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Innovation isn't always digital. The insatiable need to make products faster, stronger, smaller and lighter is driving the development of new and enhanced Advanced Materials with properties out of reach of prior generations. In this report, the latest in our Profiles in Innovation series, we explore where Advanced Materials science is on the cusp of breaking new boundaries and making the leap to commercialisation, and we chart the interconnected global ecosystem of public and private companies ripe for disruption. We hone in on advances in four key areas-Nanotechnology, Graphene, OLEDs and Cheating Moore's Law-that can address some of the biggest business challenges of the day, from rolling out a 5G network to improving the efficacy of cancer drugs to creating energy storage solutions.

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PROFILES IN INNOVATION Advanced Materials Faster, Stronger, Smaller, Lighter

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This is the sixth report in our *Profiles in Innovation* series analyzing emerging technologies that are creating profit pools and disrupting old ones. Access previous reports in the series below or <u>visit our portal</u> to learn more and see related resources.

- Virtual and Augmented Reality
- Drones
- Factory of the Future
- Blockchain
- Precision Farming



Get a 3-minute audio summary of this report from author Craig Sainsbury. Listen here We explore how AMs

can help solve critical

challenges-from

water filtration to energy storage – in

pages 51 to 63.

four case studies on

real-world

Executive summary: The DNA of Disruption

Historians often refer to pivotal eras in human history by the materials that dominated them – most notably, the Stone Age, the Bronze Age, and the Iron Age. Those times are long past, however, and modern man finds it easy to believe the current era of human history, the Digital Age, is held up by more abstract pillars – like intellect, innovation or communication. But that is only partly correct.

Materials remain crucial to human progress, and advanced materials (AMs) are the DNA of disruption for things – from the largest structures to the smallest electronic components. Each revolution in semiconductors, metals, polymers, ceramics and other substances has created and transformed new products and industries. Just as materials like concrete, Velcro, Gore-Tex, plastic and aluminum were considered advanced at one point in time, today the need to make products faster, stronger, smaller, and lighter has driven the development of materials with properties out of reach of previous generations. Yet AMs are spread so widely across industries, and their development and adoption is so uneven, that the investment implications are exceptionally wide-ranging and can impact almost any market. In this report – the latest in our *Profiles in Innovation* series – we focus on four areas that we believe have the greatest chance of commercial impact:

- Nanotechnology: The ability to understand and utilize the properties of materials at a molecular level (an atom is 0.1nm wide) has the potential to offer benefits such as size reduction and specialty material construction to continue to drive R&D and new product creation.
- Graphene: An allotrope of carbon, with properties of strength, conductivity and transparency that stem from its unique 2D structure, is showing potential in a myriad of applications from water filtration to semiconductors.
- 3) OLEDs utilise an organic compound based electroluminescent layer to emit light. Smartphones and TVs have already taken advantage of their superior display and flexibility, creating a pathway for new products that can fundamentally change mobile technology and the consumer experience.
- 4) **Cheating Moore's Law**, where the constant effort to fit more transistors onto smaller chips is fueling the drive for new materials.

Exhibit 1: The development of AMs is driven by both push and pull forces



Source: Company data, Goldman Sachs Global Investment Research.

Why Advanced Materials and why now?

The benefits of new materials run the gamut from lowering costs by substituting for something else to introducing capabilities that were previously impossible. History shows the impact when an AM reaches widespread adoption, from the development of cement and vulcanized rubber in the 19th century to stainless steel and nylon in the 20th.

Exhibit 2: A history of innovation through Advanced Materials

Year	Advanced Material developed/created/discovered	Creator/Developer
1824	Cement	Joseph Aspdin
1825	Metallic alluminum produced	Hans Christian Orsted
1839	Vulcanised Rubber	Charles Goodyear
1839	Polystyrene	Eduard Simon
1843	Vulcanite	Thomas Hancock
1856	Celluloid	Alexander Parkes
1879	Carbon Fiber	Thomas Edison
1908	Cellophane	Jacques E. Brandenberger
1909	Bakelite hard thermosetting plastic	Leo Baekeland
1911	Superconductivity	Heike Kamerlingh Onnes
1912	Stainless steel	Harry Brearley
1924	Pyrex	Corning Incorporated (Company)
1927	LED	Oleg Losev
1931	Neoprene	Julius Nieuwland
1931	Nylon	Wallace Carothers
1935	LDPE	Reginald Gibson/ Eric Fawcett
1938	Teflon (poly-tetrafluoroethylene)	Roy Plunkett
1938	Fiberglass	Owens Corning
1940	Titanium Sponge	William Kroll
1941	Polyester	W.K. Birtwhistle/ C.G. Ritchiethey
1947	Surgicel	Ethicon (company)
1951	Velcro	George de Mestral
1951	HDPE	Paul Hogan/ Robert Banks
1954	Silicon solar cells	Bell Laboratories (Company)
1954	Argon oxygen decarburization (AOD) refining	Union Carbide Corporation (company)
1954	Styrofoam	Ray McIntire
1958	Lycra	Joseph Shivers
1959	Micropore	3M
1963	Gladwrap (shrink wrap)	Dr Douglas Lyons Ford
1965	KEVLAR	Stephanie Kwolek
1966	Gore-Tex	Wilbert L Gore/ Robert W Gore
1968	Liquid crystal display (LCD)	RCA (company
1970	Silica optical fibers	Corning Incorporated (Company)
1970	Blu tack	Alan Holloway
1974	Vicryl (polyglactin 910)	Ethicon (company)
1982	PEEK	Imperial Chemical Industries
1985	Fullerene molecule discovery	Rice University
1985	Buckypaper	Robert Curl/ Harold Kroto/ Richard Smalley
1986	First high temperature superconductor	Alex Muller/ Georg Bednorz
1987	OLED	Ching W Tang & Steven Van Slyke
1980s	Zylon	SRI International
1991	Lithium-Ion battery	Sony Corporation
1991	Carbon Nanotubes	Sumio lijima
1993	Smart Pill	Jerome Schentag
1994	CMOS image concer	Bell Labs
1995	Civicos image sensor	Enc Fossum Varioue
1990	M-5 (PIPD fibre)	Akzo Nobel
1990s	Vectran	Celanese Acetate LLC
1990s	Precious Metal Clav	Masaki Morikawa
2001	Artificial liver	Dr Kenneth Matsumura & Alin Foundation
2002	Nanotex	Dr David Soane
2004	Graphene	Andre Geim & Konstantin Novoselov
2007	Nanowire battery	Various

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Source: Goldman Sachs Global Investment Research.

Whilst the path to success for a new material can often be winding and slow, new materials' ability to transform industry norms is massive. Indeed some of today's promising materials, such as graphene, have yet to fulfill their potential. Nevertheless, we see multiple drivers in place that give us confidence that today's wave of R&D in new materials will overcome the hurdles to make a significant impact across industries. These drivers include:

- Miniaturization and the race to squeeze more capabilities into ever-smaller devices.
- The urgent need to replace dwindling critical resources, such as clean water (see page 52) and rare earth metals like indium (see page 26).
- Environmental concerns and demand to reduce energy use and waste.

The next generation of AMs is set to be driven by the intertwined and symbiotic relationship between technology and materials science. On the one hand, the massive advancement in computing power over the past 20 years gives scientists and manufacturers the ability to study and structure materials at nano-scales. At the same time, constant increases in computer power place pressure on the effort to continue doubling the number of transistors that can be squeezed into a square inch of integrated circuit (as per Moore's Law). Thus, one of the key enablers of the modern development of AMs is itself dependent on the successful development of new materials.

Out of the lab, into the world: Where can Advanced Materials make a difference?

With the timing right for key AMs to make their mark, we offer case studies of four highimpact applications:

- 1. Water filtration: With more than 600mn people living without access to potable water and safe sanitation, quality water filtration has the ability to transform society as a whole. Graphene filtration technologies can enhance existing filtration systems with improved speed, scale and costs. With US\$10bn spent annually on emerging country water quality and US\$90bn on bottled water globally, the financial opportunity is significant.
- **Energy storage**: Continued advances in energy storage and efficiency are key to 2. managing the demands of a growing population and curbing carbon emissions. Nanotech is set to play a vital role in this effort, with the potential to rapidly improve battery charge times and performance.
- Nanomedicine: Prescription drugs have been a key part of medicinal recuperation for 3. decades, but nanotech has the potential to make them safer and more precise by engineering pills to target impacted areas instead of the whole body. For cancer patients, that means chemotherapy could be delivered directly to the impacted tumor cells, lessening the side effects and potentially speeding recovery. With the cancer drug market a US\$100bn industry, nanotech has the ability to generate significant value for companies that can commercialise the technology.
- Next-gen communications: The coming 5G revolution will increase demand for 4. materials capable of handling high-spectrum frequencies up to 100GHz. Gallium nitride fits this bill, offering better performance than traditional silicon-based technologies on the market today. Its higher bandgap and ability to withstand higher voltages also make it attractive to chip companies working in defense applications.

We highlight public and private company exposures to Advanced Material development in our ecosystem on page 8.

Advanced Materials the VC space; we interview Dr. John Chen, managing

have now penetrated partner of an AM venture capital firm, on page 65.

Exhibit 3: Revolution is dependent on symbiosis Technology and materials cycle



technology

Source: Goldman Sachs Global Investment Research.

Source: Goldman Sachs Global Investment Research.

Exhibit 4: AMs are not isolated silos with many of the materials and processes used in transformational

We highlight public and private players at the intersection of promising AM technology and the case studies we detail on pages 50-63, as well as incumbents at risk. The corporations exposed to the sector are a mix of generalist innovators (such as Samsung, 3M, Lockheed Martin, and BASF) and specialist innovators that are predominantly emerging unlisted corporations (such as Cyclics Corporation, Graphene Laboratories, and Solicore).

ADVANCED MATERIALS in numbers

THE LONG WINDUP IN NANOTECH

1959

The year nanotechnology—the concept of engineering materials with atomic precision—was first discussed. (p. 13)

1,944

The (limited) number of registered products that use nanoparticles today. (p. 19)

A 'MIRACLE MATERIAL' OF A COUSIN

2004

The year graphene—a material that classifies as a subset of nanotechnology and a cousin of the common LCD material graphite—was first isolated in its critical single-layer form. (p. 22)

300x

The strength of single-layer graphene compared to steel. (p. 24)

10,000,000x

Graphene's electrical current density compared to copper, a commonly used material in semiconductors. 25% of patents filed for graphene so far relate to semiconductor technology. (p. 24)

90%

The decline in graphene production costs in the past three years. We estimate costs need to fall another 90% to make graphene commercially competitive. (p. 27)

A BENDABLE SMARTPHONE

180°

The viewing angle smartphones could offer by using flexible OLED displays—essentially the ability to fold your smartphone in half and open it to lay flat. (p. 32)

\$25 billion

50x

Our estimate for the total addressable market for OLEDs by 2018. (p. 34)

FASTER COMPUTING

The electron mobility advantage of III-V materials (materials containing elements from groups III and V of the periodic table) relative to silicon, the current material of choice in semiconductors. Companies are seeking to integrate III-V materials in chips to improve processing power. (p. 47)

VISUALIZING NANOPARTICLES: SMALL SIZE, BIG AREA

75,000

The diameter of a hair follicle in nanometers. (p. 12)

25,400,000

An inch in nanometers. (p. 12)

1,536 mm²

9,600 m²

The surface area of a standard playing dice. (p. 14)

The surface area of a standard playing dice when deconstructed into its nanoparticle components. That's the equivalent of 8 Olympic-sized swimming pools. (p. 14)

The Ecosystem

Advanced Materials - Key Players A sample of companies with exposure

Generalist Investors

Samsung Electronics 3M Lockheed Martin BASF Johnson Matthey Nokia Bayer **Toray Industries** L'Oreal GE

Graphene

Graphenea

Graphene 3D Lab **Graphene Laboratories** FutureCarbon Angstron Materials **CVD** Equipment Corporation AMO GmbH **Applied Graphene Materials** Dongxu Optoelectronic Technology (000413.SZ) Xinjiang Zhongtai Chemical (002092.SZ) China Baoan Group (000009.SZ) Suzhou Jinfu New Material (300128.SZ) Haydale Graphene Industries Directa Plus Graphene Nanochem **OCSiAI** Abalonyx AS Vorbeck Materials

ZapnGo Advanced Graphene Products NanoXplore RS Mines Graphene Platform Corp Elcora Advanced Materials China Carbon Graphite Group

Osaka Gas HEAD BV Vittoria Yonex (Carbon nanotubes)

Goldman Sachs

OLED

Samsung Electronics LG Apple Universal Display **Applied Materials** ULVAC Valiant (002643.SZ) Puyang Huicheng (300481.SZ) Kangde Xin (002450.SZ) Sino Wealth Electronic (300327.SZ) Truly International (732.HK) Idemitsu Kosan (5019.T) Merck KGaA Coherent Canon Konica Minolta Nissha Printing Japan Display Sharp SCREEN Holdings Sonv Toshiba Dai Nippon Printing V-Technology Ferrotec Hirata

Nanosolar

EcoArk BrightVolt (Solicore) Solvay (Plextronics) 3M Universal Display **QD** Vision

Nanocoatings

P2i Dow Siemens Cetelon Nanotechnik Nanovere Technologies Diamon-Fusion International

Nanocomposites

Alanod-Solar **3M ESPE** Elementis Arkema **Cyclics** Corporation DuPont Showa Denko Pentair Koch Sony

Nanomedicine & Nanobiology

Merrimack Pharmaceuticals Intellia Therapeutics **Editas Medicine** Eli Lilly Fujifilm Konica Minolta NanoCarrier 3-D Matrix CellSeed

Advanced Chips Tokyo Electron

Cheating Moore's Law

Intel TSMC Samsung Electronics **Applied Materials** Lam Research ASML Tokyo Electron Qorvo MACOM

The Ecosystem Advanced Materials - Case Studies

Water Filtration

How it works: The demand for water is unwavering and ever-increasing, with advancements in water filtration technology key. Graphene oxide membranes are impermeable to all gases and vapours besides water, allowing for faster and better filtration. Working at the single-atom level, graphene water filters have a mesh with the accuracy to distinguish small percentage differences in atom sizes. The filters are also extraordinarily fast, with the potential to desalinate seawater in minutes.

Select enablers/disrupters: Lockheed Martin, Dow, GE, Pentair, 3M, Koch, Siemens Incumbents at risk: Nestle, Danone, The Coca Cola Company, Nongfu Spring, Pepsi Co.

Energy Storage

How it works: Energy storage solutions are the "holy grail" for renewables, but they're also essential to maximise the efficiency and duration of traditional energy sources. Nanotechnology can be used to enhance the properties of bulk materials like fuel cells, solar cells, and lithium ion batteries to improve their storage potential and recharge rates. For example, in solar cells, an electric current can be created by using nanophotons to release electrons from a material. In addition, nanotechnology can be used to enhance the efficiency and sourcing of fossil fuels.

