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Real Life Applications of Nanotechnology in Electronics

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Abstract
Nanotechnology is receiving a lot of attention from companies, universities and governments. The US $3.8million National Nanotechnology Initiative is matched by initiatives in Europe and Asia. But what does it mean for existing businesses and new businesses in the electronics market. Is it a real tool for today or are the applications way out in the future? Will it be economic or outrageously costly?

In reality, nanotechnology is like a toolkit for the electronics industry; it gives us tools that allow us to make nanomaterials with special properties modified by ultra-fine particle size, crystallinity, structure or surfaces. These will become commercially important when they give a cost and performance advantage over existing products or allow us to create new products.

The presentation will outline areas in nanotechnology with specific impact on semiconductors, passive components, display materials, packaging and interconnection.

Introduction
The collection of synthesis techniques collectively known as nanotechnology presents many opportunities to reshape the electronics industry from top to bottom.

Nanotechnology can offer us:

- Uniform particles – metal, oxide, ceramics, composite
- Reactive particles – as above
- Unusual optical, thermal and electronic properties – phosphors, heat pipes, and percolation based conductors.
- Nano-structured materials – tubes, balls, hooks, surfaces.
- Self-assembly – liquid-based, vapor based or even by diffusion in the solid state.

The 2004 NEMI roadmap (www.nemi.org) is a comprehensive survey that reviews the issues affecting the electronics supply chain. Gaps in the technology or infrastructure that can adversely affect NEMI members are identified, and the NEMI Research Committee was formed to prioritize and disposition the tasks and identify companies, universities and government laboratories that can address them for the mutual good.

Almost every roadmap chapter in 2004 identifies aspects of nanotechnology that can enhance existing products or replace their structure or function. Some of these are outlined below:

Long Term Issues
Once CMOS technology dips below about 20nm resolution, quantum effects such as electron tunneling start to result in phenomena like unacceptable leakage; the only way to move below that size is to utilize these and other quantum effects in new types of minute structures, be they pure electronic or bio-electronic (remember, the most effective and energy efficient computer available sits on your shoulders!). We know that if we extrapolate Moore's law we "hit the wall" with CMOS about 2015 and although we don't know which technology will replace it, it may well be disruptive. On the other hand, using atomic cluster deposition as described later may allow us to extend much of the established silicon fabrication infrastructure while creating nanoscale structures.

Mid-Term Issues
In many areas of technology, once we hit an area of concern, we can develop a workaround. Hence clock speed, which was the measure many followed as the measure of processing capability, has been replaced in some devices by distributed processing with two processors placed on the same chip. This gets the job done without reduced heat penalty and gives us a breathing space – many upper end processors generate between 100W and 200W – but the heat issue has not gone away. Several unusual properties of nanoscale materials – enhanced thermal conductivity of carbon nanotubes, diamond-like films, nano-metal dispersions – have the promise of aiding heat removal.

Shorter-Term Issues

Enhancement of shielding materials, solders, conductive adhesives, underfills etc. is now becoming possible as nano-sized materials become available and economic.

Technology Push and Market Pull – the Commercialization Challenge

Many nano materials have been developed because of their interesting properties and companies have been founded on products for which there is limited market demand (see the left half of Figure 1). This tends to lead to leading edge products with very limited immediate commercial potential.

On the other hand, the approach of many established companies has been the Market Pull approach where existing solutions are sought for market needs. This conservative approach can result in a very small increment in performance which may not show a cost-benefit improvement for that particular application.

