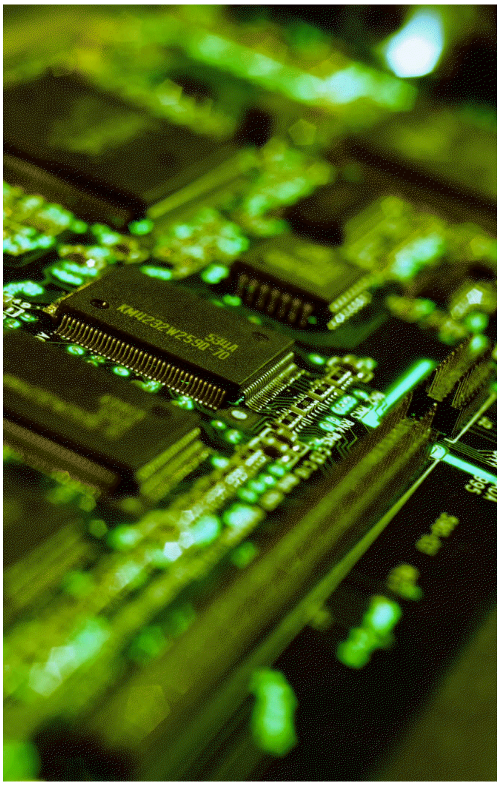

Electronics

Carbon nanotubes (CNTs) are widely investigated and utilized in electronics applications. Display applications include large area CNT flat screen color field emission displays, large area surface conduction color field emission displays, backlights for displays and PETS for medium resolution large area electronic billboards. Non-display applications include traveling wave tubes, non-radioactive sources, conductive additives for non-display applications, smart textiles, photovoltaics, transistors, neutron and gamma-ray sources and lighting devices. They are also employed in data storage.

MARKET POTENTIAL

★★★★☆

APPLICATIONS AND ESTIMATED TIME TO MARKET

- Transparent conductive films and field electron emission electrode coatings (Current)
- Color active matrix electrophoretic display (EPD) e-paper s (1-2 years)
- Heat dissipation additives in semiconductor chip packages (Current)
- Nanobuds in highly transparent, conductive and flexible films (4 years plus)

The development of future flexible and transparent electronics relies on novel materials, which are mechanically flexible, lightweight and low-cost, in addition to being electrically conductive and optically transparent. The demand for transparent conductors is expected to grow rapidly as electronic devices, such as touch screens, displays, solid state lighting and photovoltaics become ubiquitous.

In the electronics sector, the electrical properties of carbon nanotubes lend themselves to many applications including transistors, radio-frequency identification (RFID) tags, sensors, photonics, biological sensing labels, and more. After considerable research efforts, CNT products are coming to the market. After two decades of extensive research, single-walled carbon nanotubes (SWNT) are at last reaching multi-ton industrial production levels. Due to their excellent optoelectrical performance, processability, stability, and high conductivity, CNT-based transparent electrode films have been put forward as a candidate to replace indium tin oxide (ITO) currently used in touchscreens and displays. CNTs are deposited in thin films, leading to a conducting layer which can also be transparent. In relation to ITO they are more cost effective, have higher resistivity and greater flexibility. CNT electronic display applications at varying stages of commercial development include large area CNT flat screen color field emission displays, large area surface conduction colour field emission displays, backlights for displays and PETS for medium resolution large area electronic billboards.

Main applications of CNT in electronics are:

- EMI shielding
- Electronic textiles: Conductive and sensory textiles & fibers
- Transparent conducting CNT-based coatings for lower cost and flexible displays and solar cells
- Semiconducting materials in thin film transistors
- Electronic circuits for lower power and higher speed enabling new device architectures
- The thermal properties of carbon nanotubes are utilized for improved heat dissipation in semiconductor chip packages
- Conductive inks
- CNT pastes have been applied for highly efficient field emission.

Flexible and stretchable electronics are attracting great attention because of the variety of potential applications from flexible e-papers to wearable healthcare devices. The development of future flexible and

transparent electronics relies on novel materials, which are mechanically flexible, lightweight and low-cost, in addition to being electrically conductive and optically transparent.

CNTs are highly promising for application to flexible electronics not only as thin film transistors (TFTs) but also passive devices such as transparent conductive films and trace, as CNTs have a high mobility of 10-100cm^2/Vs at room temperature in addition to mechanical stability (high mechanical strength and elasticity) and chemical stability (thermal and chemical resistance).

CNT thin films have advantages in flexibility, stretchability, and performance because of these excellent electronic and mechanical properties.

Low cost manufacturing of flexible devices is also possible with good processability of CNT films. Their optical transparency is also attractive for transparent electronics applications. Applications based on CNT thin films include capacitive touch sensors, high-mobility CNT-TFTs and integrated circuits (ICs) on a transparent plastic film, all-carbon ICs demonstrating excellent stretchability and mouldability, and high-mobility TFTs fabricated with high-speed flexographic printing technique.