Select enablers/disrupters: Sony, Toshiba, Manz, BASF, 3M, DuPont Incumbents at risk: AGL, CLP Holdings, China Longyuan Power, Origin Energy

Nanomedicine

How it works: The suite of applications for nanotechnology in medicine is vast--from creating biological machines to using nanoparticles to enhance drug delivery. Taking the latter as an example, nanoparticles can be engineered to target particular areas of the body and more precisely administer drugs with fewer side effects for the patient. Nanoparticles also have the potential to act as more efficient contrast agents and biomarkers, aiding doctors in disease detection and treatment.

Select enablers/disrupters: Merrimack, Intellia Therapeutics, Editas Medicine, Eli Lilly Incumbents at risk: Non-targeted therapies & traditional contrast agents; older nanomedicines threatened by generics (Teva)

Next-Gen Communication

How it works: With data volume per consumer increasing rapidly, the move to 5th Generation or "5G" communication is necessary and inevitable. To handle higher data loads, 5G networks will need to move into higher frequencies and provide faster data transmission. Gallium nitride chips have a higher bandgap than other silicon-based radio frequency technologies, making them well-suited to handle these new requirements.

Select enablers/disrupters: Qorvo, MACOM, Applied Materials, Lam Research, Tokyo Electron Incumbents at risk: Gallium arsenide and silicon germanium producers



CASE STUDY

A Slow Build to Late Success: Lessons from Bakelite



The 70-year gap between the creation and commercialisation of Polyoxybenzylmethylenglycolanhydride — or "Bakelite" — is a classic example of the long, non-linear yet opportunity-rich path to advanced material (AM) penetration. Bakelite was the world's first plastic and first non-natural AM, developed in the early 1900s and first patented in 1907. The ability to compression-press the material into molds and cure it within minutes facilitated the mass production and adoption of low-cost telephones and radios in the 1930s.

The term Bakelite became synonymous with the style and Art Deco trend of products during the 1930s and 1940s and the material retains collector status today.

"One Word: Plastics..."

However, even with the impact of Bakelite in the 1930s, the uptake in plastic was slow and only really accelerated by conflicts such as WWII and the Korean War. In 1950, global plastic consumption was just 1.5mt globally. It was not until the mid-1970s, some 70 years after the first patent for Bakelite was granted, that plastics started to penetrate all aspects of our lives from TV sets to jet planes and everything in between. The world now consumes around 300mtpa of plastics across thousands of applications with an estimated revenue pool of US\$370bn in the United States alone.

As was the case with Bakelite, there will always be early adopters of AM, but we generally find that penetration into the masses is far harder to measure, and is influenced by a number of things. That said, the world's reliance on plastics to this day highlights the vast opportunities that advanced materials can help unleash, as well as the profit pools available to AMs that provide an improvement on the status quo. This crystallisation can take years, and even decades, but once we reach this inflection point, the opportunities are likely to be vast and highly profitable.





Source: PlasticsEurope (PEMRG), Consultic

KEY APPLICATIONS

NANOTECHNOLOGY

- History: Approaching its seventh decade, but remains at forefront of innovation
- **Benefits:** Allows us to enhance the unique properties of materials at the nanoscale offering benefits such as size reduction and specialty material construction to continue to drive R&D and new product creation
- Commercialisation: Current applications involve constructing nanomaterials from larger bulk materials; next phase of commercialisation will focus on "bottom-up" applications, or the self-assembly of atoms/molecules
- Applications: Medicine, water filtration, quantum dots, biofouling (buildup of water-based microorganisms on wetted surfaces), nanocomposites and particles, cosmetics, computer chip manufacturing
- Select company exposure: Lockheed Martin, 3M, Toray Industries, L'Oreal

Nanotechnology: A very small big deal

Nanotechnology, an umbrella term that has been around since the 1970s, is broadly used to describe the manipulation of matter on an atomic level. From a technical standpoint, a nanometer (nm) is a billionth of a meter (and, for the mathematically minded, 1×10^{-9}). To illustrate just how small this is, there are 25.4mn nm in an inch, a follicle of hair is around 75,000 nm in diameter, and a strand of DNA is 2.5 nm wide.

While nanotech may be approaching its first half century as a scientific field, it is only in its infancy as a manufacturing process.

The first generation of nanotech commercialisation has focused on product improvement. Cosmetics, paint, and sporting goods are all products that have been advanced through the development of nanotech and the inclusion of nanoparticles (particles sized at 1-100nm that behave as a unit with respect to transport and properties). Other end-products such as solar cells, lithium ion batteries, and semiconductors have all made step changes in their cost and performance dynamics through enhancements from nanotech.

The second phase of nanotech development entails building on what has already been learned and developed in order to exploit the novel properties of materials and create materials that exhibit multiple outstanding properties and are therefore particularly valuable (such as graphene, which has a unique combination of strength, conductivity, and transparency)

In our view, the long-term game changer will be the evolution of self-assembly and nanofactories. The ability to create custom, unique materials can be used to help drive improvements in fields such as semiconducting, nanomedicine through drug delivery applications, and water filtration through improved catalysis properties.

Nanotechnology – the materials toolbox of the 21st century

As AMs grow in sophistication, nanotech has increasingly become part of the materials toolbox of the 21st century. We believe the ability to understand and utilize the properties of materials at a molecular level have the potential to drive another industrial revolution.

Nanomanufacturing – the development of products on the nanoscale – is enabling the commercialisation of the broader nanotech field. Constructing materials on the nanoscale falls into two distinct approaches:

- i) Top-down approach: The construction of nanomaterial from larger bulk materials.
- ii) *Bottom-up approach*: the self-assembly of molecules/atoms through either the application of external applied force or natural physical principals.

Whilst nanotech is not limited to these areas, we believe it has the greatest ability to disrupt the status quo in the following areas:

- Medicine: Using nanotech, molecules can deliver drugs directly to specific cells in the human body, greatly reducing the adverse effects of some drug treatments (particularly chemotherapy) and potentially improve patient outcomes (see Case Study on page 55).
- Water filtration: Nanotech is a possible solution to one of society's most vexing
 problems -- over 50% of the world's population does not have access to potable
 drinking water. Nano filters and nanocatalysis are central to this effort (see Case Study
 on page 50).

The history of nanotechnology

Nanotech's focus on materials at the atomic level entails a multi-disciplinary approach – one that transcends the fields of chemistry, engineering, physics, computing, molecular biology and material science.

The first reference to the pursuit of "atomic precision" was contained in a speech in 1959 by noted physicist Richard Feynman. In the speech, entitled *There's plenty of room at the bottom*, Dr. Feynman noted that, "The principles of physics, as far as I can see, do not speak against the possibility of maneuvering things atom by atom." Although Dr. Feynman's speech did not attract very much fanfare at the time, it is now looked back on as a seminal moment in the advent of nanotech.

The concept of atomic engineering was furthered through the 1960s and 1970s, and Japanese scientist Norio Taniguchi coined the term "nanotechnology" in 1974. In the 1980s and 1990s, developments in computing power and advancements in microscope technology (namely the scanning tunneling microscope and the atomic force microscope) drove the evolution of nanotech.

Exhibit 5: Key milestones in the evolution of nanotechnology

Year	Event
1959	Feynman first suggests the concept that materials could be engineered with 'atomic precision'
1974	Taniguchi coins the term "nano-technology"
1977	Molecular nanotechnology conceived at MIT
1981	First technical paper on molecular engineering
1985	Discovery of the Buckyball
1986	First book on nanotechnology published
1988	First University course on nanotechnology offered at Stanford
1991	Japan's Ministry of International Tradee & Industry (MITI) announces bottom-up "atom factory
1996	First nanobiology conference
1997	Zyvex, first nanotechnology company founded
2000	President Clinton announces US National Nanotechnology Initiative
2003	US Congressional hearing into the societal implications of nanotechnology

Source: Foresight Institute, NNI, Goldman Sachs Global Investment Research

With nanotech approaching only its seventh decade of development, we believe it is still in the process of completing its first phase of its evolution, one that has been centered on additive materials, which alter and/or enhance the existing properties of the materials they are added to. Over the past 15 years, nanotech has been about understanding and discovering new materials in order to improve existing products. We expect the second phase of nanotech's development will focus on the exploitation of novel properties of materials, particularly the "multi-property" benefits of materials.

Most importantly, we believe this next leg of nanotech development could see the evolution of nano-factories and AMs that are able to self-assemble. Manufacturing on the nano-scale will reduce waste and facilitate the construction of bespoke materials, thereby advancing material science and propelling a further wave of corporate R&D and product development.

The benefits of nanotechnology: The world's building blocks

Nanotech has been used by nature itself to build the world as we know it through molecular and atomic construction. The unique properties of materials at the nanoscale make it possible to harness the physical properties that materials exhibit in their naturally occurring states.

The physical properties of matter change significantly from their larger bulk scales through to the nanoscale. Properties such as electrical conductivity, melting point, reactivity and colour all change as a function of particle size.

The physical properties of matter change significantly from their larger bulk scales through to the nanoscale. Properties such as electrical conductivity, melting point, reactivity and colour all change as a function of particle size.

As an example, gold when deconstructed down into nano particles displays significant catalytic properties. Whilst inert in its natural solid form, at the nano level, more gold atoms are available at the surface due to its crystalline nature. Thus more gold atoms are available to catalyse reactions than are available in its bulk format. Nano-gold is being contemplated in a range of potential applications from photo thermal cancer therapy to the catalysis (speeding up the rate of chemical reactions to achieve an objective) of clean drinking water.

One of the benefits of the nano is the surface area that can be exerted on a material, and in the case of gold, the advantages of greater atomic interface with external influences deliver significantly altered physical and chemical properties. By way of example, a standard playing dice has a 16mm face width and a total surface area of 1536mm². If that dice was comprised of nanometer-sized cubes, the total surface area of the cube – in its nano components, would be 9,600 square meters, which is almost equal to the surface area of eight Olympic-sized swimming pools.

The improved surface area allows greater atomic interface with atoms, thereby improving the catalytic nature of materials.

Nanomanufacturing: A bottom-up future

Nanomanufacturing has existed for decades, primarily in industries such as semiconductors and chemicals.

The broad field of constructing materials on the nanoscale has been segmented into two distinct approaches:

- i) Top down: The construction of nanomaterial from larger bulk materials.
- ii) *Bottom up*: The self-assembly of molecules/atoms through either the application of external applied force or natural physical principals.

The difference of the two methods (ignoring the optics of the end-product) can be likened to the whittling down of a block of wood into a bust of a human head (top down) versus replicating the same bust from individual Lego bricks (bottom up).

Exhibit 6: Nano particles can be created by breaking down bulk material in to nano components (top down) or by forcing atoms into a bespoke cluster (bottom up)



Source: Goldman Sachs Global Investment Research.

The here and now of nanotech is focused on the top-down approach and, more specifically, additive nanotech, which is focused on altering and/or enhancing existing properties of materials. However, the future of nanotech is likely to progress more toward the bottom-up approach where nano-factories and self-assembly processes will allow nanomaterials to be

constructed from the sum of their parts (i.e., molecular construction) rather than by the reduction of the whole.

Top down: Improvement by precision engineering

Top down is essentially an evolution of existing manufacturing processes, but taking it from the micro level to the nano level through increasing levels of precision engineering. The continued reduction in micro processing chip sizes over the decade (with chips down to the nanometer size currently) is a reflection of the rate of change in top-down precision engineering. In the top-down approach, the fact that the nano particles are constructed from a larger bulk component results in more waste (in terms of both material and energy). Also, the ability to specifically create a material with unique properties is the driver behind the molecular construction of the bottom-up approach.

Whilst nothing is simply defined in nanotech, we believe the top-down approach to nanoparticle construction can be broadly classified as: 1) lithography; and 2) precision engineering.

Exhibit 7: Nanomaterials are mainly developed via the top-down approach, which reduces a bulk material into nanoparticles



Source: Goldman Sachs Global Investment Research.

- Precision engineering: The construction of smaller-sized material through cutting, grinding, milling, machining and etching is currently used in a variety of industries and specifically in the electronics and semiconductor industries. The current generation of ultra-precision machining tools can define products at the sub 100nm range. Natural materials such as diamonds or synthetics such as cubic boron nitride are utilised as cutting elements.
- *Lithography*: The creation of nanomaterials through the utilisation of light, ions or electrons to create a surface that is then either etched or deposited onto a material to produce the device/material required. Electron and ion based methods can construct materials down to around 10nm in size but involve a relatively slow manufacturing process and thus are not often used in commercial applications.

The current generation of top-down technology will continue to progress. However, the law of small numbers means that the benefit of the technological advancement from top down will become incrementally smaller. Thus the second wave of nanomanufacturing – bottom up – which is still more in the conception stage than the production stage is expected to be the next driver of the nano revolution.

Bottom up: The specific structuring of atoms and molecules

Whilst the reduction of materials and elements down into their nano format alters properties and applications, it still generates waste and does not deliver a bespoke endmaterial. The concept of bottom-up nanomanufacturing entails the creation of a specific structure using the atom or molecule as a building block for its construction. The material is essentially created by the bespoke placement of atoms into a formation to create a structure with defined and distinct properties. The bottom-up approach is still evolving through the research phase with many industry experts believing that the approach is likely to start to become a viable manufacturing process within the next 5-10 years.



Exhibit 8: The bottom-up approach is the potential future of nanotechnology

Source: Goldman Sachs Global Investment Research.

There are broadly three techniques for the bottom-up construction of nanomaterials;

- *Chemical synthesis* (such as chemical vapor deposition CVD): A process whereby chemicals react to produce a nanomaterial that is deposited onto a thin film.
- Positional assembly: An external force (energy) is exerted onto atoms and molecules and they are forcibly shifted into a position to construct a desired material. Limited waste would ensue, but the application of force/energy would remain required. The construction of structures though positional assembly could make it possible to build nano-bots and other nanoscale machines. However, although the creation of nanofactories capable of churning out nanomaterials would appear to be possible; it is still at this stage a scientific dream.
- Self-assembly: Atoms arranging themselves in an ordered and engineered manner to construct a pre-determined material. Given that the construction is at the atomic level, there will be no waste and limited energy expenditure. Essentially, self-assembly has the potential to be the ultimate "green" manufacturing process.

The bottom-up approach, specifically the creation of bespoke nano-scale materials, machines and structures, is integral to the evolution of nano-manufacturing. The ability to create custom, unique materials could help develop fields such as semiconducting, nanomedicine (through drug delivery applications) and water filtration (via improved catalysis).

Thus, although nanotech is now more focused on creating additive materials to enhance existing applications, the next wave of nanomanufacturing could help solve some of the key problems that an ever-industrializing world faces. Although nanotech may be approaching its half century as a scientific field, it is only in its infancy as a manufacturing process.

The nanotech microscope evolution

Microscope: Derived from the Ancient Greek words mikrós (small) and skopeîn (to look).

Exhibit 9: Electron microscopes' ability to view nano-objects has driven R&D in the field of nanotechnology Resolving power of microscopes



Source: Goldman Sachs Goldman Investment Research

The development of microscopes has come a long way since they were first used to discover microorganisms back in in the 1600s. While optical microscopes have been the mainstay of imaging during this period, their advancement has been limited by their inability to magnify and resolve images smaller than c.200nm (constrained by the wavelength of light) and their limited depth of field (two-dimensional imaging).

