Technology Sector Report

Technology Analysis of Beyond CMOS Nanotechnologies

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1. Definition

This ICT sector sub-report “Beyond CMOS” examines nanotechnology-based functions that, in the long term, will complement or replace conventional silicon technology. Short to medium-term developments in CMOS integrated circuits are discussed in sub-report “Integrated circuits”.

Nanoelectronics refers to the use of nanotechnology in electronic components. It is not just the next evolutionary step in continuous development, but has the power to become a disruptive technology, introducing completely new capabilities and ways of operation. Significant breakthroughs can be expected in the long term from the progress in nanometre-sized features.

This report reviews nanotechnology enabled developments in future computing devices, describing some alternative candidate concepts for logic devices and information processing devices. The development of memories is discussed in ICT sector sub-report “Memory”.

In addition, the discussion is extended to include issues on heterogenous intelligent system development (integration of functions beyond computing, such as sensing, power, communication).

This overview report is based on the research priorities and extensive technology assessments reported in the ENIAC Strategic Research Agenda (SRA) and ITRS 2007 Editions on Emerging Research Devices (ERD) and Emerging Research Materials (ERM).

2. Short description

Complementary metal oxide semiconductor (CMOS) technology has long been the key driver for microelectronics. The power of CMOS technology is based on its ability to carry out digital calculations while consuming very little electrical power.

While the development of CMOS technology is expected to continue well into the next decade, inevitably a point is reached where today's semiconductor circuits meet their physical limits. Economical limits to device scaling could be reached even before that. For this reason, it is essential to explore new ideas and alternative technologies in order to create novel computing devices capable of replacing CMOS technology in the 2020 or beyond timeframe.

The novel devices should show significant advantage over ultimate CMOS transistors in power, performance, density, and/or cost to enable the semiconductor industry to extend the historical cost and performance trends for information technology.

Two main approaches are used to develop technologies that would extend the functional scaling of information processing substantially beyond the "ultimately scaled" CMOS. One is heterogeneous integration of new technologies with the CMOS platform (functional diversification). The second is to develop fundamentally new approaches to information processing.

To meet these goals, the following main challenges have been defined as the critical research issues the US Nanoelectronic Research Initiative (NRI) (acknowledged in the ENIAC SRA):

- Developing alternative schemes to encode information (new logic devices) to enable computing at low power consumption

- Inventing and developing a new information processing technology

- Managing heat transfer more efficiently through phonon engineering

The main research topics include new principles of operation (devices utilizing new computational state variables beyond electronic charge), new architectures, new materials for interconnect technologies and transistors (such as carbon nanotubes, nanowires or organic molecules), improved nanoscale thermal management and novel fabrication methods for these structures and circuits.

This report is structured according to the following categorisation:

- New logic and information processing devices:
    - Extensions to CMOS
    - Alternative state variables
    - Single electron transistors (SETs)
    - Molecular devices
    - Spin devices
    - Ferromagnetic devices
    - Nanophotonics

- New functionalities:
    - NEMS
    - Molecular sensors
    - Organic/plastic electronics
- Architecture and system level:
    - Emerging architectures
    - Thermal management
- Manufacturing and design:
    - Bottom-up techniques
    - Multiscale modeling and design tools

The contents of this report are based on two main references: The ENIAC Strategic Research Agenda (update 2007) and International Technology Roadmap for Semiconductors (ITRS) (2007 Edition, Section on Emerging Research Devices).

3. State of R&D

3.1. New logic and information processing devices

3.1.1. Extensions to CMOS: Low dimensional structures

A lot of research is currently devoted to extending traditional CMOS devices. One primary approach is to replace the FET channel with novel high carrier mobility materials. Some of these materials display a semiconducting band structure only under quantum confinement. The three main types of quantum-confined structures are carbon nanotubes (CNT), nanowires (NW), and graphene nanoribbons.

Recent research activities in nanowires and carbon nanotubes can be divided into three main categories: (i.) experimental growth and assembly, (ii.) CNT and NW device fabrication and characterization, (iii.) CNT and NW circuits and integration.

