Singapore Nanotechnology Eco System

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1. The Little Red Dot

Singapore is the smallest country in South East Asia with an area of 707 sq. Km (and growing with land reclamation) located about 1° north of equator. It has been ranked as the easiest place[1] and the most cost-competitive place[2] to do business in Asia. Singapore is a strong logistics hub within 6 hours reach of most major cities in the Asia Pacific. It is also home to companies from all parts of the value chain and has strong intellectual property (IP) protection laws. In addition, Singapore is ranked 1st for having the best labor force[3] and 2nd for the most attractive environment[4] for highly-skilled foreigners. Its low tax rates and high standard of living combined with high political stability and low crime makes it an ideal place for families. In fact, foreigners formed 30.9% of the city-state's total employment pool as of December 2006.

To maintain its place as an attractive destination for businesses of the future, Singapore has shifted its focus from cost-effectiveness and efficiency towards innovation and knowledge driven economy in 2006. As a part of this transformation, the Singapore government increased its R&D budget to S$13.6 billion and established the National Research Foundation (NRF) with a budget of S$5 billion in its Science and Technology 2010 plan. This plan supports key programs to develop research talent, to strengthen public sector research capabilities in niche areas of environment & water, life sciences and, information and digital media, to promote private sector R&D, to strengthen technology innovation capabilities in small and medium enterprises (SMEs) and to increase commercialization of public research. While nanotechnology is not identified as a strategic trust area in the Singapore Science and Technology 2010 plan, it has been recognized as a key enabler to multiple sectors and hence one of the 12 priority research areas by A*STAR - an agency within the Ministry of Trade and Industry (MTI).

1.1 Increasing Commercialization of Public Research

Singapore has over 3200 granted US patents[5] between 2000 and 2007. Of these, a large portion comes from institutes of higher learning (IHLs) and public research institutions (RIs). NRF launched the National Framework for Innovation and Enterprise (NFIE) to develop innovation and enterprise in Singapore. Under this framework, NRF provides proof-of-concept grants of up to S$250K to IHLs to demonstrate initial commercialization potential of the IP generated by them. There are also translational R&D grants available to support polytechnics to perform translational research on the R&D output from universities and research institutes (RIs) to bring research breakthroughs to the marketplace. NRF is also introducing innovation vouchers to SMEs to procure R&D and other services from IHLs and research institutions. A*STAR has several schemes to help accelerate commercialization of technologies coming out of its 14 RIs. It has a Commercialization of Technology (COT) grant of S$1M that the RIs can use work with SMEs and make the technology market ready. A*STAR has a larger

[1] Business-readiness indicators for the 21st century, PricewaterhouseCoopers, 2007
[2] KPMG Cost Competitive Alternatives Study, 2006
[3] BERI Labor Force Ranking 2005-2007
[4] IMD World Competitiveness Yearbook 2005
[5] See http://www.uspto.gov/go/oeip/taf/cst_all.htm

"Flagship program" that provides up to S$3M to identify commercially valuable technologies earlier in the research value chain for larger and more impactful outcome through interaction with industry. The Prime Ministers Office offers The Enterprise Challenge (TEC) grants to develop innovative product/service for pilot/trial to improve Singapore's public service. Unlike other grants, TEC does not have a limit on the amount of funding received and covers 90% of the costs.