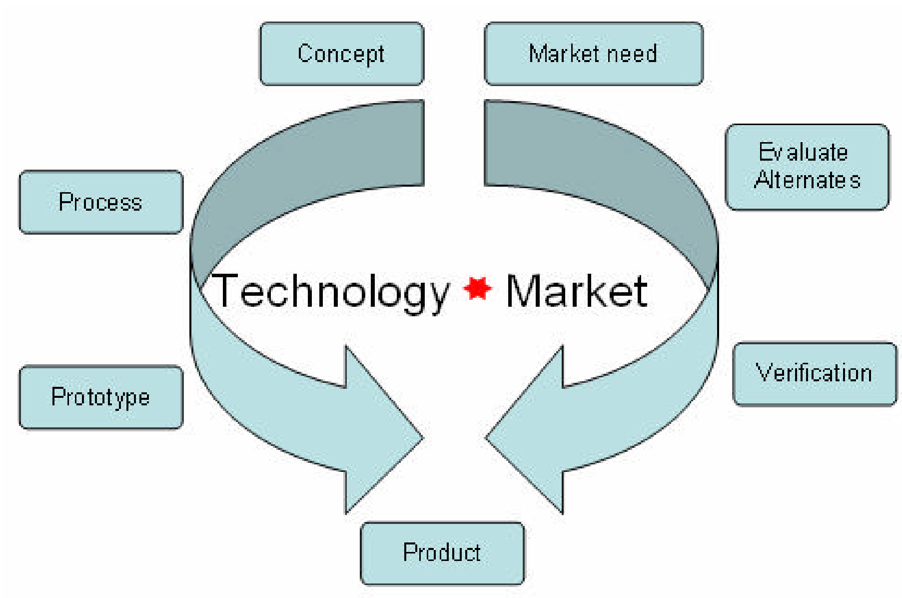

Figure 1 - The Balance between Technology Push and Market Pull

A more balanced approach followed by a number of successful companies, is to take a parallel track, constantly reviewing technology choices on a portfolio basis and applying them to market needs. Technology platforms thus developed – such as metal powders, diamond-like coatings, carbon nanotubes or atomic cluster deposition – can be applied to several other business areas in addition to pure electronics, such as structural engineering, life sciences or energy.

Nanotechnology should only be applied where there is an economic advantage coupled to a performance advantage. This is seen in industrial processes as well as consumer goods where a "luxury" new technology becomes the standard once the existing technology is reaching its limits and the new technology starts to take hold. An example in the consumer field is VCR vs. DVD vs. DVD-R vs. DVR; in the industrial field embedded capacitors vs. discretes. In each case the shape of the graph may differ but the important point is that there is a "crossover" which marks the start of market adoption of the new product.

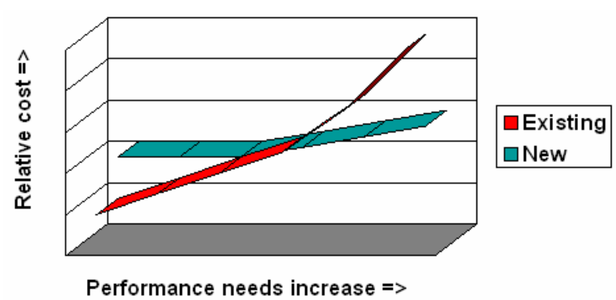

Figure 2 - Replacement of an Existing Technology by a new Technology Based on Economics.

Nanotechnology Application Areas
Semiconductor

Some of the most revolutionary applications in nanotechnology are in the semiconductor areas. As the semiconductor roadmaps look out towards 2015 and below 20 nm features, the need for different structures is becoming apparent…once we move to ultraviolet and then X-ray lithography, there is nowhere to go (in a practical sense) to image ultra small features.

Imagine doping a carbon or silicon nanotube, coating it with differently doped materials, assembling it (preferably self-assembling it) in an array. Imagine creating quantum dots that can store a single electron charge. Imagine trapping atoms inside a nanotube and using the electron spin to create a quantum computing device. There are a large number of potential routes to new computing, storage and optical devices. The devices we are making now are quite clumsy compared with established semiconductor technology. But they will surely improve!

One example of a semiconductor technology that is generating great interest is the atomic cluster deposition technology pioneered by Nano Cluster Devices (NCD) of Christchurch, New Zealand, www.nanoclusterdevices.com.