TRANSPARENT CONDUCTORS

Current global market size: Transparent electrode market $15 billion plus.

Developmental stage: Commercially available.

The demand for transparent conductive films (TCFs) is expected to grow rapidly as electronic devices, such as touch screens, displays, solid-state lighting and photovoltaics become ubiquitous. Indium tin oxide (ITO) is the dominant material for transparent electrode used in touch screens, LCD displays, solar cells, and solid state (OLED) lighting due to its relatively high transparency at high conductivities. However, ITO is brittle, lacks flexibility and the fabrication process involves high temperatures and vacuum and therefore is relatively slow and not cost effective. Other conductive metal oxides used include antimony-tin oxide, fluorine-doped tin oxide and aluminum-doped zinc oxide.

CNTs and a variety of other nanomaterials provide cheaper alternatives that also allow devices to become flexible. CNT transparent conductive films have demonstrated great potential in various optoelectronic devices and have already been used in touch panels for smartphones. Main companies developing CNTs-TCFs are Canatu, Dow, Eikos, Linde, Toray, and Unidym.

C3 Nano, Inc. (www.c3nano.com) is a recent start-up developing TCFs comprising CNT inks. These conductive inks can comprise a polar solvent-based solvent system, such as water-based, alcohol-based or solvent combinations thereof, carbon nanotubes, and one or more dopants, generally including an ionic dopant. The company states that the primary issue concerning nanotubes as

Table 15: Properties of materials for transparent conducting film (Y. Lee & J.-H Ahn)

	Thickness (nm)		Sheet resistance (Ω/sq)	Failure strain (%)	Cost
ITO	100~200	>90	10~25	1.4	120 \$/m^2
PEDOT: PSS	15~33	80~88	65~176	3~5	2.3 \$/ml
Silver	~160	92	100	~1.2	40 \$/m^2
CNT	7	90	500	~11	35 \$/m^2
	0.34	90	~35	~7	45 \$/m^2

ITO replacements to date is inferior conductivity, and they have addressed this issue by using an effective combination of a multifunctional dispersant that also acts as a p-type dopant to the CNTs in the TCF.
Besides C3 Nano, Inc. CNT inks are marketed by a number of companies, such as Eikos, Inc. (www.eikos.com) for printed electronics applications. These inks can be deposited easily onto a variety of rigid and flexible substrates with standard coating techniques including spray-coating and Aerosol Jet printing. Inkjet printing of CNTs is a more recent method that shows promise. Inkjet printing is currently being used to deposit various types of conductive nanomaterials such as gold and silver. Although these metals are excellent conductors, CNTs are cheaper and more versatile as they can behave as both a semiconductor and a conductor.
In July 2013, Linde Electronics launched SEERe- ink, licensed from the London Centre for Nanotechnology (LCN). SWNTs are difficult to isolate, and hence purify, due to their strong tendency to 'bundle' together.

Figure 14: Nanotube inks (Nanointegris)

They are also expensive to produce. The LCN approach provides a scalable, bulk technique that avoids the limiting sonication/centrifugation steps associated with other methods (https://www.london-nano.com/sites/default/files/uploads/research/highlights/Dissolution%20and%20separation%20of%20single-walled%20carbon%20nanotubes.pdf).
In July 2013, CNTouch announced they had received significant orders for their nanotube-based touch panels for entry-level and mid-range smartphones. The company is a subsidiary of Foxconn and the technology has been developed with Tsinghua University.

HIGH FREQUENCY TRANSISTORS AND INTEGRATED CIRCUITS

Current global market size: \$300 billion plus.
Developmental stage: Applied research/prptotype.

Main materials currently used for TFTs are amorphous silicon and poly-silicon. However, these materials are processed under high temperature and vacuum conditions. As a result it is difficult with conventional technologies to manufacture TFTs on low-cost plastic film substrates. Therefore CNTs have emerged as a prime candidate for manufacturing TFTs on plastic films at low temperatures.
In September 2013, NEC and the Technology Research Association for Single Wall Carbon Nanotubes (TASC) demonstrated a CNT-TFT. In addition to suppressing noise emitted during high-speed operation to one-tenth or less than that of ordinary printed transistors, this newly developed printed CNT-TFT realizes an operating speed of 500kHz, which is 10 to 50 times that of ordinary printed transistors, thanks to an output current dozens of times higher than existing printed transistors. As a result, the level of performance necessary for control circuits can be attained, thereby making it

possible to apply this printed CNT-TFT to new devices in the future, including flexible large displays and sheets mounted with multiple sensors.