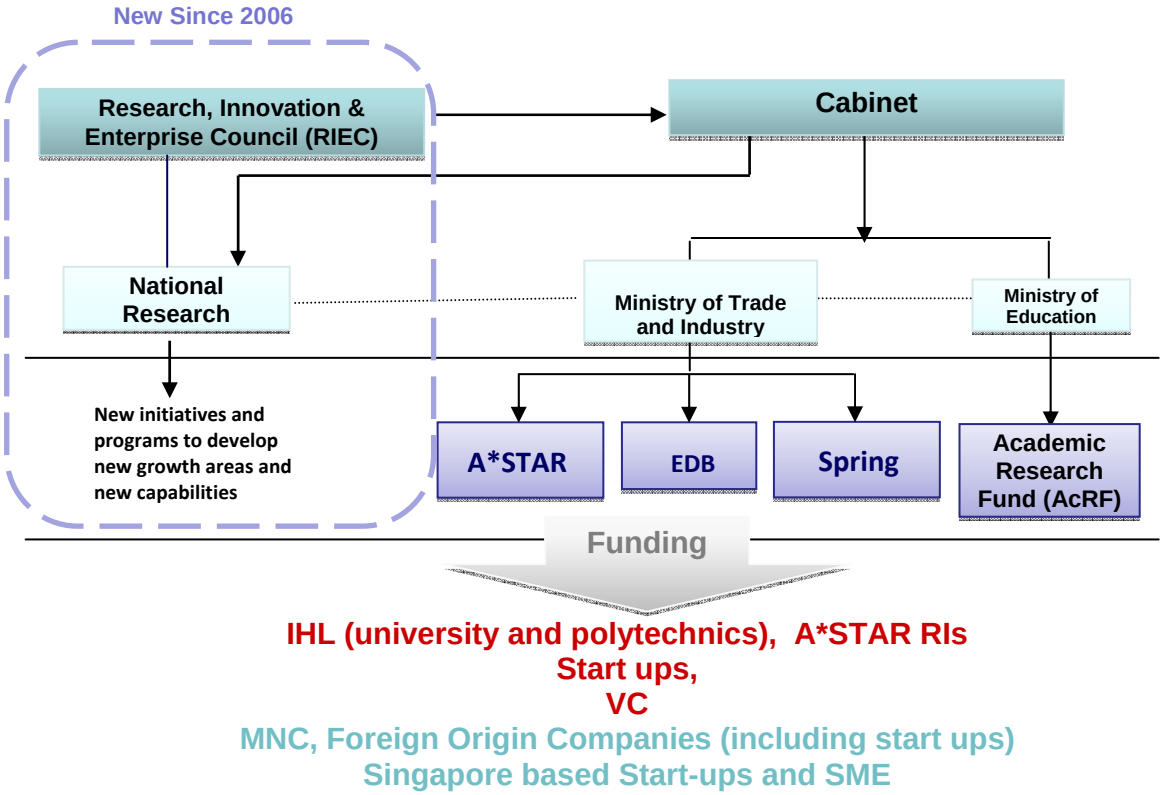

Figure 1: Singapore National R&D Framework (Adapted from Singapore Science & Technology 2010 plan)

1.2 Developing the Singapore Enterprise Eco System

The Singapore Economic Development Board (EDB) and SPRING Singapore are two agencies under MTI tasked to develop the enterprise eco system in Singapore. EDB plans and executes economic strategies that enhance Singapore's position as a global hub for business, investment and talent. Within the EDB, the New Businesses Group is responsible for developing the Singapore nanotechnology eco system. The EDB offers several incentives such as preferential corporate tax rates, approved royalties incentive to offset royalties and technical fees payable to non-residents, further deduction for R&D expenses, development schemes such as Innovation Development (IDS) Scheme, Research Incentive Scheme (RISC), Initiatives in New Technology (INTECH) and Strategic Attachment and Training Program (STRAT) to attract multinationals and foreign companies to expand and perform R&D in Singapore.

SPRING Singapore is tasked with growing innovative companies and fostering a competitive SME sector and offers different program to meet the needs of enterprises at

different stages of development. In addition to various financing schemes to support capital investments and working capital, SPRING Singapore offers funding for companies to map and execute their IP strategy, hire external experts and increase in-house technical innovation capability through its LETAS program and Technology Innovation program. SPRING also administers the Technology Enterprise Commercialisation Scheme (TECS) which was launched as part of the NFIE. Under the TECS scheme, technology based SMEs can get proof-of-concept grants of up to S$250K which covers 100% of qualifying costs. They can apply for further proof-of-value grants of up to S$500K which covers 85% of qualifying costs to develop a working prototype. Nanotechnology covers 3 of the four strategic areas identified for projects under this scheme. SPRING Singapore also offers tax deductions for investment losses of up to S$3M (Singapore does not have capital gains tax consequently capital losses are generally non-deductible) in startups to both individuals and institutions.

As part of the NFIE framework, NRF plans to provide 85% co-funding to companies funded by approved technology incubators with an option to buy out NRF's share at the next round of funding. The EDB's Fast-Tech Incubator scheme for Cleantech companies operates very similarly. These schemes are meant to provide an environment for systematic nurturing of young companies before they are ready for venture funding. NRF also matched 1:1 the funds raised (up to S$10M) by 5 early stage venture funds. The venture funds are required to invest these funds in Singapore-based technology start-ups. The key incentives and grants from all agencies most relevant to nanotechnology companies are summarized in Figure 2.

A*STAR and its 14 research institutes develop and sustain a substantial pipeline of research talent to meet industry needs. These research institutes are clustered into the biomedical cluster (managed by the Biomedical Research Council (BMRC)) and the physical science cluster (managed by the Science and Engineering Research Council (SERC)). All the research institutes under BMRC are in Biopolis which is a purpose-built biomedical research hub where researchers from the public and private sectors are co-located. Similarly, the research institutes under SERC are co-located with private sector companies in Fusionopolis which was launched in late 2008. Under EDB's Technology for Enterprise Capability Upgrade (T-Up) Scheme, companies can get 70% of the costs incurred in hiring most of the more than 2200 A*STAR researchers on a temporary basis for up to 2 years. In addition to providing manpower, A*STAR also provides shared facilities to companies establishing R&D centers in Singapore.