The technology results from the convergence of two well established technologies – atomic cluster deposition and the type of lithography currently used in semiconductor manufacture.

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The technology revolves around an ability to fabricate nanoscale wire-like structures by the assembly of conducting nanoparticles. The attractions of this approach are:

- Electrically conducting nanowires can be formed using only simple and straightforward techniques, i.e. cluster deposition and relatively low resolution lithography.
- The resulting nanowires are automatically connected to electrical contacts.
- Electrical current can be passed along the nanowires from the moment of their formation.
- No manipulation of the clusters is required to form the nanowire because the wire is "self assembled" using one of two techniques described below.
- The width of the nanowire can be controlled by the size of the cluster that is chosen.

One of the merits of the technique is that it is extremely simple: nanoscale particles, formed by inert gas aggregation, are deposited from a molecular beam onto prefabricated lithographically defined nanocontacts. The cluster deposition is random but is managed via a novel templated surface strategy or within percolation theory. In the templating approach surface structures guide the particles to the 'correct' positions so as to form a wire. In the percolation approach, a deep understanding of the theory, and sophisticated computer simulations, have been used to design device geometries that ensure a single wire-like path is formed between the contacts near the percolation threshold. In either case, an electrically conducting nanowire, which is automatically connected to electrical contacts, is therefore formed with no need to manipulate particles individually or use complex fabrication techniques. The width of the wire can be controlled by the size of the deposited particles.

Applications include:

- Chemical sensors, including hydrogen and glucose sensors
- Read heads for hard disk drives
- Transistors, interconnects and integrated Circuits (semiconducting and conducting wires).
- Photo sensors
- Deposition control systems – a spin off technology for high precision control of particle deposition in the sub-monolayer regime.

Products are under development with several companies.

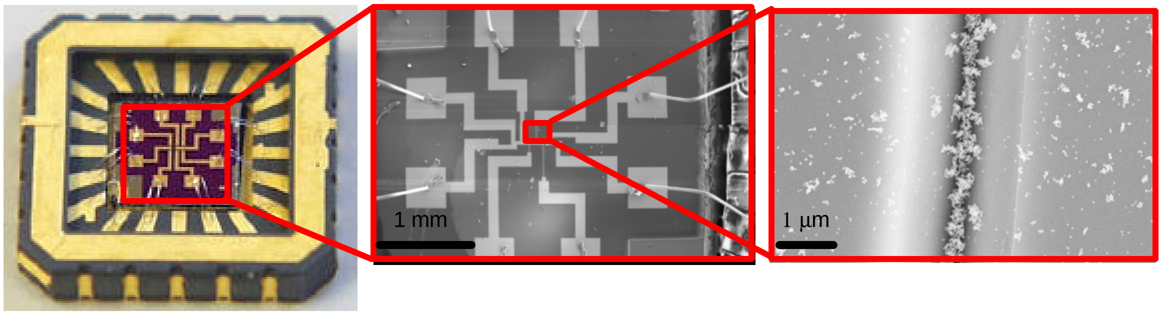

Figure 3 - An 8x8mm Square Chip Package (Low Resolution, Left) With Lithographically Defined Contacts (Higher Magnification, Centre) and A Cluster Assembled Wire (Highest Resolution, Right)

Packaging IC and MEMS Devices

Packaging of advanced devices is going to continue to be problematic since temperature is the enemy of ultra fine features which can be easily destroyed by thermal diffusion or differential expansion. In the shorter term, improved fillers for mold compounds (which are already ~90% filler) and underfills can lead to better thermal and electrical performance combined with easier flow properties.

The use of high thermal conductivity carbon nanotubes and diamond-like films with thermal conductivity over twice that of copper will provide worthwhile solutions as will CTE matched fillers with conductive and dielectric properties.