One key problem lies in the difficulty of separating different types of carbon nanotubes (semiconducting and metallic tubes) that are created together during material synthesis. Current research is investigating intensively various techniques for gaining better control over the chirality of nanotube materials (chirality is the property that determines wheter the nanotube is semiconducting or metallic).

Another key issue is to develop methods for controlling the assembly of nanostructures. Manipulating large numbers of nanotubes into position is very slow and no high-volume manufacturing processes exist today. New techniques for assembling parallel arrays of nanotubes or nanowires on substrates are currently investigated. Better control of the accuracy of these methods is necessary and requires further innovation in the assembly and fabrication technology.

Two-dimensional graphene films have generated a lot of interest recently as an interesting alternative for channel replacement material in FET structures. Graphene films are well known to behave as high mobility zero bandgap semiconductors with high carrier mobilities. When patterned to sufficiently small ribbon widths, the graphene ribbons begin to display a finite band gap resulting from quantum confinement.

3.1.2. New state variables

For a large part, future information processing will be done on information where the state variable is something other than electronic charge. This information includes optical images, image sequences, speech, and data sets derived from physical sensors.

Many different information carriers are currently researched. These include spin, molecular state, photons, phonons, nanostructures, mechanical state, resistance, quantum state (including phase) and magnetic flux.

Some of the novel devices may prove useful for various information processing tasks in addition to general purpose computing. Some of the more specialized tasks include associative processing, communication and multivalued logic. In general, these may require new a functional organization of the interconnected devices (new architecture).

3.1.3. Single-electron transistors (SETs)

SETs are switching devices that use a tunneling mechanism to transport electrons from source to drain. The latest standard MOSFETs that use thousands of electrons at any given moment in its on state, and the most sophisticated flash memory devices use roughly the same amount of electrons to store a bit of information. SETs are designed to do the same using a single electron.

Single electron devices hold the promise of ultra-low power electronics and further miniaturization. Potentially SETs can be applied to general purpose Boolean logic but significant progress on circuit and architecture development is required.

New applications and architectures that exploit the unique functionality of room-temperature operating SET circuits have been developed. Large threshold voltage variation impedes the realization of large-scale SET circuits. This currently makes it difficult for SETs to compete directly with CMOS devices used to implement Boolean logic operations.

The majority of the SET circuits demonstrated to date employ so called “voltage state logic” where a bit is represented by the voltage of capacitor charged by many electrons. Truly single-electron approaches, representing a bit by a single electron (“bit state logic”) have been limited to laboratory demonstrations.

For information processing purposes, the non-linear current-voltage characteristics of SETs can be utilized effectively as the computing primitive in certain algorithms and applied to associative recognition systems that mimic the human cognitive function. Primitive associative processing (color identification) has been experimentally demonstrated using floating-gate SETs operating at room temperature.

3.1.4. Molecular devices

Molecular electronics is targeted at creating functional blocks at the molecular or supra-molecular level that could be assembled in more complex functions. Fully molecular-based complex systems including interconnected molecular logic and molecular memory devices have still to be demonstrated. Limited molecular logic, memory and interconnect functions have been shown, based on different types of molecules, but their integration into a single chip is still an issue.

The potential of molecular devices for computing applications is based on very high densities that can be attained, a large variety of molecular characteristics, ability to self-assemble, very low power consumption, and the ability to change state via electrical, optical, or chemical means.

A lot of progress has been made in improving the desirable characteristics of the molecules themselves and developing concepts for potential architectures that would utilize molecular elements. Significant problems exist in molecular synthesis, device and circuit fabrication and reliability. In addition, there is often a large gap between projected parameters and the actual observed ones.

The use of molecules as programmable diodes (molecular switches) is the core technology underlying most of the concepts for future applications. A molecular switch is a molecule which switches reversibly between two or more positions. Reproducibility and repeatability of experimental measurements still shows significant variations between different approaches and research groups.

A lot of research effort has been devoted to developing the concept of molecule on CMOS architecture (CMOL). These are hybrid CMOS / nanoelectronic systems that are based on conventional CMOS devices connected to nanowire arrays with molecular elements functioning as programmable diodes. These are predicted to have very attractive performance potential compared to scaled CMOS systems, but no successful demonstrations have been realised so far.