This all changed in the 1930s through the invention of scanning electron microscopes (SEMs). Using electrons instead of light, they made it possible to resolve features down to a few nanometers. The electron microscope, first developed by German engineers Ernst Rusky and Max Knoll, uses a focused beam of electrons to probe a sample in a vacuumed environment, and the electronic signal is processed to form an image, achieving magnifications of up to 1,000,000 times. Early progress in material science was mostly limited to studies of small particles, and during this time microscopes could determine the size and shape of materials but not reveal their internal structure.

In 1982, the scanning tunneling microscope (STM) was invented by Gerd Binnig & Heinrich Rohrer in IBM's Zurich laboratory (they were later awarded the 1986 Nobel Prize in Physics for this invention). This was the precursor of nanotech research as the STM was able to: (i) display three-dimensional images of samples down to an atomic level; and (ii) allow for the manipulation of nanoscale particles and atoms to test for their various characteristics and functionalities. However, a major drawback of the STM was its lack of ability to interact with non-conductive materials.

In 1986, the same inventors of the STM invented the atomic force microscope (AFM); the most-used nanoscale microscope, given its ability to scan non-conductive samples. Originally used to image topography of surfaces, it is also able to measure other characteristics of materials (electric and magnetic properties, friction and chemical properties).

Today, electron microscopes are an indispensable tool for analyzing and constructing new nanomaterials. Further, microscopes have recently been integrated to perform in-situ nanomaterial engineering and fabrication using techniques such as: (i) nanomanipulation; (ii) electron beam nanolithography (using AFMs); and (iii) focused ion beam techniques. Examples of products that have improved via these techniques include lithium-ion batteries, nanomaterials and semiconductors.

Commercialising nanotechnology

The benefits of nanotech have long been recognised by governments and the private sector. The National Nanotechnology Institute (NNI) is a US government agency focused on nanotech R&D. The NNI was established in 2000 and since then has been a leader in the field. Since its inception, the NNI has received almost US\$20bn of government funding with the 2017 budget set at US\$1.4bn.





Source: CRS & NNI

Government funding is increasingly matched by spending from private equity and VC firms as well as R&D spending from larger corporations. The OECD estimates that global R&D spend on nanotech is in the order of US\$26bn pa with the United States, Korea and Japan all major contributors. Given that the data does not include regions such as China, the total spend is likely to be significantly higher, in our view.

Exhibit 11: Japan, the US and Korea dominate nanotech patents... % of nanotech patents by country (2015)



Source: OECD, Goldman Sachs Global Investment Research.

Exhibit 12: ...with the number of patents a broad reflection of R&D spend R&D spend in nanotech sector (2015)



Source: OECD, Goldman Sachs Global Investment Research

Most of the commercial aspects of nanotech have been focused on additive materials, which alter and/or enhance existing properties of materials.

According to OECD data, there are around 15,000 firms exposed to nanotech – as manufacturers or via overlaps their operations have with nanotech. Of those firms, almost 1,000 say they are dedicated solely to the field of nanotech. The range of R&D is massively broad given the scope of what nanotech entails – for instance, graphene research classifies as a subset of nanotech, and as such the spend may not represent direct investment in the research, development and propagation of nanotech and nanomanufacturing. Our analysis indicates that, to date, most of the commercial aspects of nanotech have been focused on additive materials, which alter and/or enhance existing properties of materials. For example, housing paints with nano-particles such as titanium oxide (TiO2), are considered nanotech products, and this would also be the case for a tennis racket with a slight additive of graphene (though whether the addition of the nano-material improves the product quality is another matter).

Additives - the here and now of nanotechnology

Spurred on by the never-ending demand for product improvements, companies are increasingly looking to nanotech as a way to gain a decisive edge. It remains difficult to determine how much these products are actually improved by nanotech, and how much is a marketing strategy. Using The Project on Emerging Nanotechnologies database of Consumer Product Inventory, we can identify 1,944 distinct registered applications of nanotech. The data may not be truly reflective of the amount of applications as some companies may not promote the use of nanotech in their products and some may overstate the nanotech component. However, we believe it does provide a reasonable breakdown of nanotech applications from an additive perspective.

Some market research has suggested that nanotech could be a US\$1trn market by 2030. However, we caution that this reflects the dollar value of the end-products that include nano-materials and is not a reflection of the value or revenue that actual nanoparticles deliver.

Exhibit 13: The United States is a leader in nano product development...



Source: The Project on Emerging Nanotechnologies, Goldman Sachs Global Investment Research





Source: The Project on Emerging Nanotechnologies, Goldman Sachs Global Investment Research

Goldman Sachs Global Investment Research

1000

900

800

700



Source: The Project on Emerging Nanotechnologies, Goldman Sachs Global Investment Research

Exhibit 16: ... with antimicrobial protection (sunscreen, cosmetics, etc.) the lead nano function



Source: The Project on Emerging Nanotechnologies, Goldman Sachs Global Investment Research

Other technological advancements utilising nanotech include:

- Nanocomposites: The inclusion of nanoparticles into a larger sample material (generally accounting for <5% of the mass of the main material), which enhances the physical properties of the resulting naoncomposite. Can be found in fabrics, solar cells, coatings, super capacitors, etc.
- Nano-electrodes: They perform similar to normal electrodes but on a nano scale. The high surface to volume area of the nanoparticles lead to larger electrode contact areas and thus enhance mass transport. The faster transport of the electrons results in enhanced electrical and ionic conductivity - improving charge times is one example. Lithium-ion batteries, supercapacitors, fuel cells and solar cells have all seen improved energy performance due to nano-electrodes.
- **Nano coatings:** Used in a variety of applications where nanotech can provide a coating or film that improves and alters the reactivity of the material it coats. This includes coatings on cars to reduce the need to wax, films in paints to improve washability, and utilisation in solar cells to enhance the manufacturing of photovoltaic cells.

Nano-products are clearly evolving. The next generation of products (utilising the bottomup approach to nanomanufacturing) are becoming more defined for specific tasks, and will likely start to be commercialised in coming years. In the case studies on pages 50-63, we examine several applications where we believe nanomanufacturing will have a significant impact on the current industry status quo - including boosting potable water availability in the emerging world and improving the delivery of cancer drugs.

KEY APPLICATIONS

GRAPHENE

- History: Still relatively young; first isolated in 2004
- **Benefits:** Strength, conductivity, transparency, weight and unique 2D structure
- Commercialisation: Slowly beginning to ramp up, cost reduction is key
- **Potential applications:** Mobile technology, water filtration, foldable display technology, batteries and energy storage, composite materials, sensors, paints and coatings, printing and packaging
- Select company exposure: End-consumers such as Samsung, Apple, and LG will be ultimate users of graphene in conductors and mobile technology applications. Lockheed Martin is leader in water filtration development.
 Producers of graphene such as Graphena, Dongxu Optoelectronic Technology and Graphene Laboratories are all looking to commercialise graphene manufacturing.

Graphene: The carbon source for the next industrial revolution

Graphene is a single atomic layer of graphite arranged in a hexagonal lattice, and is the world's first 2D (single layer) material.

From coal to graphene, carbon has been ever-present in the evolution of manufacturing. Just as coal was a driving force behind the development and progression of the industrial revolution, graphene has the potential to drive another phase of change. Graphene's strength (it is 300 times stronger than steel), conductivity (its electrical current density is 10⁶ greater than copper's), and transparency make it unique and well-suited for use in a myriad of end-market opportunities and products.

Whilst graphene is now mainly used in small amounts as an additive to enhance the properties of other materials, it has the potential to play a key role in the rapid development and structural change of industries – due to its use in carbon nanotubes, flexible semiconductors, water filtration, and much more.

Graphene could revolutionize audio visual technology via its use in foldable displays and devices and with non-traditional surfaces (such as windows) used as visual displays.

Given that graphene was only isolated in 2004, its potential as an enabler of new technology remain embryotic, but with companies such as Samsung and LG continually adding patents around graphene, the applications and end-markets for the material look set to ramp up sharply.

The history of graphene and its benefits

The differentiator of graphene from other carbon allotropes, such as graphite, is its size. Graphene is essentially a 2D (single layer) material and in its purest form it is only a single carbon atom thick. Its nearest cousin, graphite (the current material de jour for its use as an anode in lithium-ion batteries) has a layered planar structure. In layman's terms, an effective way to visualize the difference between graphite and graphene is to think of a deck of cards. Graphite is two to three decks of cards stacked on top of one another. Graphene is a single card. This unique structure makes graphene much stronger than graphite.

Graphene was first conceptualized in the 1940s. However it was not until microscope technology (mainly the development of transmission electron microscopes in the 1960s and 1970s) allowed the first glimpses into its physical. The first attempts to isolate graphene were conducted in the 1990s and early 2000s; they focused on isolating graphene sheets (essentially graphite) with no reported success in delivering graphene in less than 50 layers thick before 2004.

Sir Andre Geim and Sir Kostya Novoselov isolated graphene in 2004, and received a Nobel Prize in 2010 for "for groundbreaking experiments regarding the two-dimensional material graphene". The isolation of individual layers of graphene, and the exceptional properties it delivers, started a "carbon-rush" into the research and development of the material.

Since then, graphene's viral acceleration into the mainstream has resulted in more than 32,000 patent applications in the past five years and nearly 10,000 research papers published on it annually.

Allotrope: one form type in which an element can occur.

Exhibit 17: Recent years have seen an increase in the number of patents filed relating to graphene...



Source: SciVal

Exhibit 18: ...with China emerging as a leader in graphene technology, followed by Korea.



Source: World Intellectual Property Organization

The buckyball – Generation X's cautionary tale on graphene

The buckyball provides a cautionary tale for the hype around graphene. Buckyballs – or more formally Buckminsterfullerene – is a form of fullerene, which is a molecule of carbon and thus a close cousin to graphene. The buckyball is a spherical fullerene, with a broad resemblance to a soccer ball containing 60 carbon atoms.

Whilst spherical fullerene had been theorized about as early as the 1960s it was not until the mid-1980s that the buckyball was discovered using laser evaporation of graphite.

In 1986, the early pioneers of Buckminsterfullerene (like those of graphene) were awarded a Nobel Prize. The buckyball's properties of large internal space inside the molecule, its bond structure and superconductivity made it a matter of interest for scientists looking to develop applications including hydrogen storage and fuel cells, a trap for free radicals that can reduce allergic reactions, an anti-oxidant to fight multiple sclerosis and a building block for the creation of carbon nanotubes.

Sound familiar?

Despite the buckyball being the wonder of the AMs space in the 1980s and 1990s, not a single application using the buckyball has been commercialised. Interestingly, graphene is now being proposed as a possible solution for many of the applications that buckyballs were once thought to be useful for.

Whilst the lack of commercialisation of graphene's carbon cousin is not in itself a death knell for the development of graphene given their different atomic characteristics, it is certainly a cautionary tale on how hype does not always translate into profit pools.

Exhibit 19: A buckyball structure





Exhibit 20: Buckyball patents peaked 5 years after 500 patents were lodged and have been on a decline since YoY patents changes in years after first 500 patents lodged



Source: WIPO and Goldman Sachs Global Investment Research

The benefits of graphene

The attractions of graphene are its properties of strength, conductivity and transparency. Each benefit in isolation provides inherently better properties than existing materials in commercial consumption:

- Strength: 300x stronger than steel
- Conductivity: Electrical current density 10⁶ greater than copper
- Transparency: Given its single atomic thickness, sheets of graphene are transparent.

The combination of all three properties makes graphene unique in the material science field.

	Graphene	Metal only	Metal + plastic	Alumina + plastic	Graphite + plastic	Graphite sheet
Conductivity	Good	Excellent	Good	Poor	Poor	Good
Additive amount	Small	N/A	Small	Large	Large	N/A
Strength	Good	Excellent	Good	Poor	Poor	Good
Weight	Light	Heavy	Heavy	Heavy	Light	Light
Insulation property	Good	Poor	Poor	Good	Poor	Poor
Cost	Can be low	High	High	Low	High	High
Workability	Good	Poor	Poor	Poor	Poor	Poor

Exhibit 21: Graphene a miracle material found in a simple form Comparison of different materials

Source: Company data, Goldman Sachs Global Investment Research.

Almost 25% of all patents that have been filed globally for graphene relate to semiconductor technology. The commercial impact and subsequent utilisation in semi-conductors is highlighted by Samsung and Semiconductor Energy Laboratory Corporation of Japan being the two largest filers of patents with almost 1,000 patents each (2.3% of total patents filed).

On a country level, Japan and Korea are leading the charge to commercialise graphene, but China is catching up quickly, accounting for almost 30% of all patent applications in 2015. Government funding and policies coupled with world-class academic institutes and research is propelling China to the forefront of graphene research. China's five-year plan for 2006-2010 tripled nanotech funding, highlighting the importance of cutting-edge technology and materials to China's vast manufacturing base.

Patent numbers have been rising since 2006, and momentum is growing, but graphene has still yet to crack the commercial conundrum. Graphene's strength of having a vast array of applicability may also be its Achilles' heel, with researchers taking a shotgun approach to idea generation and thereby slowing down the economic commercialisation process. The range of material applications for graphene includes semiconductors, water filtration, edible packaging, carbon nanotubes and energy storage.

The fact that semiconductors are the single-biggest source of patents (and thus by default research) for graphene is a reflection of graphene's properties and the scarcity of existing conductor materials. Currently indium tin oxide (ITO) is the main material used in semiconductors. ITO's properties of electrical conductivity, heat reflection and most importantly transparency make it a perfect conducting film for the touchscreen display revolution. However, ITO has a rather finite reserve life with our analysis suggesting that

Almost 25% of all patents that have been filed globally for graphene relate to semiconductor technology. there is only around 8-10 years of global indium reserves left. Thus graphene, with its similar properties to ITO and its almost endless supply, could be the perfect replacement material – if its cost of "construction" can be reduced to become economically viable.

Exhibit 22: Graphene patents by country of application





Exhibit 23: Graphene patents by end-product application

Source: World Intellectual Property Organization

Source: World Intellectual Property Organization

Whilst semiconductors is likely to be the main focus of graphene, potential endapplications for graphene are almost endless, but we acknowledge that the key to graphene's success lies with its ability to dislodge existing materials and disrupt the status quo. On this theme, a few factors are key to crystallising widespread commercial uptake:

- Reducing costs of production.
- Developing a reputation of high product quality to drive substitution.
- Educating the masses to view graphene as value-enhancing rather than as a cost.

Whilst the here and now of graphene is still at an embryonic stage, its *potential* remains immense, in our view. Just like plastics in the 1920s and 1930s, graphene is waiting for a "killer app" to kick off exponential demand growth. WWII provided the catalysts to drive plastic demand (given limited other raw materials). Global conflict is unlikely to be the game changer for graphene, but the scarcity of critical global resources (ITO, clean water) coupled with the desire of a wealthier middle class to stay healthy (nano-medicine) will be two important drivers.