2 Nanotechnology in Singapore

Nanotechnology is recognized as a key enabler to sustain future development of the Singapore economy and Singapore agencies have put more and more emphasis on it since the late 1990s in response to growing awareness of nanotechnology worldwide. The Singapore government spent about US$300 million between 2003 and 2007 in nanotechnology-related R&D and manpower development. It is estimated that the number of researchers and engineers working in nanotechnology-related fields in the Republic, in both the public and private sectors, totals almost 1,000. Singapore is an active member of the Asia Nano Forum (ANF) as well as a participating member of the

Funding Agency	Grant/Fund Name	Grant Amount	Grant Criteria
NRF	Early Stage Venture Fund (ESVF)	up to SGD 10M	Need to raise or investment minimum SGD10M
	Technology Incubation Funding Scheme	SGD50M	Investors/Angels/ Entrepreneur in partnership with NUS, NTU and SMU; 15% co-investment
	Disruptive Innovation Incubation Fund	SGD10M	
SPRING	Equity Financing Scheme-SEED	up to SGD 1M	3rd party commitment
	Business Angel Scheme	up to SGD 10M	for business angel group
NUS	NUS Venture	Up to SGD 300K	NUS Spin-offs
	NUS CleanTech Incubator	up to SGD 500K	
NTU	NTU Nanofrontier research partnership equity funding	Flexible	Need to identify a joint research project with NanoFrontier

Funding Agency	Grant/Fund Name	Grant Amount	Grant Criteria
SPRING	Technology Enterprise Commercialization Scheme (TECS)	POC-SGD250K, POV-85% qualified cost support up to SGD500K	Singapore based SMEs
	Technology Innovation Program (TIP)	50% support on qualified cost	
NRF	Proof of Concept (POC)	SGD250K (program total SGD50M)	Researchers based in University and Polytechnics
	Technology Incubation Scheme (TIS)	Equity investment up to SGD500K, 85% support	seed stage funding for incubators in univ. and polytechnics
EDB	Initiatives in New Technology (INTECH)	SGD250/Day up to 2 Years	R & D training
	Strategic Attachment and Training Program (STRAT)	SGD4000-4500/month for up to 2 years	
	Fast-tech Fund	SGD500K per incubatee	
A*STAR	Labs in Research Institute (Labs in RI)	share facilities and manpower	
	Technology for Enterprise Capability Upgrade (T-UP)	70% support on manpower	

Figure 2: Incentives and Grants available for Technology Commercialization in Singapore

International Organization for Standardization (ISO) and International Electrotechnical Commission (IEC) Technical committees on nanotechnology. Singapore also chairs the standardization working group in the ANF.

2.1 Research Infrastructure

Research in nanotechnology mainly takes place in the two technological universities in Singapore namely, National University of Singapore (NUS) and Nanyang Technological University (NTU) and A*STAR RIs.

At NUS, the National University of Singapore Nanoscience and Nanotechnology Initiative (NUSNNI) provides the focal point for nanotechnology related activities in 6 strategic areas namely: nanobiotechnology, nanomagnetics and spintronics, nano/microfabrication, nanophotonics, sustainable energy and health & environmental impacts of nanomaterials. It consists of a loose network of more than 120 academic staff spanning 14 research labs and 5 research centers across science and engineering faculties. One of these research centers is the Singapore Synchrotron Light Source (SSLS) which provides synchrotron radiation based fabrication and characterization services to academia and industry around the world. NUS is also home to the Center for Ion Beam Applications (CIBA) which consists of a proton beam radiation source which can be used to fabricate high aspect ratio 3D nanostructures and to image deep tissues. Some state-of-the art labs at NUS include the Organic Nano Devices Laboratory (ONDL), Silicon Nano Devices Laboratory (SNDL) and Surface Science Laboratory (SSL). NUS launched NanoCore – an embedded entity within NUSNNI - in 2008 to build focused group of interdisciplinary labs of excellence in selected areas where NUS can build world class teams and make global impact. These areas include oxide electronics, graphene electronics, active plasmonics, spintronic materials, optoelectronics, ion-beam imaging and fabrication and bionanotechnology. NanoCore has state-of-the-art infrastructure like the Orion He-Ion sub-nm microscope and e-beam writer. The Solar Energy Research Institute of Singapore (SERIS) located at NUS conducts industry-oriented research and technology development and use-inspired basic research in the field of solar energy conversion, in close collaboration with industrial partners.

NanoCluster is an NTU-wide network of research centers with shared facilities for nanofabrication, nanocharacterization, and exploitation of nanotechnology applications in nanodevices, energy & catalysis, nanobiotechnology, nanomaterial synthesis, organic, molecular electronics and nanomagnetics & photonics. It consists of a loose network of 90 academic staff across 5 research centers. Major facilities include 3 cleanrooms (total net 1,000 sq m, net) for semiconductor processing, MEMs, Bio/ Organic/ Glass/ Metal fabrication/ processing, advanced characterization (TEMs/FIB surface analysis) and advanced materials synthesis. NTU also houses Computational Nanoelectronics Initiative which coordinates nanoelectronics modeling work among the IHLs and RIs.