Board/Substrate

In the last 3 years the board business has changed from a commodity business to a specialty business with materials optimized for thermal, high frequency and environmental reasons. Boards still need improvement in areas such as CTE and flatness and the embedding of passive components needs a low cost self-assembly type process in order to lower the costs to make it truly competitive.

Improved ceramic substrates are possible but in fact many ceramic operations already use the principles of nanotechnology in developing precursor particles with high reactivity and uniformity. There are options to improve conductor and embedded passive technology and to strengthen the substrates as average substrate size is increasing due to the greater use of modules.

Passive Components

There are many uses of interconnection materials within passive components. Monosize materials hold promise in tantalum capacitors and ceramic capacitors, where improved termination materials and electrode materials promise a further reduction in size and cost. In particular, reducing the electrode thickness in base metal ceramic capacitors promises a significant improvement in volumetric efficiency.

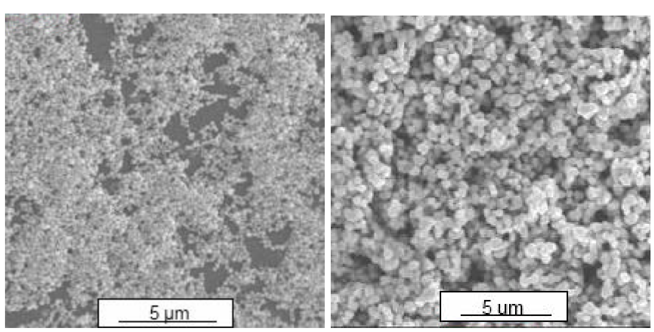

Figure 4 - 200nm Ni Powder and 600 nm Cu Powder

Advanced nano copper and nickel powders available in 2005 offer the following advantages:

- Controllable particle size.
- Virtually monosize particle size distribution.
- Monolayer oxidation resistant coating.
- Economic and scalable process

Barium titanate and other dielectric materials are already produced by "wet processes" such as hydrothermal and oxalate precipitation that produce nano-sized barium titanate particles that are subsequently grown by thermal treatment to develop optimum properties. As we move down beyond dielectric thicknesses of 1 micron we will have to move from conventional tape casting to technologies such as gel casting or vapor phase technologies to optimize performance.

Display

Display technology is similar to semiconductor, where the number of techniques to assemble devices is bewildering! Enhanced plasma displays using nanotubes, light emitting nanowires, quantum dot arrays – a lot of development work needs to be done but new products can be expected in the 2006-2007 time frame. Although carbon nanotubes have been extremely expensive – thousands of dollars a gram – new processes are dramatically reducing the cost of production and the cost will reduce past the cost of silver flake within 5 years,

Consumer and Industrial Products

Finally, nanotechnology can contribute in case design and EMI shielding. A major cell phone manufacturer has stated in public that they will have nanotube reinforced phone cases within 2 years – stronger, lower weight, EMI shielding and recyclable.

Power delivery

A great deal of work is being done in this area to enhance the properties of portable energy systems – enhancing the performance of Li-ion batteries and fuel cells.

Nano-sized electrolyte, anode and cathode materials used in solid oxide fuel cells have already increased the performance of solid oxide fuel cells (SOFC) while reducing the operating temperatures and startup time dramatically. These will become commercially available in 2005.

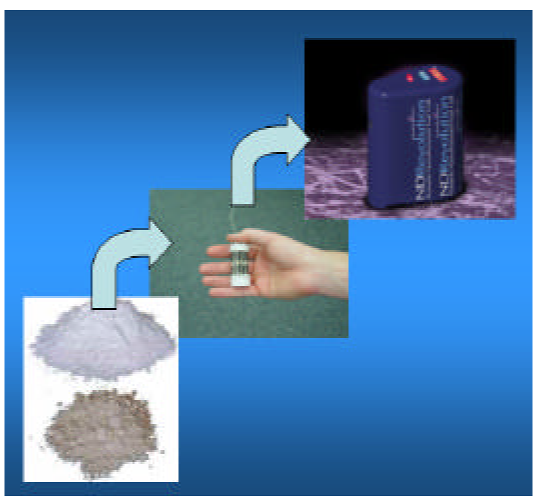

Figure 5 - Compact Solid Oxide Fuel Cell Using Nanotechnology in the Ceramic and Metal Structures