The key to graphene's success lies with its ability to dislodge existing materials and disrupt the status quo.

Where's my Indium?

Indium is a silvery-white metal that is associated with zinc, copper and tin. Indium is typically a significantly minor component of the ore assemblages with approximate concentration levels of around 50ppm. Indium is principally a byproduct of the electrolytic refining of zinc ores.

Over 70% of indium is consumed as indium-tin oxide (ITO) for liquid crystal displays. ITO's properties of electrical conductivity, heat reflection and, most importantly, transparency make it a perfect conducting film for the touchscreen display revolution.

Although reserves of indium are not classified, we can approximate off zinc reserves that there is around 10kt of indium reserves globally with about 20% of that within China. Indium supply is a combination of primary supply from mines, along with recycled indium at a rate of about 40/60 primary/recycled split.

On current demand levels, we estimate there is around 10-12 years of known indium reserves left globally.

Assuming an 8% CAGR for demand, we forecast that by 2019 indium supply will not be enough to meet demand. More importantly, indium reserves will be down to five years, impacting surety of supply for producers. Consequently, the need to replace ITO with other conducting material is both a financial and a security of supply issue.

Exhibit 24: Current indium reserves are around 10kt, which represents just over 10 years of supply Indium reserves are based on global zinc reserves and assume a 50ppm content level of indium among the zinc ore

	Indium Reserves (t)	% of world supply
USA	550	5%
Australia	3150	31%
Bolivia	250	2%
Canada	300	3%
China	1900	19%
India	500	5%
Ireland	50	0%
Kazakhstan	200	2%
Mexico	750	7%
Peru	1250	12%
Other	1300	13%
Total	10200	100%

Source: USGS, Goldman Sachs Global Investment Research.

Exhibit 25: By the end of the decade, demand for indium is set to surpass supply

Indium mine supply/demand balance



Graphene manufacturing processes

The manufacturing graphene on a commercial scale is not as straightforward. There are three main ways to produce graphene in commercial quantities:

- Chemical vapour deposition (CVD) the most common and expensive method, it produces high-quality sheets of graphene. It involves extracting carbon atoms from a carbon-rich source by reducing and depositing gaseous reactants onto a substrate to isolate carbon atoms and graphene.
- 2. Graphene powder and flakes this involves exfoliating plastics and is used to produce high-quality thermal plastics.
- 3. Graphene oxide graphite is treated with strong oxidisers like sulfuric acid in a redox reaction. The quality of graphene produced via this process is not very high.

Exhibit 26: Exfoliation is a relatively cheaper method to produce graphene

Comparison of different graphene production methods



Exhibit 27: Application areas have huge potential



Source: Graphene Platform Corporation, Goldman Sachs Global Investment Research.

Source: Graphene Platform Corporation, Goldman Sachs Global Investment Research.

Cost reduction the key for commercial success

The cost-consumption arbitrage for graphene still has a long way to go. Whilst the past decade has seen the production of graphene move from a cottage industry to a more commercial focus, it is still not a mass-production process.

Cost progression has been rapid. We estimate unit costs of graphene powder production were around US\$100/g in 2013, falling to around US\$10/g presently. However, costs need to fall further to <US\$1/g to be competitive and provide a viable substitution alternative for other materials (such as the addition carbon black in plastics). Given a 90% reduction in costs in the past three years, we believe the commercial construction of graphene at sub US\$1/g is a given.

The ability of cost-effective graphene to impact an industry is significant – take carbon black for example. Carbon black is most widely used as reinforcement in tires, and it accounts for c.25% of tire weight, (about 9-10kg for a 16-17-inch tire). According to Japan's Ministry of Economy, Trade and Industry (METI), the price of carbon black was c.US\$1.5/kg in 2015. It is thought that graphene will be able to replace carbon black in plastics while amounting for only 1%-2% of the product content– reducing per-content usage by a significant amount, while enhancing durability and grip, and reducing rolling resistance.

This would mean that graphene would become competitive vs. carbon black if it is sold at around US\$20-30/kg.

Exhibit 28: Graphene price of US\$20-30/kg would make it competitive as a tire additive Pricing simulation for tire reinforcement (carbon black vs. graphene)

Tire weight		10	kg
]	Carbon black	Graphene	
% of tire weight	25.0%	1.5%	
Total weight needed	2.5	0.2	kg
Unit price	1.5	25.0	USD/kg
Total cost as tire reinforcement	3.8	3.8	USD

Source: METI, Goldman Sachs Global Investment Research.

The history of carbon fiber resonates well with the analysis above. The early stage of carbon fiber demand was solely driven by military use, mainly in the United States and the United Kingdom. When the Japanese manufacturers became successful in the commercial production of carbon fiber in the early 1970s, companies searched for consumer-facing applications, but for a long time demand was limited to niche sports categories such as golf shafts, fishing rods, and tennis rackets. It took nearly 30 years until the industry saw a meaningful pick-up in global carbon fiber demand, which was driven by industrial applications. By the early 2000s, prices for general-industrial grade carbon fiber had come down to US\$3,000 per kilogram, from US\$9,000 back in the late 1980s.

However, while the development of carbon fiber was relatively slow, we believe there are several reasons why graphene has the potential to evolve in a more super-charged manner:

- Computing and general scientific technology is now much more advanced than in the 1980s and 1990s and should enable the scientific development of graphene to proceed much faster than was the case with carbon fiber.
- The desire of consumers for smaller, faster, and lighter products provides the pull factor for producers to utilise graphene in their R&D programs and product development.
- 3. The pick-up in carbon fiber demand in the early 2000s coincided with higher oil prices and the global push toward environmental protection. Graphene properties are exceptionally environmentally friendly.

Exhibit 29: Global demand for carbon fiber took off as a result of lower prices

Historical development for global carbon fiber demand and prices for general industrial-grade carbon fiber



Source: Toray Industries, Nikkei Shimbun, Goldman Sachs Global Investment Research

Potential applications for graphene

Graphene's superior strength-to-weight ratio, electric and thermal conductivity, durability, transparency, elasticity and impermeability mean that potential applications could be massive and disruptive to some of the incumbent materials and industries. Let us take a look at some areas where graphene could be used.

As mentioned before, the current global market size for graphene is estimated to be under US\$50mn, with limited commercial applications such as tennis rackets, battery straps and oilfield chemicals. Below are some examples of potential areas of graphene applications that we believe hold significant potential.

Foldable display (wearables): Bendable smartphones are in the R&D programs of many of the world's phone manufacturers. Graphene can be used as a transparent electrode placed between titanium oxide (TiO2) and conducting polymer layers in OLED displays. On June 7, 2016, Bloomberg reported that Samsung is close to selling a phones with 5-inch bendable screens, possibly in 2017. China's tech-startup, Moxi Group, surprised the world when it showcased a flexible smartphone at a trade show in China earlier this year.

Batteries and energy storage: Although lithium-ion batteries are in the spotlight with Tesla's Gigafactory and the potential rise in the global electric vehicle (EV) market, graphene batteries reportedly charge much more quickly and hold power for longer. Graphenano, a Spain-based company, has tied up with China's Chint Group, a power transmission and distribution company, to develop graphene polymer batteries that would significantly increase cruising distance for EVs. Although much skepticism remains about graphene's superiority over incumbent lithium-ion batteries, implications for the EV industry could be massive (especially for companies like Tesla) if graphene batteries can make a commercial debut.

Composite materials: Adding graphene to a composite material is said to be one of the easiest ways to enjoy the superior properties of graphene as it enhances the properties of the existing material. For instance, Haydale Graphene Industries a UK-based public company that specializes in developing and functionalizing graphene, recently announced the launch of graphene-enhanced carbon fiber prepreg (pre-impregnated product), which is capable of faster composite part production (reducing process cycle times), enduring higher temperatures, and high-accuracy tooling. The addition of graphene is also said to double the strength of epoxy resin, which is typically used in carbo fiber composites. This could be a game changer and could facilitate adoption of carbon fiber composites into wider applications.

Sensors: Graphene could be used in high-performance sensors as its large surface-tovolume ratio and bulk-less properties make it very well-suited for sensor functions. Graphene has the potential to replace silicon as it could exhibit superior electron properties while enabling sensors to be smaller and lighter. Applications could be widespread, including biosensors, gas sensors, PH sensors, and more. In July 2015, Germany-based Bosch successfully created a graphene-based magnetic sensor that is 100 times more sensitive (i.e., required less power and footprint requirements) than the traditional siliconbased sensor, although the company thinks it might take another 5-10 years for graphenebase sensors to become commercially viable.

Paints and coatings, printing and packaging: Conductive printing and packaging is another potentially promising area of graphene use. A UK-based technology company, Novalia, together with researchers at University of Cambridge, recently developed a graphene-based conductive ink that could be used on a large-scale commercial printing press at high speed – a development that could potentially replace silver. A successful commercialization of graphene ink could mean cheaper printable electronics, but would also open up potential applications for smart packaging and disposable sensors.

KEY APPLICATIONS



- History: Modern OLEDs were developed by Eastman Kodak in 1987
- **Benefits:** Better contrast ratios, colour schemes and saturation, flexible and bendable properties
- **Commercialisation:** Present-day applications already attractive, mobile (smartphones and tablets) are already in the early stages of adoption
- **Potential applications:** Smartphones, tablets, TVs, revolutionizing what is classified as audio-visual equipment (turning a window into a TV display)
- Select company exposure: Samsung, Apple, LG, Universal Display, Applied Materials, ULVAC

OLEDs: Bending the future

If the term organic light-emitting diodes (OLEDs) seems more familiar than the other AMs we discuss in this report, that is likely due to the mass branding and marketing of the term in products such as mobile devices and TVs. OLEDs have the potential to leverage and collaborate with both graphene and nanotech to fundamentally shift the world's mobile technology landscape.

The flexible nature of OLEDs gives them the ability to challenge what society perceives as audio-visual equipment. TVs remain a separate and distinct piece of furniture in our households. OLEDs have the ability to make a window or mirror or fish tank into something that can project a visual message.

The ability to utilise buildings, windows, and shop fronts as new mediums for commercial messages could change how we advertise and interact in our daily shopping experiences.

Much as the mobile phone continues to challenge and alter our audio communication trends, OLEDs have the potential to drastically alter our visual communication consumption.



Source: Goldman Sachs Global Investment Research.

Source: Goldman Sachs Global Investment Research.

A brief history of OLEDs and why they matter

OLEDs utilise the scientific property of electroluminescence, where a material emits light when an electric current is sent through it. OLEDs use a flat light-emitting technology, made by placing a series of organic thin films between two conductors.

The basic structure of an OLED includes a cathode (which injects electrons), an emissive layer, and an anode (which removes electrons). Modern OLED devices use multiple layers in order to boost efficiency, but the basic functionality remains the same.

Exhibit 32: Organic polymers usually make up the emissive and conducive layers in OLEDs Simplified OLED components



Exhibit 33: Diagram of the structure of an OLED



Source: Goldman Sachs Global Investment Research.

Source: Goldman Sachs Global Investment Research.

While light emitting diodes (LEDs) have been around for over 50 years, OLEDs are a more recent development in the AM space with the most significant advances in OLED technology being made in the late 1980s.

Following those advances, the pace and progress of OLED development increased markedly over the next decade. However, it was not until the late 1990s that the first commercial OLED-based products began to reach the market, led by the Pioneer Corporation's passive matrix OLED (PMOLE) display for car audio in 1997. Fast forward another decade and in 2007 Samsung Mobile Display released the first commercial active matrix OLED (AMOLED) display. AMOLED is now the technology currently used in virtually all OLED displays found in portable electronics and larger area flat-panel displays.

OLEDs have a number of properties that are superior to those of more established technologies like LCDs and LEDs. LEDs are solid-state devices that emit light via the movement of electrons through a semiconductor but are too big to be appropriate for use as pixels in TVs. As such, they are actually used as backlights for LCD TVs. A key differentiator for OLEDs is that their structure enables their organic compounds to light up when electricity is transmitted through them. As a result, OLEDs are small and flexible enough to serve as pixels in OLED TVs.

When used in mobile devices, OLED screens are distinctly better than traditional LCD displays in terms of contrast ratios, colour schemes and colour saturation – not to mention their flexible and bendable properties.

Advantages of OLED versus LCD	Disadvantages of OLED versus LCD
Thinner size as backlight is not required	Higher per-unit production costs
Lighter	Lower production yield
Smaller bezel	Lower life span
Wider viewing angles	Unwanted burn-in of images
More vibrant display, deeper black, and vivid colors	
Better color reproduction	
Faster response time	
Higher peak brightness	

Exhibit 34: Key advantages and disadvantages of OLEDs vs. LCDs

Source: DisplayMate, IHS, Goldman Sachs Global Investment Research.

The hype: Present-day applications already attractive

Samsung, the global leader in smartphones (23% market share) uses OLEDs in their flagship products, which has curved edges, and the ability to be tailored by the consumer in terms of functionality.

Exhibit 35: The potential of flexible phones is vast... Flexible OLED phone indicative image



Source: Goldman Sachs Global Investment Research.

Exhibit 36: ...with flexible OLED technology being used in mainstream phone models to create curved edges



Source: Goldman Sachs Global Investment Research.

We believe this is only the beginning, however, with flexible mobile technology having the potential to drive change and consolidation in the mobile industry, i.e. in smartphones, tablets, smartwatches. Samsung is at the forefront of this, having filed a number of patents for an assortment of digital devices that include scrollable, tab style, and bendable features.

With the leading mobile innovators filing patents for a variety of modern applications (e.g. Samsung for both scrollable and foldable smartphones), the profit pools and growth in TAMs are potentially mind-boggling.

Having discussed the potential for OLEDs to transform the mobile landscape, it is important to note that present-day applications are still highly commercially attractive; we estimate a total addressable market of c.US\$25bn by 2018.

Exhibit 37: Current mobile technology applications are the main demand drivers for OLED technology

OLED applications



Source: Goldman Sachs Global Investment Research.

The promise: Mobile technology, all roads lead to OLEDs

Mobile devices (smartphones and tablets) are already in the early stages of OLED adoption, with the better quality and increased longevity of OLEDs being integral to the disruption of traditional LCD screens. In our view, there will be a transcendent structural shift to OLEDs from LCDs within the next three to five years. We note that Samsung Display is currently the only company mass-producing OLED-based screens; however, there are a growing number of Chinese manufacturers trying to enter the space (Huawei, Lenovo, Xuamei).





Source: IHS

Smartphones are already integral to modern society (c.90% penetration), and are set to become even more important to our personal Internet of Things as they become a one-stop shop for wallets, payments, wearable hubs, and remotes connecting all aspects of our lives.

90%

80%

70%

60% (%

50% etration

40%

30%

20% 10%

0%

20178

đ



Exhibit 39: We expect emerging markets to drive smartphone growth

region



Samsung and Apple (combined 39% market share) have been the dominant smartphone vendors over the last five years. However, both have lost share from their peaks (Samsung at 30%/31% in 2012/13 and Apple at 19%/20% in 2011/12) primarily because of the mix shift from mature to emerging markets, where new low-priced Chinese vendors have gained traction. Indeed, the next three biggest smartphone manufacturers are all Chinese vendors: Huawei (over 7%), Lenovo (5%, including acquisition of Motorola) and Xiaomi (5%).