Among the 14 A*STAR RIs, nanotechnology related research is concentrated in Institute of Materials Research & Engineering (IMRE), Institute of Microelectronics (IME), Singapore Institute of Manufacturing Technology (SIMTech) and Institute of Bioengineering & Nanotechnology (IBN). A*STAR has setup the SERC's

Nanofabrication and Characterization Facility (SNFC) to provide access all the fabrication and characterization facilities available under its SERC to Singapore nanotech community. This facility - managed by IMRE - consists of fabrication facilities such as inkjet printing system, metalorganic CVD systems & e-beam lithography equipment. It also has characterization equipment such as microRaman system, UHV TEM, TOF-SIMS and X-ray photoelectron spectroscopy. IMRE also manages a wafer scale nanoimprint lithography facility that provides commercial prototyping and foundry services. IME's Silicon Photonics MPW (Multi-Projects Wafer) Prototyping facility provides access to 8-inch wafer-scale CMOS fabrication facilities to academic and industrial R&D groups to perform research and prototyping of photonic integrated circuits. SIMTech has setup a Microfluidics Manufacturing Programme to accelerate prototyping and pilot run base for microfluidic development. A*STAR also has a Center for Nanometrology Excellence, a 200mm Si-based wafer processing and a MEMS prototyping facility that are available for use by the wider nanotech community in Singapore.

In addition to world-class research infrastructure, Singapore also has a wide variety of programs to train manpower required for nanotech companies at different levels of expertise. The Institute of Bioengineering and Nanotechnology (IBN) – an A*STAR RI – recently launched Nano-Bio kits to educate school children and these kits have been incorporated into secondary school curriculum in Singapore. The Nanyang Polytechnic and Republic Polytechnic offer diploma level courses in nanotechnology. The National University of Singapore offers double degree B.S. in Physics and Material Science which emphasizes nanotechnology and an Engineering Science program in Nanotechnology. Both NUS and NTU offer a variety of research programs in nanotechnology at masters and Ph.D level through their traditional departments. There is no specific M.Sc or Ph.D. in Nanotechnology in either university at present although NUS' NanoCore has plans to launch a joint engineering and business Ph.D level program.

2.2 Commercialization Infrastructure

Technology transfer is well developed at IHLs and A*STAR RIs in Singapore. At NUS, technology transfer and collaborations are managed by the Industry Liaison Office (ILO) which is part of NUS Enterprise. NUS Enterprise also has a division called the NUS Entrepreneurship Center (NEC) which administers the proof-of-concept grants, assists in the formation of spin-offs and selectively provides seed stage funding for them. NEC also manages a cleantech incubator to mentor cleantech startups under EDB's Fast-tech program. NanoCore supports the commercialization and entrepreneurship activities specifically in nanotechnology through NanoSpark.

The Innovation & Technology Transfer Office (ITTO) at NTU is the key point of contact for technology transfer and collaborations at NTU. In 2005, NTU with support from EDB setup NanoFrontier Pte. Ltd. - a nanotechnology incubator – to provide companies in various industries a platform to expand their research and development efforts in nanotechnology related areas. NanoFrontier also provides start-ups and technopreneurs a safe and strategic place to develop their nanotech inventions both technically and commercially.

All IP generated by the A*STAR institutions are commercialized by Exploit Technologies Pte. Ltd. Exploit Technologies also manages collaborations with A*STAR RIs and provides seed funding for their spin-offs companies.

In addition to the grants schemes discussed in Section 1 and the commercialization infrastructure here, Singapore also has a number of private sector venture capital firms actively investing in nanotech companies. These companies are shown in Figure 3.

Figure 3: Venture Capital Firms Investing in Nanotech Companies in Singapore

2.3 Application Specific Strengths

Singapore's investment in nanotechnology has already resulted in contribution of nanotechnology related products and services growing at about 8-21% and the number of nanotechnology companies in Singapore has grown from 10 in 2004 to the present 58. Multi-national companies such as BASF, Bayer, ST Microelectronics and Zyvex have decided to setup substantial R&D facilities in Singapore to take advantage and contribute to the growing nanotechnology ecosystem in Singapore. Here, we highlight a few application-specific strengths of Singapore and the ecosystem to capitalize on them.

2.3.1 Biomedical applications of Nanotechnology

Singapore has world class research in drug delivery systems, tissue engineering and bio-imaging applications of nanotechnology. NUS is ranked #1[6] in drug targeting and drug delivery systems, #2 (after MIT) in tissue engineering and bio-imaging applications. NUS also contributed 6 of the top 10 researchers in this area in Singapore, while NTU and A*STAR's IBN contributed 2 researchers each to round up the top 10 list.

[6] Based on citations from 2003-2009

Drug delivery systems
Researchers at NUS have developed novel biodegradable copolymers for sustained and controlled release of anti-cancer and AIDS drugs increasing the oral bioavailability to 91% while decreasing side effects. They are also using these polymers for developing vaccines and gene therapies with minimal side effects. Another group at NUS is studying the role of nano-biomechanics to understand the patho-physiology of malaria and cancer to develop highly sensitive and accurate high-throughput assays that can help detect diseases in early stages. Researchers at NTU are developing biodegradable stents with capacity to deliver multiple drugs and to reduce restenosis and thrombosis. IMRE is developing thermal and pH responsive degradable polymers via graft of NIPAAm (N-isopropylacrylamide) that can be used in hydrogels and micelles for drug delivery applications.