Perhaps the first potential application is using the bistable behaviour of certain molecules to produce memories with an extremely high density. Specific issues, such as contacting the molecule, carrying enough current to provide noise immunity and a reasonable fan-out, and the addressing and read out of specific blocks remain to be solved.

In addition to logic operations, molecular devices could potentially be used for several other applications. For example, molecular schemes for combinatorial logic have been envisaged. Computing has been demonstrated using DNA molecules utilizing self-assembly to perform computational steps in test-tubes.

The key challenges for molecular devices include the ability to electrically stimulate and measure response or the state. In some systems, protons have been used to communicate signals. Optical signal communication is also being investigated. Tunneling transport between molecular wires and devices is actively being researched and may be a viable option.

The subject of molecular and DNA switches is also discussed in the report on “Novel Biomaterials”.

3.1.5. Spin devices

Spintronics (spin transport electronics, also known as magnetoelectronics) is an emerging technology which exploits the intrinsic spin of electrons and its associated magnetic moment, in addition to its fundamental electronic charge.

Spintronics has many potential advantages, including low power operation, non-volatility and co-localisation of data processing and storage.

Metal-based spintronics: The simplest method of generating a spin-polarised current in a metal is to pass the current through a ferromagnetic material. The most common application of this effect is a giant magnetoresistance (GMR) device. Metal-based spintronics is likely to be first introduced for data storage applications using either spin torque switching (spin torque transfer magnetic RAM, STT-MRAM) or domain wall effects (e.g. IBM Racetrack Memory).

Semiconductor-based spintronics: Spintronics using ferromagnetic semiconductor nanostructures holds promises for novel nanodevices sensitive to magnetic field. This could find application from information processing to sensors, though major breakthroughs are needed in materials (e.g. semiconductors with a higher critical temperature), devices (e.g. injection/detection trade-off), cointegration with CMOS or in exploring promising physical phenomena.

Spintronics using half-metals and molecules also need to be explored.

3.1.6. Ferromagnetic logic devices

Ferromagnetic logic devices are a class of alternative logic devices that use the local magnetization orientation of a domain of ferromagnetic material to store the computational state. Their operation is based on collective magnetic effects associated with the magnetic polarity of a nanodomain.

Ferromagnetic devices have the potential of being non-volatile and radiation hard, which is derived from the properties of the ferromagnetic materials themselves. They can be fabricated with ferromagnetic, metallic wires patterned to form Boolean logic devices.

The propagation of domain wall boundaries separating magnetic nanodomains has been shown to reach a velocity of several hundred meters per second. This has led to geometric realization of NOT gates, AND gates, fanout structures, cross-over structures, and shift registers using the domain wall movement driven by the external magnetic field.

3.1.7. Nanophotonics

A promising alternative for information transfer is to use light in the visible or infrared range. Nanophotonics allows the confinement and interaction of photons and electrons in a small volume which opens up the possibility of processing data at high frequency.

This subject is discussed in detail in ICT subsector report “Photonics”.

3.2. New functionalities

3.2.1. Nanoelectromechanical systems (NEMS)

NEMS devices hold the promise to improve abilities to measure small displacements and forces at a molecular scale. The ITRS 2007 edition contains NEMS memory as a new entry for the Emerging Research Devices section.

3.2.2. Nanosensors

Nanosensors are any type of sensors (biological, chemical or other) that convey molecular-level information to the macroscopic world. Future multifunctional systems are envisioned to integrate nanoscale computing devices with sensing capabilities for use in various application areas ranging from communications to medical uses.

The potential of nanosensors as part of future computing systems lies in their capability to provide the link between other forms of nanotechnology and the macroscopic world. This would allow full exploitation of the potential of miniaturisation of computer chips while vastly expanding their storage potential.

However, before widespread implementation to consumer products becomes feasible, developers must overcome several major issues related to reliability, compatibility with CMOS technology, difficulties in mass manufacturing and high costs of production.

The topic of nanosensors and biosensors is also discussed in ICT sector report “Integrated circuits”.

3.2.3. Organic / Plastic electronics

Organic electronics, plastic electronics or polymer electronics is an emerging branch of electronics that deals with conductive polymers, plastics, or small molecules. The field not only includes organic semiconductors, but also dielectrics, conductors and light emitters.