A clear sign of the disruptive nature of OLED screens can be seen by the recently negotiated US\$2.6bn agreement whereby Samsung will supply Apple with 100mn 5.5-inch OLED display units from 2017. We expect this agreement to expand to all sizes of iPhones

Source: Gartner, Goldman Sachs Global Investment Research.

in 2018, and we also expect other players like Huawei to follow suit in switching from LCDs to OLEDs.

Exhibit 43: Summary of global technology sector implications from OLED adoption in iPhone

Sub-sector/product	Potential impact	Related Companies	Note	Last Close (23 Sep 2016)
OLED Makers	Positive	Samsung Electronics (Neutral)	Key beneficiary of iPhone's OLED adoption as we expect SEC to be the main supplier	¥1571000
iPhone	Slightly Positive	Apple (Buy)	Innovation with OLED could help drive iPhone demand	US\$112.71
LCD makers	Negative	Japan Display (Neutral)	LCD to lose share in iPhone display as OLED iPhone share rises	US\$163
OLED Material Makers	Positive	Universal Display (Buy)	Secular winner in the shift to next generation displays	US\$58.82
Glass Makers	Near term Neutral; long term risk	Corning (CL-Buy)	For Corning, higher share in OLED devices more than offsets potential loss of glass content per device	US\$23.14
Equipment Makers	Positive	Applied Materials (CL-Buy), Ulvac (CL- Buy)	Increased OLED capex generates incremental business opportunities for OLED equipment	US\$29.66, ¥2863
Touch Makers	Positive	TPK (Neutral)	Transition from in-cell to out-cell will expand addressable market for touch suppliers	TW\$52.2
Casing Makers	Neutral	Catcher (Buy), Casetek (Buy)	Metals casing will still be used in a curved screen, but may see design limitations in foldable screen	TW\$267, TW\$118
Polarizer/ITO Makers	Neutral (polarizer: Slightly negative/ITO: positive)	Nitto Denko (Neutral)	OLED requires one polarizer compared to two for LCD, but higher value per film partially offsets the downside. ITO film needed for out-cell	¥6668
BLU Makers	Negative	Minebea (Neutral)	Backlights are not required in OLED	954

Source: Goldman Sachs Global Investment Research.

The future of television: OLEDs or quantum dots?

In our primary research thus far, we have found that the application of OLEDs to the global television market is a unique exercise.

The incumbent liquid crystal display (LCD) TVs are now structurally challenged given the ability of manufacturers to produce higher-quality product using OLEDs at equivalent or lower production costs.

We caution that the TV industry has been in an ex-growth phase since 2013-14. As such, the impact of OLED adoption will not be as commercially viable as that of mobile – in the short term at least.

That being said, Samsung and LG have both indicated their desire to transition into the OLED TV market from the current status quo of LCDs. OLED-TVs have a number of advantages over LCD technology, with key points of difference being a marked improvement in image quality (with no backlight required) and increased energy efficiency.

Another new technology Samsung has been pursuing over the last couple of years is quantum dot (QD) TVs. They have developed a cadmium-free QD TV and are 1.5 to 2 years ahead of competitors. A point of debate, much like an earlier consumer decision of whether to go plasma or LCD, is OLED vs QD. Both technologies have redeeming qualities as well as slight negatives compared to each other, and we believe the consumer's decision is based on personal preference and subjective viewpoints.

We see both OLED and QD as branching technologies, effectively using different processes and methods but in the end achieving a vastly similar outcome.

Exhibit 44: Both have positives and negatives, but OLEDs have more upside if cost of production can be reduced OLEDs versus QDs

Category	OLED	Quantum Dots
Colour gamut	Better	Worse
Colour accuracy	Worse	Better
Contrast	Better	Worse
Viewing angles	Better	Worse
Costs	Worse	Better
Lifespan	Worse	Better

Source: Goldman Sachs Global Investment Research.

We expect the TAM of OLED TVs to be c.US\$2.2bn by 2018 with strong consumer adoption to be offset by structural headwinds in the broader TV market.

The future of visual entertainment

The flexible nature of OLEDs, coupled with their transparency, have the potential to radically change audio-visual entertainment. While the TV industry is in an ex-growth phase, OLEDs could totally change our conception of what constitutes a TV. The ability to place images on what amounts to flexible transparent thin film should make it possible for any flat surface in the home (windows, mirrors, fish tanks, etc.) to become TVs.

As a result, windows and display cabinets in department stores could be turned into multimedia applications. Windows on buildings could be billboards.

OLEDs have the potential to alter how society thinks of what is needed to produce and how we consume visual entertainment.

3D TVs: A cautionary tale

In early 2009, prototypes of 3D TVs were unveiled in Las Vegas and were soon released to the mass market with Samsung and LG leading the charge. Interest and hype peaked following the release of James Cameron's Avatar, where moviegoers were captivated by the use of vivid colours and cutting-edge movie technology to create a 3D spectacle. Unfortunately, in the case of 3D TVS, the hype train never really left the station as issues with a lack of content, the physical hassle of wearing 3D glasses, and substitution toward high resolution (e.g., 4K, OLED) and smart TV functionality taking the air out of the 3D movement.

This change in fundamentals is evidenced by the actions of commercial players. In 2016, Samsung for the first time cut 3D functionality from its TVs, Philips have limited their range to flat TVs only, and LG cut 3D TV production by half from 2015. Content providers are in the same boat, with Sky cancelling its 3D channel and BBC having ceased producing 3D material in 2013.

So where to now? 3D still has a place, but more as a subset of the virtual reality/augmented reality revolution, which encompasses the technology within a broader and far more dynamic framework. The consumer has made its choice, and 3D TVs have not presented a compelling case for broad-based adoption.

Exhibit 45: The hype train can run out of puff very quickly...

Lessons Learnt

- * Breadth of content is key
- * Convenience is necessary in a time poor world
- * There needs to be a compelling reason to switch from the status quo

Source: Goldman Sachs Global Investment Research.

KEY APPLICATIONS

CHEATING MOORE'S LAW

- **History:** Rapid innovation in the last 50 years (reflected by Moore's Law) but reaching the limits of current materials
- Benefits: New materials (strained silicon, high-k metal gate, Cu interconnect, III-V materials, graphene) and new construction techniques (FinFET, 3D NAND, GAA/nanowires) can help cheat the end of Moore's Law and improve processing power
- **Commercialisation:** Economic transition from research/development phases is crucial to get fruitful end market outcomes
- Select company exposure: Intel, TSMC, Samsung, Applied Materials, Lam Research

Cheating Moore's Law

Moore's Law is an observation that the number of transistors per square inch on an integrated circuit doubles every year.

AMs, lithography, and innovative device structures have all played important roles in the history of the semiconductor market, enabling manufacturers to push the limits of Moore's Law and pack more features on successive generations of smaller chips. We have moved from having hundreds of features per chip to having billions of features today. As a result of the relentless pursuit of Moore's Law, we are able to do things like stream high-definition video on our iPhones, a task that would have required a multi-million dollar room-sized supercomputer 30 years ago.

Interestingly, this rapid advancement now leaves us in a situation where we are approaching the physical limits of shrinking semiconductor chips. While much of the historical focus from chip makers has been on the size of the semiconductor, the limitations of technology are forcing the shift in attention to other areas to improve performance, namely new materials and new construction techniques. Lithography has been the primary enabler of smaller, more powerful semiconductor chips; however, we believe AMs and new device structures will play a more important role in the coming decades.

Although hard to predict with 100% accuracy, we have identified graphene, nanowires, and III-V materials as potential innovations that could propel Moore's Law into the late 2020s. Further out, the future becomes even harder to predict, though we believe the number of companies producing leading-edge chips and new technologies could itself shrink as greater scale is required to research and develop more AMs.

Exhibit 46: Increasing computing processing power has been a major driver of the advancement of AMs



Source: Atomic Scale Design Network

Exhibit 47: While US\$/mm2 has increased, scaling has enabled chip manufacturers to pack more transistors onto each chip, reducing the cost per transistor



Source: Copyright Intel, used with permission.

Semiconductors 101

What is a semiconductor and what does it do?

Semiconductors are materials that can act as both conductors and insulators. Silicon is the most widely used semiconductor today and is used to make wafers that are then processed into chips.

Chips vs. microprocessors

Semiconductor chips are manufactured on wafers and a single wafer can contain hundreds to thousands of individual chips. Microprocessors are one type of chip used in everything from PCs to smartphones to data center servers. Intel is the world's largest microprocessor manufacturer with a 99% share of the data center processor market and an 85% share of the notebook and desktop processor markets.

What is a transistor?

The circuitry of semiconductor chips is made up of many transistors that are all packed in an area the size of a postage stamp. Transistors are the building blocks of integrated circuits and serve as switches that control the flow of electrons. Transistors can exist in "off (0s)" and "on (1s)" states depending on whether or not a current has been applied. The ability to generate signals by turning the flow of electrons on and off is what allows computers to process information.

Exhibit 48: Microprocessors are made up of various special blocks dedicated to different functions Intel's Skylake processor, released in Sep 2015



Source: Copyright Intel, used with permission.

What else does a PM who hasn't looked at this space need to know?

Semiconductors represent a US\$300bn+ market and serve as the backbone of today's information society. While computing is the largest end-market for semiconductors, they are also crucial components in communications, consumer, automotive, and industrial applications. As the semiconductor industry has matured, growth has slowed to 5% pa today. However, we still expect select sub-segments to benefit from favourable secular trends, including:

- Automotive applications: We expect the continued electrification of automobiles as well as long-term trends such as advanced driver assist systems and autonomous vehicle to drive semiconductor content growth. We highlight NXP Semiconductors NV (NXPI) and NVIDIA Corporation (NVDA) as key beneficiaries.
- Graphics processing units (GPUs): We believe virtual reality will drive a strong refresh cycle for gaming GPUs, and we view GPUs as uniquely positioned to serve the growing market for machine learning and artificial intelligence applications with NVDA as a key beneficiary.
- Radio frequency (RF) chips are used to filter out unwanted radio signals and enable faster data speeds/greater bandwidth. More RF chips are needed as the number of RF signals increases. We expect 5G to lead to an overall increase in radio frequency usage and, in turn, RF complexity. We view this as a long-term driver of content growth for the RF industry. Key market participants include Skyworks Solutions Inc (SWKS), Broadcom Limited (AVGO), and Qorvo (QRVO).

Getting smaller & smaller... a history of process improvement

Moore's Law started as a simple observation made in 1965 by Gordon Moore (co-founder of Intel), that the number of components on an integrated circuit had roughly doubled each year in 1959-1965. While the doubling period was later revised to every two years, over the last 50 years Moore's Law has come to represent the rapid pace of technology innovation occurring in the semiconductor space.

To provide context, in the first generation of microprocessors there was a gap between each transistor of around 10,000nm in width. Current microprocessors exhibit a gap closer to 14nm, yet an iPhone now has more computing power than a supercomputer from the 1960s. The difference in 14 to 10,000nm is the difference between the length of an i-Phone and the 100m sprint at the Olympics.



Exhibit 49: The evolution in processing capacity

Source: Intel, Press Reports, Bob Colwell,, Linley Group, IB Consulting, The Economist, Goldman Sachs Global Investment Research.

Improved lithography processes have resulted in reductions in transistor size, and size is everything for a transistor. The smaller the transistor, the less power is required to turn it on and off. Smaller size also allows a quicker transition between on and off. Smaller transistors also enable the production of smaller chips, which allow semiconductor manufacturers to fit more chips on each wafer, ultimately driving down cost/transistor. Thus the past decade has seen chip manufacturers focus on reducing size.

Lithography has been the primary enabler of transistor scaling in the semiconductor industry; though in recent years this dynamic has begun to face headwinds.

Lithography – driving the reduction in size

Simply put, lithography is the process of using light to transfer circuit patterns to a wafer. This process is repeated many times over for numerous layers and exposures using different photomasks (think of them as the blueprints) to create the final chip circuit.

More commonly today, the technique of immersion lithography is used. This involves beaming light through ultra-purified water in order to increase resolution and achieve smaller feature sizes.

While immersion lithography has enabled manufacturers to scale feature sizes down to 14nm, new techniques such as multi-patterning have been developed to produce smaller feature sizes. Multi-patterning consists of splitting a single exposure into multiple exposures in situations where feature sizes are too small to use just one exposure. The result is smaller feature sizes, but also higher manufacturing costs.





Source: Goldman Sachs Global Investment Research

However, as we discussed in the nano-technology section, the ability to construct materials from a top-down approach (taking something big and making it smaller – which is essentially lithography) is reaching its practical and technical limitations. The evolution now is not making something big small; it is making something small in a bespoke manner (self-assembly). Thus, unless self-assembly can be proved to be a viable manufacturing technique, and it is not yet there, the continual shrinking in the size of transistors is approaching its practical limitations.

Material issues

Another factor exacerbating the size constraints of semiconductors is the materials from which they are made. As the term semiconductor implies, they are both conductors and insulators of electrical current. Silicon has been the dominant material used in semiconductor devices. Its low material cost, conducting properties and ability to operate under relatively high temperatures has made it the material of choice.

The conductivity and insulating properties of silicon enables transistors to turn electrical current on and off. However, as transistors become smaller, their ability to control electrical current is weakened (this is known as leakage). The leakage of current produces heat, which wastes electricity/power and hurts performance.

Whilst the slowing of the rate of transistor scaling is driving an increased chorus calling the end of Moore's Law, new materials and new construction techniques could enable it to continue into its seventh decade.

Materials and construction to help cheat Moore's Law

To help overcome the stalling of processing power, and the death of Moore's Law, chip makers are looking at two distinct ways to improve transistor performance:

- i) New materials
- ii) New construction techniques

Exhibit 51: The innovations described above are just some of the many options being explored



Source: Copyright Intel, used with permission.

i) New materials

Whilst doping (using impurities to change the properties of semiconductors) has always been a factor in semiconductor manufacturing, material science is opening up new avenues and materials to be used in the next wave of semiconductors. Below we profile some of the current technologies as well as some of the next-generation materials that could be used to continue the advancement of semiconductor processing power.

- Strained silicon was developed as a means of enhancing electron mobility/speed through a transistor and is achieved by growing a strained layer of silicon atop a silicon germanium substrate. Products featuring strained silicon were initially introduced by Intel at the 90nm node in 2003 and subsequently enabled chip manufacturers to continue to provide higher levels of performance and lower energy consumption while continuing to scale transistor dimensions.
- High-k metal gate. To combat the effects of scaling-induced leakage, Intel introduced a "high-k metal gate" into its process in 2007. The "gate" acts as a switch that controls the flow of electrons in a circuit. Below the gate lies an insulator, or gate oxide, that helps the gate focus its power.