Toray has also developed a spray-coated CNT-TFT demonstrating the world's highest performance levels: mobility of 2.5cm²/Vs and on/off ratio of 106, by combining its proprietary semiconductor polymer and single wall carbon nanotubes.

In June 2014, Aneeve Nanoechnologies LLC announded they had overcome a major issue in carbon nanotube technology by developing a flexible, energy-efficient hybrid circuit combining carbon nanotube thin film transistors with other thin film transistors. The company stated that this hybrid could take the place of silicon as the traditional transistor material used in electronic chips, since carbon nanotubes are more transparent, flexible, and can be processed at a lower cost.

Research Developments 2013-2014

July 2014

Canatu launch Carbon Nanobud (CNB) Flex film, a TCF which according to the company can withstand 180° bending tests at a 1 mm radius, without compromising the conductivity.

July 2014

IBM announces that it expects to have commercialised its carbon nanotube transistor technology in the early 2020s, thanks to a new design that would allow the transistors to be built on silicon wafers using similar techniques to existing chip manufacturing plants.

MEMORY DEVICES

Current global market size: $75 billion plus
Developmental stage: Applied research.

Nanomaterials have potential to meet a wide range of memory device needs including speed, power consumption, density, reliability, non-volatility, and cost. There are a number of nanotechnology-based approaches to the development of data storage; Magnetoresistive Random Access Memory (MRAM), Ferroelectric RAM, (FeRAM), Resistive RAM (RRAM), and NRAM (Nanotube RAM). GMR and TMR effects has been observed in multilayered nanostructures of the form FM (Å)/NM(Å)/FM(Å), which FM is a transition-metal ferromagnetic layer (Fe,Co,Ni or alloys) and NM is a non ferromagnetic metal (Cr, Cu, Ag etc.) or an isolating (tunnel) barrier in case of Tunnel Magneto-Resistance Effect.

PRODUCT DEVELOPERS

Alnair Labs Corporation

Products based on the technology developed in the field of optical communications (ultra-short pulse fiber mode-locked laser incorporated CNT, EO probe for sensing electrical field, devices for generating a high-frequency electrical pulses). www.alnair-labs.com

Aneeve Nanotechnologies LLC

The company is developing aligned carbon nanotubes on insulator materials and silicon for high frequency, low noise and highly linear device applications. The company's technologies are being applied to printable electronics and carbon nanoelectronics. www.aneeve.com

Applied Nanotech, Inc.

Applied Nanotech, Inc. has developed a carbon nanotube (CNT) electron emission lamp suitable for use as a backlight for large area LCD TVs, industrial or medical lighting applications. ANI has developed electron and ion sources for industrial and medical sensing and monitoring. Other applications have been on large area display applications (CNT Field Emission Displays, CNT-FEDs). www.appliednanotech.net

Buckeye Composites

The company's carbon nanomembrane, or "buckypaper," is a thin, paper-like membrane of carbon nanotubes, nanofiber, nanoplatelets and/or other carbon nanomaterial. Buckypaper can be comprised of 100% carbon nanomaterial or can be pre-impregnated or "prepregged" with resin. www.buckeyecomposites.com

C3Nano Inc.

The company is a spin-out from Stanford University who are developing a carbon nanotube based electrode for touch-screen electronic devices. www.c3nano.com

Canatu Oy

Canatu Oy produces carbon nanotubes and a novel NanoBud™ nanomaterial. Carbon NanoBuds™. Carbon NanoBuds™ are utilized as electron field emitters. www.canatu.com

Catalytic Materials LLC

The company produces high purity multi-walled carbon nanotubes and graphite nanofibers for the electrically conductive/antistatic polymer market. www.catalytic-materials.com

CNTouch

The company is producing CNT touch panels forthe low cost smartphone market. www.cntouch.com

Dupont Microcircuit Materials

Developing nanotubes for flexible displays. www2.dupont.com

Environmental Energy Nanotech Research Institute CO., Ltd. (EEnanoTech)

The company produces carbon nanohorns in cooperation with TIE GmbH. EEnanoTech has developed an industrial production process for Carbon Nanohorns (CNH). www.eenanotech.co.jp

Eikos, Inc.

The company is developing transparent, electrically conductive carbon nanotube films and nanotube inks for transparent conductive coatings. Eikos has branded its technology as Invisicon. Eikos is aiming to replace indium tin oxide (ITO) and conducting polymers with carbon nanotube transparent conductors in several common electronic devices, such as touch screens, LCDs, OLEDs, photovoltaics, electroluminescent lamps, electronic paper. www.eikos.com

Fujitsu Laboratories

The company is developing various applications of nano-carbon materials-such as carbon nanotube (CNT) transistors, CNT interconnects, and CNT-graphene composites-for semiconductor electronics.
The company has combined carbon nanotubes and grapheme to self-form a new nanoscale carbon composite, at the relatively low temperature of 510 degrees Celsius. http://jp.fujitsu.com/group/labs/en

GS Nanotech Co., Ltd.