Conductive polymers are lighter, more flexible and less expensive than inorganic conductors. Potential application areas include consumer electronics, displays, packaging and photovoltaics.

Organic electronics is often associated with printed electronics. The processability of organic electronically functional materials in liquid form allows their use as functional inks in printing. Electronic thin-film devices are prepared by printing several functional layers on top of each other.

Printed electronics is expected to facilitate the establishment of “low-cost electronics” for application fields where high performance is not necessary. Examples of applications include flexible displays, light-emitting diodes, smart labels (RFID) and active clothing.

Electronic applications with high switching frequencies and high integration density ("high-end electronics") will be dominated for a foreseeable future by conventional electronics.

The development of displays is discussed in detail in ICT sub-sector report “Displays”. Sector reports on Energy and Textiles include information on photovoltaics and active clothing.

3.3. Architecture and system level

3.3.1. Emerging architectures

Architecture refers to the functional arrangement of interconnected devices that includes embedded computational components. New computational schemes, such as neural networks or DNA computing, are being investigated as future alternatives to deterministic computing

Reliability will be one key issue for future nanoelectronics devices. The number of fabrication flaws is unavoidably increases when devices shrink towards the nanometer scale. Emerging devices are expected to be more defective, less reliable and less controlled in both their position and physical properties. It will be necessary to develop methods for error resiliency and trade off error rate against performance (e.g. speed, power consumption).

It is also important to pay attention to the “systemability” of emerging devices, i.e. the capacity of a device to be integrated into a complex system. Emerging technologies can eventually lead to paradigm shifts in the whole concept of computing and will therefore require completely different design flows in order to exploit them in systems. It will be essential to involve multidisciplinary teams of system architects and nanotechnology researchers in order to optimise the overall performance of a system.This research will link system-level objectives such as high performance and reliability to the development of advanced nanoscale devices.

3.3.2. Thermal management

The emerging field of phononics aims to control phonon movement by using engineered nanostructures. It brings new opportunities in the interaction between quasi-particles (e.g.

electrons, photons, spins) and phonons, potentially allowing better heat removal, isolation from thermal noise and better carrier mobility.

It is much harder to control the flow of heat in a solid than it is to control the flow of electrons. However, researchers have recently demonstrated thermal diodes, thermal transistors and thermal logic gates. Such components also raise the possibility that heat could also be used to process information.

3.4. Manufacturing and design issues

3.4.1. Bottom-up techniques

The ability to manufacture billions of devices on chip with full control over their properties presents an overwhelming challenge that is threatening to lead to unbearable production costs.

New potential manufacturing techniques include various “bottom-up” approaches. These processes are attractive because they are fast and versatile, but they are generally incompatible with conventional fabrication.

Self-assembly and bio-inspired techniques are viewed as attractive concepts that need further investigation. Directed self-assembly is essential to fabricate complex structures composed of nanoscale building blocks. Bio-inspired processes may be used to develop self-adapting and self-repair properties.

Some examples of technologies that utilize bottom-up approaches exist today, such as self-aligned “optical fringing” nanotubes and self-assembled quantum dots. However, larger scale advances will require long term development. Such huge research effort has been devoted to the development and optimization of the CMOS platform that it is probable that novel bottom-up technologies are first combined with traditional approaches to achieve increased performance and cost effectiveness.

Full-scale utilization of bottom-up manufacturing would require that circuits be designed entirely differently. Research into new architectures may help on this path by relaxing the need for a deterministic approach to controlling the properties of the elementary devices.

3.4.2. Multiscale modelling and design tools

Next generation technologies will present major challenges to the design environment. It will be necessary to build suitable simulation methods and design tools that link nanoscale device models with higher-level heterogeneous system design environments.

Current research is putting a lot of emphasis on the physical properties and fabrication of new device structures. Much less effort is spent on how to design complex systems using these novel devices. This so-called “design gap” continues to grow. Therefore more research is needed to improve the ability to integrate new technologies into functional systems.

Numerical modeling will be an essential tool for integration of multiscale functionalities to future products. The key challenge is bridging the enormous gap in time and length scales when linking the nanoscale elements to macroscale systems.