Initially, manufacturers reduced the thickness of the insulator as they made the width of the gate smaller, eventually down to a thickness of about 5 atoms. At this point the insulator became ineffective, leading to power drain and lower performance. To counteract this, manufacturers developed "high-k" dielectric materials for the insulator and replaced standard polysilicon gates with proprietary metal ones (the "recipes" are

still closely guarded). High-k metal gates allowed manufacturers to continue pursuing smaller transistor sizes.



Source: Company data, Goldman Sachs Global Investment Research.

• III-V (Indium, Gallium, Arsenide, etc.). Materials classified as III-V are those that contain elements from group III and group V of the periodic table. Currently III-V materials are primarily used in optoelectronics for telecommunications applications, lasers, and LEDs.

Given the high electron mobility (i.e., the speed that electrons move across a semiconductor) of III-V materials (up to 50X that of silicon), chip companies are seeking to integrate them ith on silicon in order to drive performance gains. Adoption of III-V materials on silicon could potentially displace the strained silicon and germanium layers of transistors.

In our discussions with market participants, many view adoption at the 10nm node as unlikely and indicate that the earliest timeframe may be at the 5nm node, in the mid-tolate 2020s. However, we believe there is a chance that adoption could come after 5nm, given the difficulty associated with implementing both new III-V materials and EUV lithography at the same node.

• **Graphene**. Graphene is a single atomic layer of graphite arranged in a hexagonal lattice, and is the world's first 2D material. Graphene's higher electron mobility should allow for transistors with even greater levels of performance than III-V materials, though we note that research scientists and manufacturers have faced problems with producing a form of graphene that has sufficient conductor and insulator properties to allow it to replace transistors.

ii) New construction techniques

Although the advancements in semiconductor technology have been perceived to be bound by the limits of physics (i.e., a transistor can not be made smaller than an atom) there is a lot of research and development being done to create efficiencies elsewhere along the production chain.

FinFET (Fin Field Effect Transistor). FinFETs were commercially introduced in 2011 with Intel's 22nm process technology and has a conducting channel that resembles a fin. Planar transistors were used prior to FinFET transistors. Wrapped around the fin is a gate that controls the flow of electrons. The ability to turn the flow of electrons "on" and "off" is what generates the 1s and 0s that serve as the foundation of modern computing processes. The resulting effect of the "fin" is to create a structure that maintains the small feature size, but also has a vertical dimension to allow for more contact area around the gate (3 points vs. 1 prior, see Exhibit 53). This new structure allowed chip manufacturers to continue production at smaller geometries without losing performance/power efficiency due to leakage.

Exhibit 53: Planar vs 3D transistor

3D transistors allow for more surface area contact with the channel as device structures become smaller



Source: Company data, Goldman Sachs Global Investment Research.

3D NAND. Imagine if every building in Manhattan was one story – it would be highly unlikely that the island could support its current population. Now imagine that every building in Manhattan is the same height as the World Trade Center – it becomes a lot easier to fit everyone. This simple analogy illustrates the benefits of 3D NAND, which is essentially layers and layers of memory cells. NAND memory is what is used for storage in devices like smartphones, tablets, laptops, and portable hard drives. Traditionally, memory cells ("bits") were scaled down to keep pace with Moore's Law and allow for more memory/chip. As device scaling became harder, it became more difficult for memory manufacturers to increase the amount of memory/chip. Manufacturers began vertically stacking memory cells in 2013 as a means of keeping pace with generational density improvements and driving the cost of memory down.

Exhibit 54: Density is improved by scaling bits Illustration of planar NAND







Source: Goldman Sachs Global Investment Research

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Source: Goldman Sachs Global Investment Research
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Gate all around (GAA)/nanowires. Similar to FinFETs, GAA structures further address the problems associated with scaling device sizes smaller. The key concept behind GAA structures is that contact area is increased by creating four contact points for the gate as opposed to three as is the case with 3D FinFETs (see Exhibit 56). The "all-around" structure allows the transistor to control the flow of electrons more easily and prevent performance loss. Current efforts have been able to produce circuits with effective dimensions of approximately 13nm, which is slightly larger than the 10nm circuits we expect Intel to release in 2017. We believe GAAs will replace FinFETs just as FinFETs replaced planar structures, sometime after the 5nm node, though we note that the manufacturing challenges are substantial given the radically different process required to manufacture nanowire structures.

Exhibit 56: Gate all around (GAA) structure GAA structures allow for more surface area contact with the channel compared to 3D FinFET



Source: Goldman Sachs Global Investment Research

Commercialising the evolution of the semiconductor

In our previous discussions with Intel and as recently as the Intel Developer Forum (mid-August 2016), management has demonstrated confidence in its ability to economically scale to the 10nm and 7nm nodes, noting that 10nm cost/transistor is actually below the historical trend. However, management has said EUV (extreme ultraviolet lithography) will be needed to effectively produce 5nm chips. Intel is becoming increasingly confident that in the next couple of years they will see an EUV tool that can provide stable power, which should allow manufacturers to employ this technology.

That said, Mark Bohr, Intel's director of process architecture and integration, has noted in prior discussions with us that his team is working on other technologies to make 5nm possible without EUV, including materials engineering. Mr. Bohr highlighted past developments such as strained silicon, high-k metal gates, and FinFET as examples of the types of projects the company is researching for implementation on future nodes, though the company did not go into detail on its plans. Given that EUV has long been seen as a game changer and is expected to finally be available at the 5nm node, we view Intel's continued focus on materials enabled innovations as illustrative of the importance of AMs in the semiconductor market.

Key semi/SPE companies looking at alternate conductor materials:

- Intel Market share leader in consumer and data center microprocessors.
- TSMC Leading foundry used for manufacturing of applications processors and GPUs.
- Samsung One of the leading producers of memory chips and applications processors.
- Applied Materials Semiconductor production equipment company focused on materials-enabled innovation.

CASE STUDIES

- **1.** Water filtration: Creating a sustainable future
- 2. Energy storage: The shift to renewables
- 3. Nanomedicine: A plethora of possibility
- 4. 5G communications: Speeding up the future

CASE STUDY 1

Water filtration: Creating a sustainable future

Advanced materials: Nanotechnology, graphene

Potential addressable markets:

- US\$8bn pa spent by governments on drinking water.
- US\$5bn pa spent on the global separation & membrane technology market with expectations for the market to double by 2020.
- Bottled water market is around US\$90bn with double-digit growth rates.

The opportunities:

- Potential to prevent some of the 5,000 deaths per day from unsafe water, sanitation and hygiene.
- Nanotechnology is being explored as a way of developing improved filtration/separation membranes.
- Graphene is a possible material given its water-repelling properties.

Population growth, climate change and urban creep are all placing increased pressure on the world's natural ecosystem. Water is becoming an increasingly scarce commodity. The World Health Organisation (WHO) estimates that over 1 bn people do not have access to clean water, and over 5,000 people die every day from deaths attributable to unsafe water, sanitation and hygiene. The organization cites "better tools and procedures to improve and protect drinking water quality" to improve water quality and maximize health benefits.

Exhibit 57: Sub-Saharan Africa has extremely scarce sources of renewable water Total renewable water resources per capita (2013)



quality and sanitation in emerging markets US\$bn spend on water and sanitation by NGOs and governments in developing markets

Exhibit 58: Almost US\$8bn is spent on improving water



Source: UNESCO



To combat the challenge of ensuring sufficient potable water, governments and NGOs are committing significant amounts of their R&D budgets to deliver a sustainable water balance. NGOs are spending almost US\$3bn pa directly on water and sanitation in developing countries.

Bottling water is a means of transporting potable water, but the consumption and disposal of plastics places other environmental strains on the environment. For instance, the amount of energy required to meet US demand for plastic bottles is equivalent to 17mn barrels of oil.

Exhibit 59: Global bottled water market has almost doubled in size in the past five years, placing increasing pressure on the ecosystem.

Bottled water consumption per capita

Rank Countries		Gallons p	er Capita
панк	Countries	2009	2014
1	Mexico	59.2	69.8
2	2 Thailand	26.3	65.1
3	8 Italy	49.0	53.1
4	Belgium-Luxembourg	35.5	39.4
5	6 Germany	34.7	39.2
6	United Arab Emirates	25.0	41.6
7	' France	34.4	37.4
8	3 United States	27.6	34.0
g) Spain	27.7	32.1
10) Hong Kong	22.2	32.7
11	11 Lebanon		28.2
12 Croatia		26.5	29.1
13 Slovenia		26.6	28.4
14 Hungary		27.9	28.8
15	15 Saudi Arabia		29.9
16	Switzerland	25.6	28.0
17	' Austria	23.1	24.3
18	8 Brazil	22.0	25.5
19	Poland	19.7	25.0
20	Romania	19.8	23.2
C	Global Average	7.8	10.3

Exhibit 60: Chinese consumption of bottled water has more than doubled in the past five, years indicating the pressures from the development of emerging markets Bottled water consumption – total in gallons

Dank	Countrios	Millions o		
панк	Countries	2009	2014	CAGN (70)
1	China	5692	11459	15.0%
2	United States	8453	10875	5.2%
3	Mexico	892	8645	4.6%
4	Indonesia	2941	5307	12.5%
5	Brazil	4255	5151	3.9%
6	Thailand	1743	4376	20.2%
7	Italy	2949	3241	1.9%
8	Germany	2843	3227	2.6%
9	France	2165	2411	2.2%
10	India	1112	2069	13.2%
	Top 10 Total	33044	56760	7.8%
	All Others	14513	17948	4.3%
	World Total	47558	74708	6.9%

Source: Bottledwater.org

Source: Bottledwater.org

The ability to provide a simple quality filtration process has the potential to both tackle the emerging market water shortage and challenge the profit pools of the bottled water market.

Advanced Material filtration

Against this backdrop, graphene comes to the fore, particularly given its hydrophobic properties. It has been discovered that thin membranes made from graphene oxide are impermeable to all gases and vapors, besides water, and further research has shown it can be made to allow separation of atomic materials that are very similar in size – enabling filtration at 9x the normal speed. This opens the door to the possibility of using seawater as a drinking water resource, in a fast and relatively simple way. Furthermore, given graphene's small weight and size, the technology has the capability to be lightweight, energy-efficient and environmentally friendly when making water filters and desalinators.

Companies: Nanofiltration the focus

Lockheed Martin has developed and patented a new energy efficient graphene-based water desalination technology. The "Perforene" membrane is a one-atom thick sheet of graphene, featuring holes all the way down to one nanometer in length. Integrating the membrane within a filter of a larger system can trap unwanted substances and concurrently improve the flow through of water molecules, reducing clogging and pressure on the membrane and filter, lowering energy usage (by 10-20%) of the overall system.

Other firms working in nanofiltration include Dow, which is looking at a pressure-driven separation process that employs a semi-permeable membrane and the principles of cross-flow filtration. GE, Pentair, 3M, Koch and Siemens are also active in the field.

CASE STUDY 2

Energy storage: The shift to renewables

Advanced materials: Nanotechnology, graphene, OLEDs

Potential addressable markets:

- Supercapacitors: US\$1bn
- Nano-optimised photovoltaics: US\$1bn
- Catalysts: US\$6bn
- Nano-optimised fuel cells: US\$5bn

The opportunities:

- Nano-particles can alter and enhance the properties of bulk materials to deliver superior performance
- Energy storage and conversion in solar cells can be greatly enhanced
- Nano-electrodes can improve battery storage, discharge and re-charge rates

According to the International Energy Agency, global energy demand is expected to rise by c.50% to 2030, with over 80% of current demand supplied by fossil fuels. In an increasingly densely populated, but also environmentally conscious world, the ability to generate, harness and utilise energy sources efficiently is vital to the sustainability and development of the quality of life of the global citizen. Quite simply, renewable energy sources are the way of the future.

Exhibit 61: Energy demand set to rise c.50% by 2040 Global energy demand



Exhibit 62: Energy storage part of the broader supply chain complex Energy supply chains



Source: EIA

Nanotech is set to play a vital role as an enabler and solution provider to one of the biggest challenges we face. In the view of buckyball inventor, Nobel Prize winning Richard Smalley, "Nanotechnology is the key to achieving a sustainable energy future."

Nanotech is set to be influential in the early parts of the energy value chain, creating efficiencies and better performance in a number of key areas. The International Energy Commission estimates that 1 in every 2 research papers written about electrical storage technology references nanotech.

Visit our <u>"Great</u> Battery Race" portal

for our latest thematic and company research on energy storage solutions. The use of nanotech in energy storage is a significantly rapidly growing area of nanotech and AM, which has been driven by the green shift and mainstream utilisation of concepts such as solar panels, EVs and off-grid battery storage.

In the area of energy storage, applications of nanotech mainly apply to improving conversion rates, boosting recharge and dissipation rates, increasing efficiency and lowering costs. The prime nano-areas being explored in the field include:

- Nano electrodes: Perform similar to normal electrodes but on a nano scale. The high surface to volume area of the nanoparticles lead to larger electrode contact areas and thus enhance mass transport. The faster transport of the electrons results in enhanced electrical and ionic conductivity improving charge times is one example. Lithium-ion batteries, supercapacitors, fuel cells and solar cells have all seen improved energy performance due to nano-electrodes. Graphene/graphite are emerging materials but other 'traditional' electrode/anode materials such as the metals (indium, zinc, etc.) are also being broken down in to their nano-scale. *Companies exposed include Sony, Toshiba and Manz.*
- **Nanocomposites**: The inclusion of nanoparticles into a larger sample material. The creation of nanocomposites results in enhanced physical properties of the macro material. In energy storage, nanocomposites can be found in the electrolytic gel of solar panels, the coating of the panels and in super capacitors. Nanoparticles are also thought to be of use in devices converting carbon dioxide in to hydrocarbon fuels. *Companies exposed include BASF, 3M, and DuPont.*
- **Nanocatalysts**: The greater surface area of nanoparticles accelerates the catalytic capacity of materials. Nanoscale platinum is used in hydrogen fuel cells and the use of nanomaterials for catalytic convertors could improve environmental emissions.

The total addressable market for nanotech in energy storage is an exceptionally difficult figure to define. As the end-product demand structurally accelerates (i.e., Tesla electric car technology increases penetration rate) the need for AMs will intensify – both in terms of growing physical demand, but also continued technological demand to continue to improve the processes/technology that help deliver the cars their green credentials.

We estimate the current addressable market for nanotech in energy storage is around US\$10-15bn, and we believe this could grow to around US\$20bn by 2020 (the base case figure is based off International Electrotechnical Commission (IEC) research, and we have utilised a 10% demand growth rate scenario). More aggressive demand growth of the end-markets could see the TAM increased to an upper band of some US\$30bn.

CASE STUDY 3

Nanomedicine: A plethora of possibility

Advanced materials: Nanotechnology

Potential addressable markets:

 The US oncology market is over US\$100bn per annum. Assuming 10% penetration, the TAM for oncology nanomedicine in the US is potentially US\$12bn plus per annum.

The opportunities:

- Penicillin revolutionized the drug market in the 1940/50s. Nanotechnology could deliver the same scale of change in coming years.
- Drug delivery can be targeted through nanotechnology to attack only sick cells, reducing side effects.
- Diagnostics can be improved through nanotechnology allowing early detection and treatment.