Tissue Engineering
Researchers at NUS are developing a novel intra-guidance channel using electrospun biodegradable PLGA fiber that can be used with commercially available nerve conduit. Other tissue engineering applications of nano-fibers being investigated include biomineralized scaffolds for bone and cartilage repair, skin grafts for wound dressing and nanofiber covered stents to reduce restenosis. Another group at NUS is developing methods to combat bio-material centered infection using surface functionalization techniques especially in Ti implants. Researchers at IBN have developed novel fibrous scaffolds where the porosity can be manipulated by hydroentanglement and use of microparticles. These scaffolds can deliver growth factors customized to the cells and incorporate extracellular matrix thus attaining effective tissue regeneration.

Bioimaging
Bioimaging is an area of intense research by various groups in Singapore. Most notable among them is them is the research work done at IBN to develop water soluble silica-coated magnetic quantum dot nanocomposites. At NUS, researchers are developing water-dispersible magnetic nanoparticles for MRI applications and thermotherapy. Other groups at NUS are developing water soluble upconversion nanoparticles for bio-imaging as they reduce photo-damage and for phototherapy as they can be excited using infrared light to generate heat at targeted sites.

Spin-Offs

Amaranth Medical (www.amaranthmedical.com)
Amaranth Medical Pte. Ltd. is a spinoff from NTU to commercialize the bioresorbable stent technology developed for treatment of peripheral vascular disease. The company is developing implantable bioresorbable stent technologies (drug eluting and non-drug eluting) for treatment of vascular disease. Amaranth Medical has two operational sites, one in Singapore and the other in Silicon Valley of California. It is incubated by NanoFrontier Pte. Ltd.

Curiox BioSystems (www.curiox.com)
Curiox BioSystems Pte. Ltd. is a spinoff from IBN to commercialize the technology for miniaturization of heterogeneous bioassay. Curiox's patent-pending miniaturization

platform, DropArray™, provides up to 1,000 times savings in sample and reagent consumption, and up to 10 times reduction in assay time. It is backed by NanoStart AG and Exploit Technologies.

Biomers (www.biomerbraces.com)
Biomers Pte. Ltd. is a spinoff from NUS to commercialize fabrication technology to produce fiber-reinforced polymer composite materials. The company is engaged in developing novel polymer composite products for numerous biomedical applications. While orthodontics is the immediate application area, dentistry and the medical field are also application targets for this innovative and patented technology. The company's first products are the patented translucent arch wires and retainer wires for the orthodontic and general dentistry treatment market. It is incubated by NUS Enterprise and received additional funding from private investors.

Other Companies in the Eco System

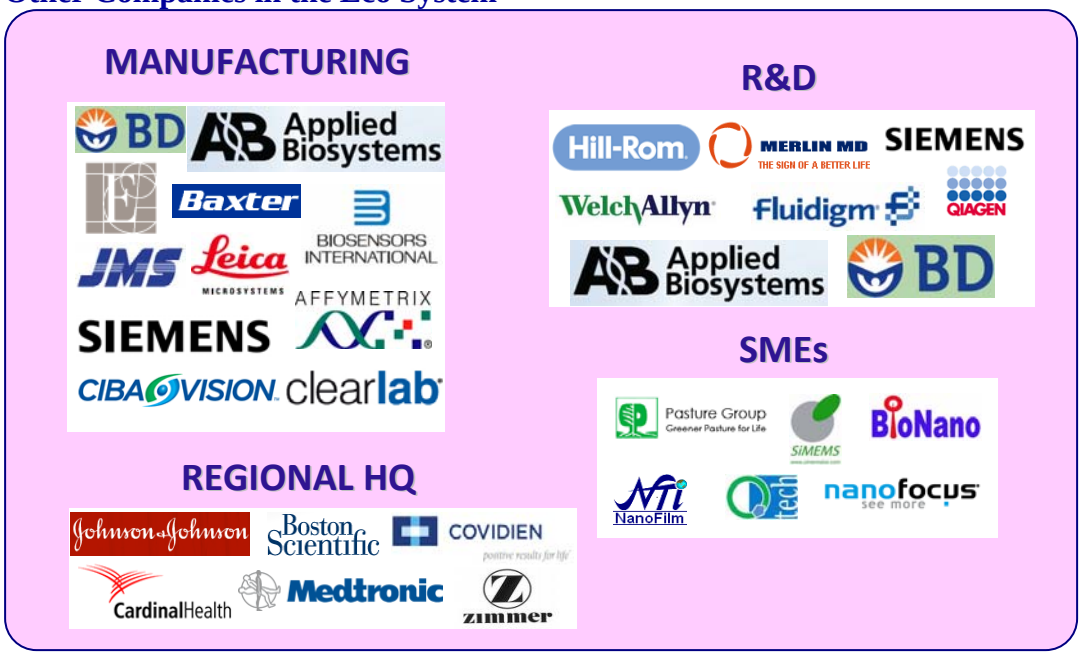

Figure 4: Medtech Eco System in Singapore

2.3.2 Energy applications of Nanotechnology

Energy was recognized as one of the 12 priority research areas by A*STAR as part of a tech scan exercise it carried out prior to the launch of Singapore's Science & Technology 2010 plan. A significant portion of energy related nanotechnology research in Singapore is focused on third generation solar cells – specifically in organic and dye sensitized solar cells. Another significant area of research related to energy is the development of OLEDs.