Conductive adhesives

Most conventional isotropic adhesives use silver flake in a resin base, typically epoxy, and have limitations in terms of conductivity, strength and moisture resistance. They typically cure in the $120\text{-}150^{0}$C range, much lower than the reflow temperature of solders.

Copper flakes with oxidation resistant or silver coatings are also being employed in conductive adhesive and EMI shielding.

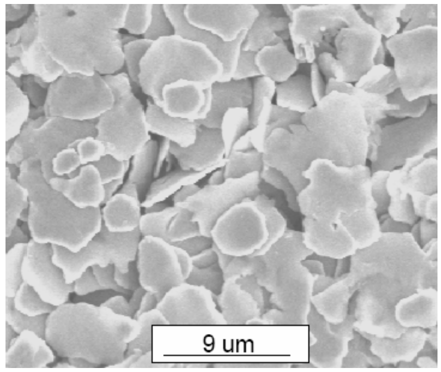

Figure 6 - High Aspect Ratio Oxidation Resistant Copper Flake, Thickness 150 nm

Anisotropic adhesives are largely based on Au plated polymer spheres dispersed in a resin. As the resin shrinks on cooling the conductive surfaces are pulled together and the spheres compressed between them.

There are many opportunities to use novel conductive adhesive systems to reduce processing temperatures but issues of strength under physical shock and high moisture environments still have to be solved. Nanomaterials of various types can exploit percolation and other effects to produce stronger, more conductive adhesives, be they polymer or frit based.

Novel Attachment Structures

Conductive hook and loop and other types of mechanical fasteners based on carbon nanotubes have the potential of replacing conventional inter-connections as strong entangled loops promise thermal and electrical conductivity, compliance and strength, calculated at up to 30 times the strength of conventional adhesives on an area basis (see news@nature.com, 22 October 2003.). Arrays of hooks can be synthesized which can entangle other hooks or a nanotube mat as shown below:

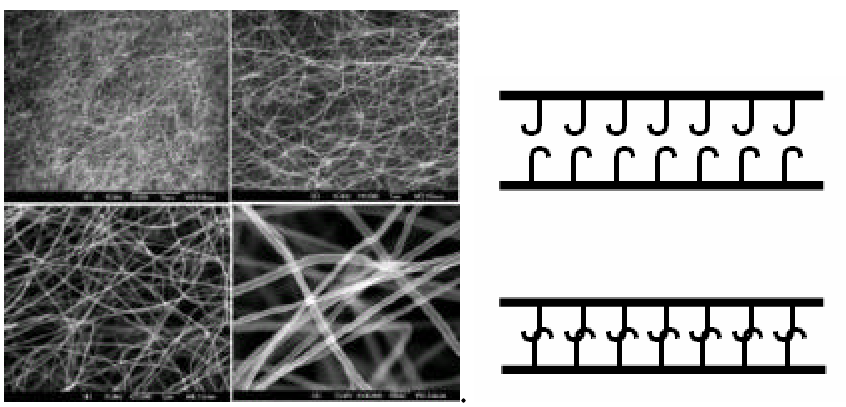

Figure 7 - Carbon Nanotube Fiber Mat and a Nanotube Hook Attachment Concept

Summary

Over the next five years we will see significant introduction of nanomaterials and novel production processes based on nanotechnology which will address key issues of importance to the electronics industry. Longer term the use of nanotechnology will allow us to meet customer requirements by extending existing technologies or replacing them with new ones.