Computer modelling of nanostructured materials needs to integrate a range of approaches from first-principles quantum mechanics, to forcefield-based molecular mechanics and mesoscale simulation methods. Further research is needed develop simulation methods that would allow modelling of complex nanoscale systems.

Increased system complexity represents another huge challenge: it is necessary to include elements of mechanics, hydraulics, chemistry, magnetics and (bio)sensors, together with the trend towards multiprocessor, defect-tolerant and power-managed implementation architectures. No applicable models, methodologies, or tools exist today.

4. Additional demand for research

The development of technologies in the “Beyond CMOS” domain involves a very complex environment, including everything in the development cycle from idea to realization and in the supply chain from materials science to volume manufacturing. In-depth know-how is needed at every stage in the process, while application markets are changing at the same time.

Emerging technologies offer very high option diversity and initially fragmented application markets. One of the main challenges will be to select promising technologies at a sufficiently early stage, while still keeping an open mind for possible disruptive ideas. Demonstrating the integration of innovative concepts into complex systems is essential. Better cooperation is needed to close the gap between system development and nanoscale device technologies.

Narrowing down the options should be done at successive decision points before committing to further R&D costs that often are at least an order of magnitude higher for each successive development stage. This process should bring ideas progressively to industrial relevance by involving multidisciplinary teams of material and device scientists, function designers and manufacturing experts.

Research topics for further computation scaling have been fairly well defined by the ITRS and the US Nanoelectronics Resarch Initiative (NRI), but a significant effort is still needed to define research vectors to investigate how nanotechnologies could provide application-driven new functionalities. A special emphasis should be put on the necessary co-development of emerging devices and of the associated system architectures needed for different applications.

5. Applications and perspectives

Moore’s Law has been governing the development of silicon technology for over 50 years. Fundamentally new concepts, such as molecular electronics, hold the promise of extending Moore’s Law beyond the physical limits of silicon in the 2020 timeframe. At the same time, development toward wide-scale emergence of intelligent multifunctional systems is opening up a wide range of new application areas for future computing devices.

Beyond CMOS domain is very long-term research. At this stage, no one is quite yet sure what these technologies will be, but whatever they are, they are unlikely to result in sudden transitions. Candidate technologies will almost certainly have to be first integrated heterogeneously with silicon.

6. Key players and experts

For a list of European research centres and companies working in the field of nanoelectronics, see ICT sub-sector report “Integrated Circuits”.

Key industry associations are listed below.

ENIAC:
The European Nanoelectronics Initiative Advisory Council (ENIAC) is the governing structure of the European Technology Platform - a bottom-up initiative that brings together leading European players in Nanoelectronics from industry, research and academia to develop and implement a coherent European vision and strategic agenda for this sector. ENIAC is working in close coordination with European and national public authorities and financial institutions, to implement its Strategic Research Agenda.
www.eniac.eu

ITRS:
The International Technology Roadmap for Semiconductors (ITRS) is the fifteen-year assessment of the semiconductor industry’s future technology requirements. It is sponsored by the five leading chip manufacturing regions in the world: Europe, Japan, Korea, Taiwan, and the United States. The objective of the ITRS is to ensure cost-effective advancements in the performance of the integrated circuit and the products that employ such devices, thereby continuing the health and success of this industry. Emerging technologies are highlighted in two roadmap sections: Emerging Research Devices and Emerging Research Materials.
www.itrs.net

Nanoelectronics Research Initiative (NRI) (US):
NRI is a university-based research consortium looking toward nanoelectronics in the year 2020, cooperatively funded by industry and federal and state governments. NRI's primary goal is to discover the next switch, a new mechanism for computing that goes beyond simply improving today's transistor.
http://nri.src.org/

7. References and Literature

The contents of this report are based on two main references:

ENIAC Strategic Research Agenda (update 2007),
http://www.eniac.eu/web/downloads/SRA2007.pdf

International Technology Roadmap for Semiconductors (ITRS), 2007 Edition, Sections on Emerging Research Devices and Emerging Research Materials www.itrs.net

Additional sources of information:

ENIAC (European Nanoelectronics Initiative Advisory Council) website:
www.eniac.eu

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