Producing carbon-based anode materials for batteries. www.gsnanotech.co.kr

Hanwha Nanotech Co., Ltd.

The company has been producing carbon nanotubes since 2000, mainly for the electronics and displays markets. www.hanwhananotech.co.kr

Honjo Chemical Corporation

The company manufactures electrode materials for the next generation flat display's panel by using carbon nanotubes. The company has a nanotube and fullerene mass-production plant in Japan at Neyagawa Factory under a cooperation agreement with Mitsubishi Corp., Fullerene International Corp. (FIC) and MER Corp. www.honjo-chem.co.jp

Hyperion Catalysis International, Inc.

FIBRIL nanotubes are used to make statically dissipative plastic compounds that are fabricated into devices designed for use in environments where particulate and chemical cleanliness is critical. Applications include test sockets for ICs, silicon wafer handling and computer disk drives. http://hyperioncatalysis.com

Linde Gas

The company's scalable reductive dissolution technology uses liquid ammonia to produce solubilised carbon nanotubes in the form of inks, which can then be deposited as films. The negative charge on the SWNTs within the ink allows for further functionalisation, extending the field of potential applications to composites, sensors and biology. www.linde-gas.com

Nanocomp Technologies, Inc.

The company was formed in 2004 as a spin-out of Synergy Innovations, Inc. The company is a developer of energy saving performance materials and component products from CNTs. www.nanocomptech.com

Nanocyl

Nanocyl®-7000 series in applications requiring low electrical percolation threshold such as high-performance electrostatic dissipative plastics or coatings. www.nanocyl.com

Nanomaterials Discovery Corporation

Nanomaterials Discovery Corporation (NDC) develops nanostructured materials, including carbon nanotubes, using high-throughput combinatorial electrochemical methods. Their technology and intellectual property is focused on the discovery and refinement of fuel cell catalysts, rechargeable battery electrodes, flat panel display phosphors, and other inorganic and organic nanostructured materials. www.nanomaterialsdiscovery.com

Nantero

Nantero is developing NRAM™, a high-density non-volatile random access memory chip. The proprietary NRAM™ design uses carbon nanotubes as the active memory elements. www.nantero.com

Noritake Co., Limited

The company is developing carbon nanotubes as field emitters for high-voltage field emission displays. www.noritake-itron.jp

Samsung Electronics

The company is developing carbon nanotube-based color active matrix electrophoretic display (EPD) e-paper based on Unidym's nanomaterials. www.samsung.com

SouthWest Nanotechnologies

The company are seeking to commercialize printed TFTs using semiconducting inks, based on its single-wall carbon nanotube (SWCNT) technology. www.swentnano.com

TECO Nanotech Co., Ltd

The company is focusing on the development of carbon nanotube field emission displays. XinNano Materials, Inc. is a joint venture of TECO Nanotech Co., Ltd. and Xintek, Inc. XinNano Materials, Inc. is market leader in producing high quality field emission grade carbon nanotubes (FECNTs) and components for commercial applications such as flat panel displays and X-ray. wwwe.teconano.com.tw

TOP Nanosys

Produce SWNT transparent conductive films. www.topnanosys.com

Unidym, Inc.

The company produces high-purity, electronics-grade carbon nanotubes (CNTs) for its current applications using an in-house, fully-scalable, and proprietary chemical vapor deposition (CVD) production process. www.unidym.com

XinNano Materials, Inc.

The company has developed carbon nanotube ink that can be easily applied to substrates to produce transparent conducting film (TCF) and anti-static film used for touch panel, flexible display and EMI shielding applications. The company also produces Field Emission Grade Carbon Nanotubes. www.xinnano-materials.com

Xintek

The Company develops and manufactures nano-material-based field emission technologies and products for a broad range of applications including diagnostic medical imaging, homeland security, and information display. www.xintek.com

Table 16: Global revenue estimates for the electronics market impacted by carbon nanotubes

ORNL	Transparent electrode market 2011: $4 billion. 2013: $26 billion. 2015: $58 billion
Nanomarkets	Global conductive coatings market 2012: $9 billion. 2019: $19 billion
University of Sheffield	Global electronics coatings and films market, in 2010 is estimated to be $3 billion
Observatory Nano	Global data storage market 2010: $110 billion
Engineer Live	The electronic displays market, in 2010 is estimated to be $100 billion. Touchscreens account for approximately 13% of this total.
Department for Business Innovation and Skills UK	Plastic electronics market 2020: $120 billion
IC Insights	IC sales 2013: $300 billion
USDC Flexible Displays Report	Flexible electronics market 2015: $62.5 billion