities for equipment innovations to enhance throughput or quality of deposition.

The production of nanocrystalline silicon materials for inks faces shortcomings in some circumstances, such as in preventing the formation of native oxide on the nanoparticles. Some of these issues may be addressable with advances in equipment, for instance preventing exposure of the nanocrystals to sources of oxidation.

E.2.2 Opportunities for the Traditional Silicon Materials Industry

The equipment used for printing with nanocrystalline silicon inks is vastly different from that used for other, more conventional methods of nanocrystalline silicon deposition such as CVD. However, those conventional deposition methods for nanocrystalline silicon do not differ tremendously from the deposition of conventional silicon in terms of the basic design of the equipment used; variables such as process temperatures, gas ratios, and other process conditions instead determine the size distributions of the crystallites and the proportion of nanocrystalline material to microcrystalline or amorphous silicon. Hence, much of the same equipment as is being used for the deposition of conventional silicon films may also be suitable for nanocrystalline silicon film deposition. The opportunity that this presents is obvious: firms using conventional silicon films for devices like TFTs or PV cells may be able to begin developing nanocrystalline silicon processes with only modest—instead of huge—outlays for new equipment. This is likely to accelerate the development of commercial nanocrystalline silicon devices since the capital risks are lessened.

Another opportunity for the traditional silicon materials industry is the application of nanocrystalline silicon to crystalline silicon wafer-based PV cells to form hybrid crystalline/nanocrystalline cells. Hybrid cells based on crystalline silicon and amorphous silicon already exist—Sanyo's HIT cells are a prime example—and are among the highest-performing PV cells in the industry. Nanocrystalline/crystalline hybrid cells such as Innovalight's first product, which is still in development, may boost wafer-based silicon PV cells to a new, higher level of conversion efficiency.

E.2.3 Nanocrystalline Silicon Inks

Printing with nanocrystalline silicon inks is primarily seen as a way to reduce costs. And the cost-saving opportunities available just by using these inks and printing processes are tremendous. Besides the lower cost of deposition equipment and processing conditions, the higher throughput potentially available could significantly alter the balance of market share for the different PV technologies. Granted, this market shift wouldn't happen all at once, or even all in the eight years covered by this report. But if nanocrystalline silicon PV can achieve these lower costs and higher throughput, rapid growth is almost certain.

The formulation of the inks is very important in addition to simply the use of the inks. Aside from simply making the inks printable and compatible with the substrates used, additional features can further expand their suitability for various uses. The development of no-cure inks—or at least lower-temperature cure—could widen the variety of substrates and underlying layers on which they could be used. Some work in this area is focused on preventing the nanocrystals from oxidizing within the ink. And inks formulated to cause the nanoparticles within to self-assemble into regular patterns or to stick specifically to certain portions of a substrate can enhance the patterning capabilities of the printing process and also help ease the transition to nanostructured silicon materials.

E.3 Marketing Nanosilicon as a "Green" Material

It doesn't take much to make the connection between nanocrystalline silicon and green technology. Two nanosilicon applications in particular are all about reducing the consumption of traditionally-generated (fossil fuel) energy: nanocrystalline silicon photovoltaics and nanocrystalline silicon lighting. As with all of the PV and the low-energy lighting technologies, the nanocrystalline silicon versions of these technologies are certainly considered part of the "green" movement and the cleantech industry. But nanocrystalline silicon can even be seen as "cleaner" and "greener" than some other PV technologies. For one thing, nanocrystalline silicon does not rely on scarce or toxic metals as CIGS PV, CdTe PV, fluorescent lighting, and some inorganic LED devices do. Additionally, the use of nanocrystalline silicon for these technologies represents a reduction in material usage as compared to conventional silicon or many other materials, particular when printing is used as the deposition method. And when printing is used, the processing conditions for deposition are less energy intensive, making the manufacturing process "greener" as well.

Greener manufacturing applies as well to the other applications of nanocrystalline silicon. Printed nanocrystalline silicon TFTs would benefit from the reduced material and energy usage just as printed nanocrystalline silicon lighting or PV would. Even for nanocrystalline floating-gate memories, nanocrystalline silicon can help reduce energy and materials consumption by enabling more rapid scaling, which reduces the quantities of materials and energy used per gigabyte of memory.

E.4 Firms to Watch in this Space

What follows is a brief list of companies that are most likely to achieve commercialization of nanocrystalline silicon products within the next few years. This is not an exhaustive list of companies that have done any work in the area, rather these are the ones that have made significant progress and continued to do so since the economic shakeup of late 2008.

Innovalight: Innovalight is closest to commercialization of nanocrystalline silicon PV with major equipment installations in 2009. Watch for the release of prototype cell data—for its hybrid crystalline/nanocrystalline silicon PV cells—and announcements of completed capacity.