Dye Sensitized Solar Cells
Researchers at NUS are investigating the use of diameter controlled anatase TiO2 nanofibers in dye sensitized solar cells. They are also researching the impact of electrospinning and hot pressing 1D metal oxide nanorods on to substrates as guides for electron transport. Initial results indicate that they can produce dye sensitized solar cells

with conversion efficiencies of ~6%. Another group at NUS is investigating mesoscopic metal oxide electrodes (TiO_2, Al_2O_3, etc.) and their assemblies with functional molecules to produce high efficiency, low cost dye sensitized and 3D solar cells. Other groups are investigating the use of conjugate polymers and nanocrystalline inorganic materials for solid state dye-sensitized solar cells. At NTU, researchers have developed dye sensitized solar cells based on ZnO nanoflowers with a conversion efficiency of 1.9%.

Organic Solar Cells

A*STAR's IMRE has developed translucent organic solar cells that can be easily printed on flexible substrates. These solar cells can not only be produced cheaply but also can have wider variety of applications from window panes to portable electronics. At NTU, researchers are incorporating silver nanoprisms as median layer between the electron and hole to increase the amount of light absorbed and enhance charge transport. At NUS, platform technologies such as advanced nanometal inks, DUV and i-line crosslinkable formulations for producing organic transistors and novel columnar hetrostructures for highly efficiency photovoltaics are being developed. Researchers at NUS are also investigating production of low-cost, high quality graphene by chemical exfoliation and its use in transistors and solar cells.

OLED

IMRE and NUS researchers have developed a technology to fabricate all-in-one white LEDs by growing multiple quantum wells using InGaN/GaN on sapphire substrate. This is an important milestone in obtaining while light LEDs that are cheaper, stable and less complex without using phosphors. Another research group at IMRE is developing top emitting OLEDs on flexible substrates and has developed robust plastic substrates with effective barrier against oxygen and moisture to increase their life time. They have also achieved significant improvement in electroluminescent efficiency in top emitting OLED by overlaying an optical coupling layer on a semitransparent cathode. Researchers at IMRE have also developed blue emitters with increased lifetime and efficiency that is solution-processible, making them cheap to produce.

Spin-Offs

NanoBright Technologies (www.nanobright.com.sg*)*

NanoBright Technologies Pte. Ltd. is a spin-off from NUS to develop applications using luminescent materials. Some of the applications that NanoBright is capable of developing include - security ink that can be used in defence or anti-fraud detection; long afterglow paint that will reduce the need for lighting in dark areas; increasing the efficiency of solar cells using our up and down conversion materials and bio-imaging probes with the capability to replace quantum dots, being some of them.