Just as penicillin did in the 1940s, nanomedicine has the potential to revolutionize the way we treat disease. The key advantage of nanomedicine is that it operates on the same scale as many natural biological processes and molecules. If, utilizing the properties of nanomedicine, medicines can be delivered and targeted directly to the impacted cells in the specific dose required, the potential for a successful outcome may be increased. A targeted drug approach should also reduce side effects and improve morbidity. Thus specific tailored drugs and targeted delivery methods have the potential to increase the personalization of disease treatment.

Along with disease treatment and management, nanotech has the potential to improve the detection and prevention of disease. Through new contrast agents, nanomedicine can improve on current diagnostic imaging capabilities, leading to earlier detection of disease and ideally an improved prognosis.

The development of nanomedicine and nanobiology could significantly alter not only our ability to prevent and treat disease, but also the profit pools of the existing pharmaceutical and medical industries. Nanomedicine is already a rapidly growing industry with around US\$16bn of sales in 2015. R&D spend is growing with the NNI spending upward of US\$300m pa supporting R&D in to nanomedicine.

As an illustration, a 10% penetration of the existing US cancer treatment industry represents a +US\$10bn market for nanomedicine. These attractive profit pools, combined with the medical benefits are what is attracting both small and large industry players such as Intellia and Merrimack to lift their investment in and exposure to nanomedicine.

Exhibit 63: With viruses, antibodies and bacteria all operating on the nanoscale in our bodies, the utilisation of nanotechnology in medical applications will allow for more specific targeting of diseases, leading to potentially better recovery



Source: NCI, Goldman Sachs Global Investment Research.

The history and benefits of nanomedicines

One of the earliest nanomedicines, Doxil, was approved by the FDA in 1995. Since then numerous other nanomedicines have been commercialized and approved with a broad range of applications including treatment of cancer, fungal infections, and infection prevention.

The physical properties of nanoparticles have a number of clinical benefits that are of interest to clinicians and industry. Operating at the nanoscale could improve both the efficacy of treatments and how drugs interact with the human body, i.e. toxicity and side effects. The benefits of nanotech for the pharmaceutical industry are based on:

- **Improved solubility**: Nanoparticles have higher solubility than their bulk counterparts, potentially enabling drugs with poor solubility to be reinvestigated. In addition, higher solubility reduces the need to use organic solvents, which are toxic.
- Higher permeability: The size of nanoparticles may enable them to cross physiological barriers such as the blood brain barrier, or enter tumors. This has important implications for drug delivery in numerous disease areas such as oncology and neurology.
- Longer circulation: Nanoparticles can be engineered to increase the circulation time of drugs.
- Large surface area: This increases the reactiveness of nanoparticles. The greater surface allows nanoparticles drugs to engage with the impacted cells, allowing greater ability for the drugs to work.

Exhibit 64: Pharmaceutical nanotechnology

	Technology type	Size range
	Liposomes	100 nm
Established technologies	Drug nanocrystals/Nanoparticles	50 – 1000 nm
	Micelles, SMEDDS, SNEDDS	10 – 200 nm
	Polymer-based nanoparticles	5 nm – 5µm
	Lipid based nanoparticles (SLN, NLC)	20 – 200 nm
	Dendrimers	10 nm – 500 nm
	Fullerenes	0.7 nm
Subject to current	Nanotubes	10 – 200 nm
research	Quantum dots	2 – 10 nm
	Nanostructured biomaterials	50 – 500 nm
	Drug-Nanoparticle conjugates	
Future applications	Nanodevices	?

Source: European Medicines Agency

From a drug delivery perspective, using nanomaterials to deliver drugs has several benefits compared to existing delivery methods such as injections, pills etc.

- Polymer-based materials can allow for better pharmacokinetics and bio distribution of drugs
- **Triggered response** techniques would allow drugs imbedded in the body to be released when certain triggers are induced, allowing rapid and targeted drug delivery.

Key areas of focus

Nanomedicine has a vast array of potential applications, with two major interrelated areas of focus, including drug delivery and disease diagnosis and monitoring.

- **Drug delivery**: Nanopharmaceuticals can either be reduced to the nanoscale or engineered at the nanoscale, and functionalized to have specific characteristics. These characteristics can enable targeted drug delivery directly to the area of focus along with customized drug release, improving treatment efficacy and reducing side effects for the patient.
- Medical diagnostics: Earlier detection of disease would aid the ability of physicians to treat these diseases, for instance detecting cancer pre metastasis, potentially improving treatment success rates.

Drug delivery

Through physical and chemical modifications, nanomedicines can be "functionalized" to have certain characteristics, enabling different clinical applications. In particular, nanoparticles can be engineered to target particular areas of the body through the use of biomarkers and molecules such as peptides and nucleic acids. These nanoparticles can be further modified so that, once delivered, they release their drug load in a controlled manner. Triggers for drug delivery may include pH, light, or tumor specific conditions. Key benefits of this targeted drug delivery include reduced dose size and lower side effects (it is important to note that the nanoscale of these drugs can also result in disparate side effects/ toxicities to their bulk counterparts).

This technology has been and has the potential to be applied in numerous clinical areas including cancer and neurodegenerative disorders. The majority of clinically available nanomedicines in this are either liposomes or polymer-based nanoformulations.

Treatment of solid tumors

Numerous different treatment methods have been developed and are in development for cancers using nanomedicine. In treating solid tumors, nanoparticles are able to utilize the enhanced permeability and retention (ERP) effect whereby the reduced lymphatic drainage of tumors result in nanoparticles being accumulated and retained. This ERP effect is also referred to as passive targeting.

Neurological diseases

Treatment of diseases of the central nervous system (CNS) are challenged by the existence of barriers, including the blood brain barrier (BBB) and blood cerebrospinal fluid barrier (BCSF), which selectively prevent molecules from crossing from the bloodstream into the CNS. Molecules blocked from entering the brain, for instance, include most traditional pharmaceuticals and chemotherapy.

An exciting horizon for nanomedicine is therefore the development of nanomolecules that are able to cross the BBB/BCSF given their small size and molecular weight. Conditions that could be targeted include neuro-oncology, Alzheimer's/dementia, stroke and epilepsy.

Medical diagnostics

In addition to the treatment of disease, nanomedicine shows promise in detection and monitoring.

Medical imaging

According to the National Cancer Institute, traditional diagnostic imaging (DI) techniques in use today are only able to detect cancers once tissue has altered visibly. This means that diagnosis could occur post metastasis (spread to secondary organ/ tissue), greatly reducing the likelihood that treatment will be successful. In addition, to gain further information on tumors (e.g. malignant or benign), an invasive biopsy must often be taken.

Nanotech has the potential to improve upon this status quo, principally through new contrast agents. Nanoparticles such as superparamagnetic iron oxide nanoparticles can be engineered to target and accumulate at the tumor site. In addition, contrast agents could be developed that identify characteristics of the tumor such as type and the stage the cancer is at.

Biomarkers

The National Cancer Institute defines biomarkers (biological marker) as "a biological molecule found in blood, other body fluids, or tissues that is a sign of a normal or abnormal process, or of a condition or disease. A biomarker may be used to see how well the body responds to a treatment for a disease or condition". Nanomedicine offers the potential to detect changes that have occurred in only a small number of cells.

Quantum dots (QD) are a type of nanomedicine commonly cited for this purpose, given that these nanocrystals are fluorescent, display different colors depending on size, and are far brighter in vivo than organic dyes. In addition, QDs are able to circulate throughout the body due to their small size, enabling tumors to be targeted. However, as is the case with a number of potential nanomedicines, whilst QDs show tremendous potential, there are toxicity concerns that must be addressed before human application

Multipurpose nanomedicines - theranostic

An ideal outcome from the development of nanomedicine would be the commercialization of nanoparticles that have both therapeutic and diagnostic uses (theranostic - *thera*py diag*nostic*). For example, a drug that is able to target and release its load at a particular tumor site, while also enabling DI to track the progress and success of this treatment.

In addition to the applications discussed above, there are a multitude of existing and potential clinical applications of nanomedicine. Key areas of interest include non-viral gene vector delivery, regenerative medicine/ tissue engineering and implantable nanodevices.

The opportunity: Looking forward/profit pools

The opportunities for nanotech to alter the medicinal and pharmaceutical field are significant and wide ranging. To provide some context to the scale of opportunity and potential profit pools, we look at two areas where we see nanotech having a significant impact: i) oncology, which has existing commercialized nanomedicines, and ii) gene therapy, which is in the investigational phase.

New frontiers in cancer treatment and market opportunity (>US\$10bn market)

According to the Centres for Disease Control and Prevention (CDC), cancer was the cause of just under 600,000 deaths in the US in 2014, the second-highest cause after cardiovascular disease. The National Cancer Institute (NCI) expects that in the US there will be 1,690,000 new cases diagnosed with c. 600,000 deaths in 2016 alone.

Current treatments include chemotherapy, immunotherapy, surgery and radiation therapy. These have downsides including their non-targeted nature; for example, chemotherapy impacts healthy tissue as well the tumor of interest, resulting in common side effects such as hair loss.

Nanomedicines for the treatment of cancer have been commercially available for a number of years; indeed, Doxil was first approved by the FDA in 1995 for the treatment of AIDSrelated Kaposi's sarcoma and has now gone generic. The majority of these approved treatments, however, are non-targeted. Therefore, they are commonly considered firstgeneration nanomedicines. For example, first generation breast cancer treatment Abraxane targets tumors passively through the ERP effect.

Second generation cancer treatments would actively target tumor tissue, effectively a form of personalized medicine. There are currently no second generation nanoparticles clinically available; however, there are a number of actively targeted treatments in phase I or II clinical trials.

Treatment costs in the US amounted to just under US\$125bn in 2010, and the NCI projects total expenditure of US\$156bn in 2020. If we assume a 10% penetration of nano-oncology, the potential is for a c.US\$12bn plus market per annum.

Nanomedicine in genetic disorders

Gene therapy, and its closely related field genome editing, are being investigated for a wide range of genetic disorders, with a small number of therapies approved in different

jurisdictions. Broadly, gene therapies involve inserting into a cell a copy of the desired gene, whereas genome editing 'edits' genomes inside the cell.

In developing a gene therapy, a key area of consideration is the delivery method chosen. A large number of programs utilise viral vectors, e.g. adeno-associated viral vectors (AAV), such as Spark Therapeutic's SPK-FIX for hemophilia B, however, viral vectors face safety concerns. Nanotechnologies provide potential alternatives to viral vectors, i.e. non-viral or synthetic vectors, and are being explored by a number of biotech companies:

- Intellia Therapeutics (NTLX): Intellia is investigating the use of genome editing technology CRISPR/ Cas9 for a range of conditions including alpha 1 antitrypsin deficiency, transthyretin amyloidosis and hepatitis B. As these diseases relate to the liver, Intellia is utilizing lipid nanoparticles to deliver the technology to the liver.
- Editas Medicine (EDIT): Similarly to Intellia, Editas identifies lipid nanoparticles as a means of targeting CRISPR to the disease area. Editas is investigating diseases ranging from Duchenne Muscular Dystrophy, alpha 1 antitrypsin deficiency and cystic fibrosis.

To illustrate the genetic conditions being investigated by these companies, we look at alpha 1 antitrypsin deficiency. Current treatment includes replacement therapy, where patients are infused with plasma derived alpha 1 antitrypsin. CSL and Grifols are the two largest producers of alpha 1 antitrypsin; the Marketing Research Bureau estimates that total US sales of alpha 1 antitrypsin were US\$690mn in 2015.

CASE STUDY 4

5G communications: Speeding up the future

Advanced materials: Gallium nitride (GaN)

Potential addressable markets:

- Communications infrastructure: US\$1bn
- Defense applications: US\$1bn

The opportunities:

- Enabling use of higher frequency spectrum
- Driving faster data speeds and greater bandwidth
- Providing greater energy efficiency

We see GaN as a potential disrupter of the LDMOS power amplifier market

Gallium nitride (GaN) is a III-V compound used most often in radio frequency (RF) devices for mobile communications as well as communications infrastructure applications. Key suppliers include MACOM (MTSI, covered by Mark Delaney) and Qorvo (QRVO, covered by Toshiya Hari). Given that they are III-V compounds and thus have higher bandgaps, GaN devices offer significantly better performance over other compound and silicon-based technologies today. Due to the higher bandgap, GaN chips are able to perform better than silicon devices at higher frequencies, voltages, power densities and temperatures, making them particularly applicable to 5G networks, which are expected to utilize spectrum at higher frequencies than today's networks. On the network infrastructure side, we see GaN as a potential disrupter of the ~US\$1bn LDMOS power amplifier market.

Exhibit 65: GaN offers greater performance compared to GaAs and silicon chips in power and RF applications

GaN vs. GaAs and Si on key metrics



Source: GaN Systems, Goldman Sachs Global Investment Research.

Today RF devices primarily utilize compound technologies such as gallium arsenide (GaAs) and silicon-based technologies such as silicon germanium (SiGe). GaN currently occupies niche segments including radar and comms/cable infrastructure, with many of these applications are subsidized by government funding (see Exhibit 66). Out of a total high performance RF market of ~US\$3bn, GaN revenue accounted for US\$300mn in 2015 and is expected to grow to almost US\$1bn by 2022.



GaN market by application



Source: Yole Development

While GaN technology has been in development for several years, chip companies have only recently begun applying GaN in more applications. Applications for GaN include RF applications for frequencies of 10GHz+, power semiconductors, and DC switching, where GaN technology is able to withstand significantly higher voltages.

Key drivers of future growth for GaN include 5G base station deployment and defense spending. For example, Qorvo estimates that these areas could enable the GaN market to potentially grow at a 25% CAGR. One of the biggest trends that we are monitoring though is the coming 5G network infrastructure build out. 5G will extend the range of frequencies used for cellular communication in order to be able to handle increased traffic capacity and enable bandwidths required for very high data rates. In the past, high-frequency spectrum has not played a major role in wireless networks because the shorter wavelengths do not travel over long distances. While 5G technology does not fundamentally overcome this challenge, we expect 5G to be deployed as carriers densify their networks and believe higher frequency spectrum will become increasingly useful because signals will not need to travel as far from cell sites to reach customers.

Communications networks are made up of base stations that transmit and receive radio signals. Currently, the power amplifier portion of the base station market is dominated by LDMOS power amplifiers, though we highlight the potential for GaN to disrupt this dynamic given that 5G networks are expected to utilize higher spectrum frequencies, i.e. up to 100GHz, which are better serviced by GaN technology.

For more on the coming 5G revolution, including companies that could benefit, see Simona Jankowski's April 2016 <u>deep dive</u>.