Freescale: Freescale is generally regarded as the leader in development of nanocrystalline silicon floating gate memories and at one point had scheduled product trials and sampling for 2009; NanoMarkets believes this has slid to 2010 because of market conditions. Watch for more information as these trials are completed.

Samsung: This is an important firm to watch not simply because it has done some work in developing nanocrystalline silicon floating gate memories but also because it is such a large part of the memory industry and because it has its hands in many pies; Samsung produces ovonic memories and has also been involved in development of magnetoresistive RAM and other nonvolatile RAM technologies. This is a company that could rapidly scale up nanocrystalline floating gate RAM even if Freescale beats them to the first release.

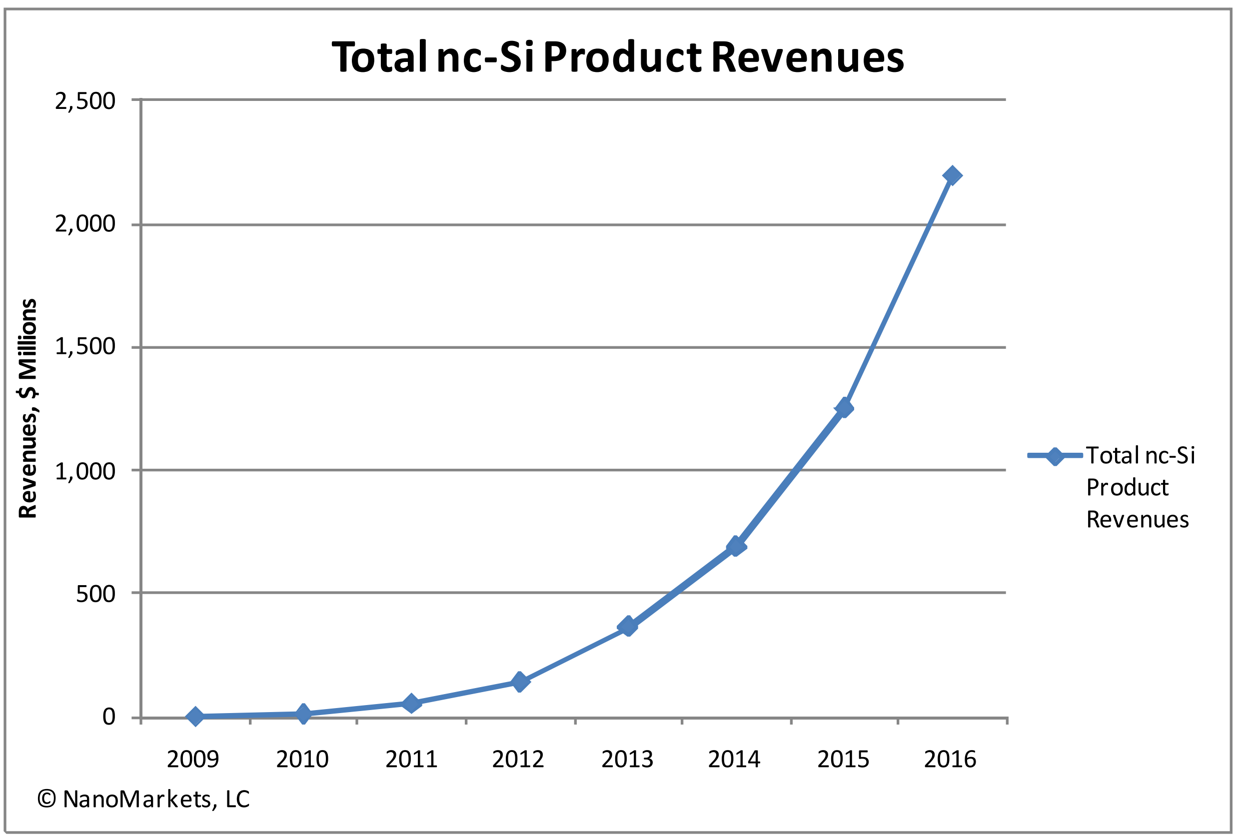
Kovio: Kovio, the leader in developing nanocrystalline silicon inks for printing TFTs, is still receiving investor funding even in 2009, with the goal of starting high-volume production of RFIDs. Watch for an RFID product development and the announcement of capacity.

E.5 Summary of Eight-Year Forecasts of Nanocrystalline Silicon Markets

Below are the summaries of our eight-year forecasts of nanocrystalline silicon materials and of the products made with them.

Exhibit E-1
Nanocrystalline Silicon Product Revenues ($ Millions)

	2009	2010	2011	2012	2013	2014	2015	2016
nc-Si PV Product Revenues								
nc-Si Memory Product Revenues								
nc-Si Display Backplane Product Revenues								
nc-Si RFID Product Revenues								
nc-Si Other Product Revenues								
Total nc-Si Product Revenues								



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