Other Companies in the Eco System

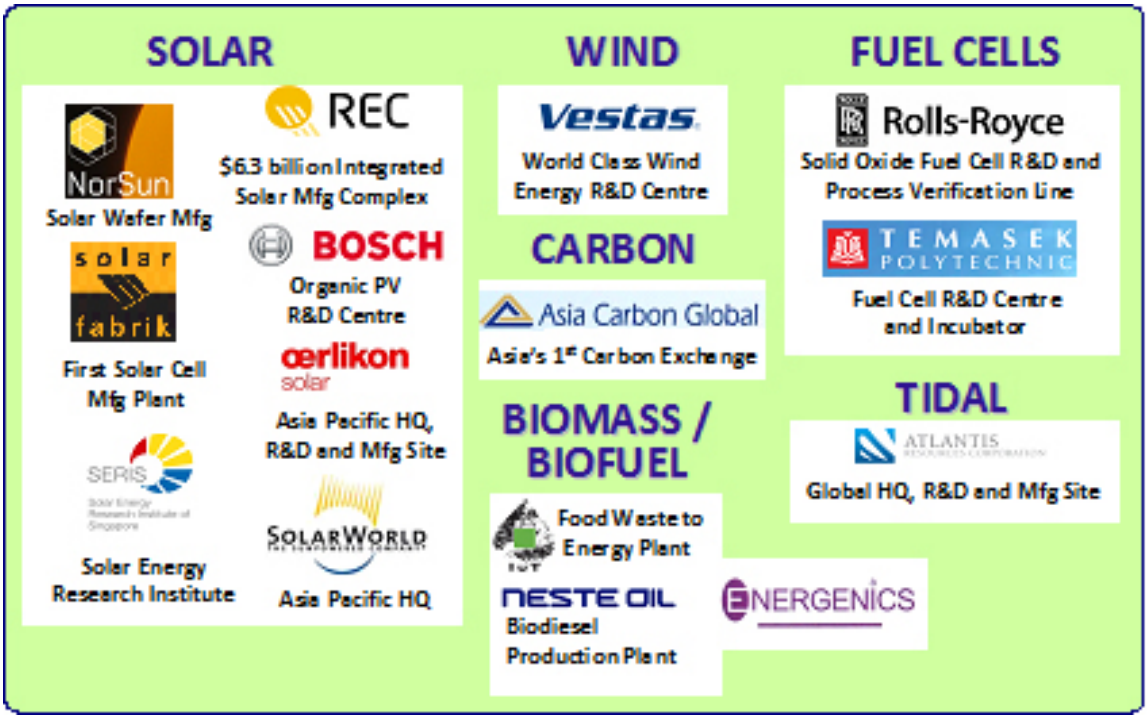

Figure 5 Energy Eco System in Singapore

2.3.3 Environment and Water related applications of Nanotechnology

Environment and water sector was recognized as one of two new strategic sectors for growth in Singapore in the Singapore Science & Technology 2010 plan. A significant part of environment and water related applications of nanotechnology is in the area of membranes with NUS being recognized as the world leader. Environmental sensors are another area of increasing research.

Membranes

NUS is the first to publish a study of forward osmosis by fabricating nanofiltration (NF) hollow fiber membranes for osmotically driven membrane processes. Researchers there are studying novel membrane materials for natural gas applications and have synthesized several novel and promising flourinated polyimides with high gas permeability and selectivity. They have enhanced anti-plasticization properties of the membranes using innovative chemical cross-linking technologies and have achieved significant breakthrough in membrane distillation using dual-layer microporous hollow fibers. Another group at NUS is exploring the use of surface modification techniques such as plasma-induced graft copolymerization on electrospun nanofibrous membranes to achieve smaller pores while retaining their high flux performance with potential applications in water filtration. At NTU, researchers are investigating the use of TiO2 nanofiber membranes for concurrent photocatalytic oxidation and filtration to reduce membrane fouling problems in large scale water treatment applications. They are also developing bimetallic zerovalent metal particles for catalytic reduction of contaminants in

water and nanostructured materials such as layered double hydroxides to adsorb trace inorganic contaminants and biomaterials.

Environmental Sensors

Researchers at NUS have developed an instrumentation free sensor system to detect the presence of mercury at room temperature using DNA modified gold nanoparticles. Another group there has developed liquid crystal based detection system for environmental applications. At IBN, researchers have developed an ultrasensitive electrochemical detection system for biomolecules using nanoparticle tagging. NTU's researchers, meanwhile, have synthesized semiconductor & ferroelectric nano-structured metal oxide and composite materials for use in gas sensors. Another group there has developed sensors based on modified gold electrodes using ZnO nanocombs.

Companies in the Eco System

Figure 6 Environment and Water Eco System in Singapore

2.3.4 Electronic applications of Nanotechnology

Electronics is one of the main industry clusters in the Singapore manufacturing sector and data storage and semiconductors are the two most important sectors within it. Hence there is a critical mass of research in this area and infrastructure to support it in Singapore.

NanoDevices

NUS is first in the world to demonstrate the use of a new material comprising silicon and carbon in transistors to enhance the speed of electronics. NUS broke the world's sub-threshold record for semiconductor devices by developing a CMOS-compatible L-shaped impact-ionization MOS (IMOS) technology based on silicon-germanium (SiGe) to enable next generation of ultra-low power devices. It is also first in the world to demonstrate HfN/SiO_2 and HfN/HfO_2 gate stack technology and to develop a proton beam writing technology with unique ability to direct-write 3-dimensional structures down to the 30nm level in both polymer and semi-conductor materials. NTU developed the world's first metamorphic indium phosphide double-heterojunction bipolar transistor technology to

manufacture high performance III-V monolithic microwave integrated circuits cheaply. It has also developed filtered cathodic vacuum arc (FCVA) coating technology which overcomes many of the disadvantages in existing FCVA technologies. Potential applications of FCVA technology being explored include the deposition and characterization of ZrO2 to replace SiO2 as a gate dielectric and the deposition of ZnO on silicon substrates for optoelectronic applications. IMRE successfully fabricated high-quality high-k oxides on semiconductors and the improved the performance of Ge-based MOSFETS by using Gemanides such as NiGe as Schottky source/drain. Researchers there have also been successful in using silicide materials such as NiSi and ErSi2 in sub-90nm nanodevices. IME successfully demonstrated the integration of Gate-All-Around (GAA) Si-nanowire transistors into CMOS inverters using top-down approach. They also fabricated P-channel omega-gated SiGe nanowire FETs with high-k/metal gate using a top-down approach, thus enabling the integration of nearly pure Ge nanowire transistors into CMOS logic circuits. Another key result achieved by researchers at IME is the development of Wafer Transfer Technology to effect wafer level transfer of circuit patterns from Si onto plastic, glass or rubber. Researchers at SIMTech have developed lead free nanocomposite solders by strengthening the solder with fine second phase particles to provide good mechanical, electrical and thermal properties.