Companies

MACOM (MTSI, covered by Mark Delaney) MACOM is an analog and photonic semiconductor company with about 70% of its revenue derived from the communications end-market. MACOM's revenue has historically been tied to applications in long-haul optical, CATV, and PON. However, the company is targeting new growth opportunities in base stations, metro, and datacenters. MACOM offers GaN on silicon power amplifier chips and hopes to be able to gain share in the roughly US\$1 bn annual base station PA end-market. We believe that while MACOM has the potential to penetrate this market in late 2016 or 2017 with its GaN on silicon technology for LTE (as MACOM's approach to GaN can be done at competitive costs), and that the higher frequencies used in 5G will require the performance of GaN semiconductors that companies such as MACOM offer. In addition, MACOM believes its GaN technology will allow it to improve performance in other applications such as microwaves and its catalog portfolio.

Qorvo (QRVO, covered by Toshiya Hari). Qorvo is an RF communication company with about 20% of revenue derived from the comms infrastructure and defense markets (the remainder is primarily from handset RF solutions). Like MACOM, the company offers GaN process expertise and has highlighted both 5G and military applications (i.e. radar and electronic warfare applications) as key driver of growth for its infrastructure product portfolio. Management has noted that new defense applications represent a potential US\$500mn+ market for GaN products.

An interview with...



Dr. Chen is a Managing General Partner and cofounder of Phoenix Venture Partners (PVP). Phoenix Venture Partners is a specialist fund that looks for transformative advanced materials innovations, including novel engineered

materials, new device architectures, and advanced process technologies and tools. PVP invests in innovations that enable entirely new products, dramatic performance improvements of existing products, enhanced-efficiency, and/or greener manufacturing processes for major industries such as Consumer Electronics, Drug

Delivery, Chemicals, Energy Generation, Energy Storage, Solar, Water, and Building Materials, to name a few.

Dr. Chen earned his BS in Physics, PhD in Materials Science and Engineering, and MBA from MIT. In addition to his investment and board roles with PVP, Dr. Chen serves on the Commercialization Advisory Board for Oregon Built Environment & Sustainability Technologies (BEST), is an active mentor to several startups through the MIT Venture Mentoring Service, and is a long-time member of the Materials Research Society

Advanced materials is an extremely wide ranging and broad topic, so let's start off by asking how you would define an advanced material.

You are absolutely correct to observe that advanced materials encompasses an extremely diverse and broad set of technologies. At PVP, we have loosely defined advanced materials as a collection of technologies that include novel engineered materials, device architectures, processes, and metrology/tools which enable disruptive performance through the precision engineering, design, and or measurement of molecular scale properties. Advanced materials or materials science based technologies are also interdisciplinary in nature drawing

Dr. John Chen, Phoenix Venture Partners

from physics, chemistry, biology, and the engineering disciplines.

What, in your view, makes the advanced materials space so attractive from a VC perspective?

PVP sees the advanced materials space as highly attractive from an investment perspective because these technologies have the potential to generate significant value by enabling next-generation product performance as well as delivering disruptive cost reduction and manufacturing efficiencies for both well-established and rapidly emerging markets. The platform nature of advanced materials technologies also often allows them to enable applications that transcend industry verticals which can lead to multiple exit scenarios. The advanced materials space is experiencing a sustained wave of rapid innovation which has been fueled by decades of R&D investment by both the private and public sectors. From a VC perspective, the advanced materials space is also attractive because startups don't face the extreme competitive pressures of other sectors (e.g., software, consumer internet) and very few venture capital firms are active in this area and even fewer have the necessary teams, expertise or track record to be successful in this space.

In terms of your investment process, would you describe it as top-down (sector preferences then drill down into the most appropriate company to reflect the theme) or bottom up (very company fundamental specific)?

By the very nature of the advanced materials space, PVP employs a unique investment process which is a bit of both. Without going into too much detail, PVP proactively researches and looks at the unmet needs of critically important industry sectors (e.g. energy storage, consumer electronics, life sciences, etc.) and keeps track of disruptive emerging technology trends (e.g. printed electronics, 3D printing, graphene, etc.) to formulate our investment thesis while also maintaining an extensive network and robust global scouting platform to find the most promising startups developing breakthrough technologies. As a VC, what makes investing in the advanced materials space different from other sectors? What are the unique skills you need to succeed here versus elsewhere? What are the main challenges you face operating in the advanced materials space?

Several characteristics of the advanced materials space make it a challenging sector to invest in for generalist VCs. The enormous scope, diversity and technical complexity of advanced materials technologies requires an investment team which has deep domain knowledge in specific fields of science and engineering (i.e. PhD level) as well as multidisciplinary and complimentary backgrounds (e.g. materials science, physics, chemistry, life sciences, etc.) to be able to adequately evaluate investment opportunities and recognize truly disruptive companies from me-too's. Compared to other sectors, a greater degree of detailed knowledge of IP and IP strategy is key to creating and preserving long-term value. It is also critically important that investors in this space have had first-hand experience of the challenges and hurdles startups face building a successful company and getting advanced materials technologies adopted by the market so that they can navigate portfolio companies through the inevitable difficult times. Last but not least, experienced investors in the advanced materials space know from the "school of hard knocks" which business models to pursue and which to avoid.

Is there one or two sectors within the advanced materials space, e.g. Solar, Building materials, consumer electronics etc. that you believe stands out in terms of growth?

Many sectors within advanced materials are growing rapidly but off hand two that come to mind are energy storage materials and graphene.

Can you give us a brief guide into a typical investment lifecycle? How long is the process between idea generation and actual investment in a company? What are the main sticking points/obstacles you face in that lifecycle?

Every investment is unique and follows its own timeline and venture capital is more of an art than a science. Some of our investments take 3 months from start to end and others we have tracked for three years until they satisfied our criteria for investment and we closed the investment.

Advanced materials is an evolving yet under invested area of innovation. Why do you think that is? Is it because of the technical skillset and expertise required, or lack of awareness of how rapidly the industry is growing?

Advanced materials is an under-served sector for venture capitalists for many reasons. The formidable barriers to entry and being successful I alluded to in the previous question dissuade many investors from taking the plunge. Second, for the uninitiated an untrained, much of the innovation falls under the radar screen of mainstream media and is also often miscategorized and lumped into other "hotter" sectors such as clean tech, energy, life sciences and IT. Finally, for reasons I don't entirely understand, investors have a mistaken perception that advanced materials is a "niche" market and not very attractive. I'd like to point out to your readers that the entire semiconductor industry is based on advanced materials innovations (e.g. silicon processing, copper deposition, photolithography, etc.), the revolution in electric vehicles is being driven largely by advances in new materials for Li-ion batteries (e.g., cathodes, anodes, separators, electrolytes, etc.), and the widespread adoption of cheap solar energy was in part enabled by new materials (e.g. CdTe, CIGS), just to name a few examples.

How large and industry do you think the broad categories of advanced materials can become?

PVP investment professionals have been directly involved in the advanced materials space for decades and these estimates are provided by our own proprietary research as well as from publicly available market research on sectors which overlap with and are decent proxies for advanced materials such as nanotechnology, clean tech, printed/organic electronics, additive manufacturing, etc. That said, systematic and accurate coverage of this space and its impact on industry is far from perfect. If I were to make a best guess I would say US\$3trn is the industrial impact of advanced materials innovation over the next ten years, which is likely to be conservative and underestimates the true impact.

Disclosure Appendix

Reg AC

We, Craig Sainsbury, Jay Shyam, CFA, Shuhei Nakamura, Toshiya Hari, Marcus Shin, Charles Long, Robert D. Boroujerdi, Hugo Scott-Gall, Ian Abbott, Shin Horie, Richard Manley, Brian Lee, CFA, Matthew McNee, Grace Fulton, Giuni Lee, Ken Lek, Ayaka Misonou, Frank He, Julian Zhu, Eddie Ow, CFA, Anita Dinshaw and Isabelle Dawson, hereby certify that all of the views expressed in this report accurately reflect our personal views about the subject company or companies and its or their securities. We also certify that no part of our compensation was, is or will be, directly or indirectly, related to the specific recommendations or views expressed in this report.

I, Peter Callahan, hereby certify that all of the views expressed in this report accurately reflect my personal views, which have not been influenced by considerations of the firm's business or client relationships.

Unless otherwise stated, the individuals listed on the cover page of this report are analysts in Goldman Sachs' Global Investment Research division.

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The Goldman Sachs Investment Profile provides investment context for a security by comparing key attributes of that security to its peer group and market. The four key attributes depicted are: growth, returns, multiple and volatility. Growth, returns and multiple are indexed based on composites of several methodologies to determine the stocks percentile ranking within the region's coverage universe.

The precise calculation of each metric may vary depending on the fiscal year, industry and region but the standard approach is as follows:

Growth is a composite of next year's estimate over current year's estimate, e.g. EPS, EBITDA, Revenue. **Return** is a year one prospective aggregate of various return on capital measures, e.g. CROCI, ROACE, and ROE. **Multiple** is a composite of one-year forward valuation ratios, e.g. P/E, dividend yield, EV/FCF, EV/EBITDA, EV/DACF, Price/Book. **Volatility** is measured as trailing twelve-month volatility adjusted for dividends.

Quantum

Quantum is Goldman Sachs' proprietary database providing access to detailed financial statement histories, forecasts and ratios. It can be used for in-depth analysis of a single company, or to make comparisons between companies in different sectors and markets.

GS SUSTAIN

GS SUSTAIN is a global investment strategy aimed at long-term, long-only performance with a low turnover of ideas. The GS SUSTAIN focus list includes leaders our analysis shows to be well positioned to deliver long term outperformance through sustained competitive advantage and superior returns on capital relative to their global industry peers. Leaders are identified based on quantifiable analysis of three aspects of corporate performance: cash return on cash invested, industry positioning and management quality (the effectiveness of companies' management of the environmental, social and governance issues facing their industry).

Disclosures

Coverage group(s) of stocks by primary analyst(s)

Craig Sainsbury: Australia-Resources. Shuhei Nakamura: Japan-Advanced Materials sector. Toshiya Hari: America-Semiconductor Capital Equipment, America-Semiconductors. Marcus Shin: Korea Technology. Ian Abbott: Australia-Healthcare. Brian Lee, CFA: America-Clean Energy, America-Solar Energy. Matthew McNee: Australia-Agriculture, Australia-Building Materials, Australia-Chemicals. Frank He: Asia Pacific Conglomerates, China Clean Energy. Julian Zhu: Asia Commodities Companies.

America-Clean Energy: Acuity Brands Inc., Cree Inc., Silver Spring Networks Inc., TerraVia Holdings, Universal Display Corp., Veeco Instruments Inc.. America-Semiconductor Capital Equipment: Applied Materials Inc., Keysight Technologies Inc., Lam Research Corp., SunEdison Semiconductor Ltd., Teradyne Inc..

America-Semiconductors: Analog Devices Inc., Broadcom Ltd., Intel Corp., Linear Technology Corp., Maxim Integrated Products, Nvidia Corp., NXP Semiconductors NV, Qorvo Inc., Skyworks Solutions Inc., Texas Instruments Inc., Xilinx Corp..

America-Solar Energy: 8point3 Energy Partners, First Solar Inc., SolarCity Corp., SolarEdge Technologies Inc., SunPower Corp., Sunrun Inc., TerraForm Global Inc., TerraForm Power Inc., Vivint Solar Inc.,

Asia Commodities Companies: ACC Ltd., Aluminum Corp. of China (A), Aluminum Corp. of China (H), Ambuja Cements, Angang Steel (A), Angang Steel (H), Anhui Conch Cement (A), Anhui Conch Cement (H), Baoshan Iron & Steel, BBMG Corp. (A), BBMG Corp. (H), Beijing Enterprises Water Group, Beijing Originwater Technology, Beijing Water Business Doctor, China Coal Energy (A), China Coal Energy (H), China Conch Venture Holdings, China Everbright International Ltd., China Hongqiao Group, China Molybdenum Co., China National Building Material, China Resources Cement Holdings, China Shenhua Energy (A), China Shenhua Energy (H), Dongjiang Environmental Co. (A), Dongjiang Environmental Co. (H), GrandBlue Environmental Co., Jiangxi Copper (A), Jiangxi Copper (A), Tianjin Motimo Membrane Tech, TUS-Sound, Ultratech Cement, Yanzhou Coal Mining (A), Yanzhou Coal Mining (H), Zhaojin Mining Industry, Zijin Mining (A), Zijin Mining (H).

Asia Pacific Conglomerates: Beijing Enterprises Holdings, Cheung Kong Infrastructure, China Gas Holdings, China Merchants Holdings, China Resources Gas Group, China Suntien Green Energy, CITIC Ltd., CK Hutchison Holdings, COSCO Pacific, ENN Energy Holdings, Fosun International, Galaxy Entertainment Group, Hutchison Port Holdings, Jardine Matheson, Kunlun Energy Co., Legend Holdings, Melco Crown Entertainment (ADR), Melco International Development, MGM China, MTR Corp., Sands China, Shanghai Industrial, Sinopec Kantons, SJM Holdings, Summit Ascent Holdings, Swire Pacific, Tianhe Chemicals Group, Towngas China, Wharf Holdings, Wheelock and Co., Wynn Macau.

Australia-Agriculture: Costa Group, GrainCorp Ltd., Nufarm.

Australia-Building Materials: Adelaide Brighton, Boral, CSR, James Hardie.

Australia-Chemicals: Incitec Pivot Ltd., Orica Ltd..

Australia-Healthcare: Ansell, Australian Pharmaceutical Inds., Cochlear Ltd., CSL Ltd., EBOS Group, Fisher & Paykel Healthcare, Healthscope Ltd., Medibank Private Ltd., NIB Holdings, Primary Health Care, Ramsay Health Care, ResMed Inc., Sigma Pharmaceuticals, Sonic Healthcare. Australia-Resources: Alumina, BHP Billiton, Fortescue Metals Group, Iluka Resources, Independence Group, Newcrest Mining, Northern Star Resources Ltd., OZ Minerals, Regis Resources, Rio Tinto, Sandfire Resources, South32 Ltd., Western Areas.

China Clean Energy: Canadian Solar Inc., China High Speed Transmission, GCL-Poly Energy Holdings, JinkoSolar Holding, Longi Silicon Materials, Shenzhen Clou Electronics Co., Singyes Solar, Sungrow Power Supply Co., Trina Solar, Xinjiang Goldwind (A), Xinjiang Goldwind (H), Xinyi Solar Holdings.

Japan-Advanced Materials sector: Daicel, Daido Steel, Hitachi Metals, JFE Holdings, Kansai Paint, Kobe Steel, Kuraray, Nippon Carbon, Nippon Paint Holdings, Nippon Shokubai, Nippon Steel & Sumitomo Metal, Tokyo Steel Manufacturing, Toray Industries, UACJ.

Korea Technology: Samsung Electro-Mechanics, Samsung Electronics, Samsung SDI Co., Samsung SDS Co., Seoul Semiconductor, SK Hynix Inc..

Company-specific regulatory disclosures

Compendium report: please see disclosures at http://www.gs.com/research/hedge.html. Disclosures applicable to the companies included in this compendium can be found in the latest relevant published research

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	Rating Distribution				Investment Banking Relationships			
	Buy	Hold	Sell	_	Buy	Hold	Sell	_
obal	31%	54%	15%	-	66%	60%	50%	_

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