Photonics and Magnetics

NUS researchers are developing novel spintronic materials such as oxide based ferro-magnets created by doping wide bandgap oxides such as TiO2, HfO2, Cu2O, SnO2, ZnO and using them to build multifunctional spintronic devices for information storage and processing. Another group at NUS is exploring heterostructure, supperlattices, or/and quantum wells between various epitaxial films with particular emphasis on materials with unconventional electronic, optical, magnetic and thermal properties. Other groups at NUS are examining nonlinear optical effects of intense laser pulses on novel materials with large higher order nonlinear optical susceptibility to identify materials for applications in optical switching, or optical limiting, or optical imaging. Researchers at NTU are developing mesocoscopic structures for routing and processing light that can be integrated with active devices such as lasers and detectors in a very compact form factor. They are exploring the integration of photonic devices based on III-V quantum dots grown using the molecular beam epitaxy process into a silicon-based substrate platform. Another group there has fabricated ZnO waveguides that achieve amplified spontaneous emission, pointing the way to directional ZnO lasers. That work is part of a larger program to fabricate of ZnO optoelectronics based on silicon substrate and integrate them with the silicon electronics using FCVA deposition technique. IMRE researchers have developed perfluorinated materials for use as barrier films and lubricants for hard disk drives. At IME, researchers established a full suite of passives components library based SOI nanowires and SiN waveguides with the final goal of achieving monolithic integration of all electronic and photonic devices in a single chip. They have also monolithically integrated Ge-Photodetector on Si-CMOS compatible photonics platform. Another group at IME has reported electron luminescence on an electrically pumped silicon light-emitting device with thin multi-layer stacked amorphous silicon/silicon nitride structure.

Organic and Molecular electronics

NTU researchers developed a tunable computer-generated hologram stored in polymer-dispersed liquid crystals bringing them one step closer to rewritable holographic disks. Another group there is developing superior semiconductor single wall carbon nanotubes networks to build field effect transistors (FETs) with high mobility, on/off ratio and yield for printed electronics. As mentioned in Section 2.3.2, NUS researchers are developing a platform technology to develop organic electronic systems. Another group at NUS is developing new methods to make graphene related materials using chemical and physical means and integrating these materials into specially created device structure for investigating electron transport. NUS is also studying charge and spin transport in lithographically patterned graphene nanostructures and the manipulation of the magnetization of nanoscale ferromagnets by means of spin currents. As mentioned in Section 2.3.2, IMRE researchers have developed top emitting OLEDs on flexible substrates. They are developing nanocomposite dendrimers consisting of a rigid core with active organic peripheries for use in solar cells and transistors.

Characterization

NUS is home to the inventor of portable scanning electron microscope(SEM) concept and researchers there have developed several attachments to SEM to significantly enhance the performance of standard SEM. Another group there has developed an image collection and processing system to control, capture, store and process images from SEMs. This group developed a cathodoluminescence detection system capable of performing monochromatic and extended the capabilities of the SEM to deep, sub-surface analysis presently not detectable in the SEM using the detection of thermal-acoustically generated signals. There is also ongoing research at NUS to build photoelectron emission microscope (PEEM) to enable imaging of plasmonic devices with high special and temporal resolution. IMRE researchers are using photoemission spectroscopy to determine hetero-junction band offsets to optimize and tune devices to specific applications. Another group there has developed Ballistic Electron Emission Microscopy (BEEM) – which is a modified version of Scanning Tunnel Microscope (STM) which allows local charge injection barrier measurements for a buried interface such as in electronic devices. Researchers there have also developed a high sensitivity oxygen and water vapor permeation measurement system for use in flexible OLED device lifetime and degradation studies.

Spin-Offs

Semicaps Corporation (www.semicaps.com)

Semicaps Corporation Pte Ltd is a spinoff from NUS to commercialize the scanning electron microscope image collection and processing system (SEMICAPS). They offer a range of optical fault localization microscopy for FA, Product Engineering and Yield Enhancement. Features of these microscopes include: Multi detector capabilities (SiCCD, InGaAs, MCT), visible and NIR spectroscopy for defect fingerprinting, Multiple laser stimulation techniques (TIVA, LIVA, OBIRCH, TBIP, OBIC, SCOBIC, SDL, RIL), ultra

high precision stages (<0.5um repeatability). They have more than 300 installations worldwide.

Nanofilm Technologies (www.nanofilm.com.sg**)**
Nanofilm Technologies International Pte Ltd is a spinoff from NTU to commercialize Filtered Cathodic Vacuum Arc (FCVA) technology to produce thin films. The company has expanded its patent portfolio and expanded the application of the technology multiple industry sectors from hard disk drive (HDD) industry to the glass lens mold industry.

Other Companies in the Eco System

Figure 7 Electronics Eco System in Singapore

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