# Silicon Nanoelectronics and Beyond: An Overview and Recent Developments

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*This year marks the 40th anniversary of the invention of the first beam-lead device by Lepselter et al. Lepselter and coworkers proposed a method of fabricating a new semiconductor device structure and its application to high-frequency silicon switching transistors and ultra-high-speed integrated circuits. Beam-lead technology, also known as air-bridge technology, has established itself for its unsurpassed reliability in high-frequency silicon switching transistors and ultra-high-speed integrated circuits for telecommunications and missile systems. The beam-lead device became the first example of a commercial microelectromechanical structure (MEMS). Since its inception, MEMS has taken advantage of the evolving silicon technology, resulting in today's nano-electromechanical structure and nano-optomechanical structure. In this paper, an overview of recent developments of silicon nanoelectronics is presented.*

## INTRODUCTION

In April 1965, Lepselter and colleagues[1] proposed a technique of fabricating a structure consisting of depositing an array of thick contacts on the surface of a slice of standard planar-oxidized devices. The excess semiconductor from under the contacts was removed, thereby separating the individual devices and leaving them with semi-rigid beam leads cantilevered beyond the semiconductor. The contacts served as electrical leads in addition to also serving the purpose of structural support for the devices. These devices were called beam-lead devices. In Figure 1, a cut-away cross section of a high-frequency beam-lead switching transistor, proposed by Lepselter et al.,[1] is presented, while Figure 2 shows an isolated monolithic integrated circuit (isolith) fabricated by Lepselter et al. The circuit is a four-input direct-coupled transistor logic (DCTL) gate and consists of four n-p-n transistors.[2]

Figure 3 shows a summary of sensor development activities in the United States since their beginnings in the 1950s.[3] This figure takes into account the materials-oriented research at Bell Telephone Laboratories, Honeywell, and Westinghouse. As part of the development of Lepselter's beam-lead (air-isolated) integrated circuits at Bell Telephone Laboratories in the 1960s, precision silicon etching technology was developed. By the mid-1970s, this technology had been utilized in important ways by the sensor community and had been called "micromachining." Many of these new devices were micro-actuators, micro-sensors, and micro-motors. The integration of these devices led to micro-instrumentation systems on a single chip. The term "microelectromechanical structures (MEMS)" was born in the late 1980s to describe one of the results of the sensor-actuator field.

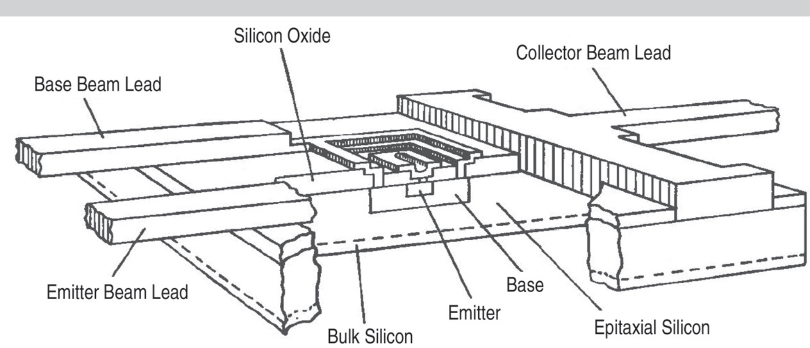


Figure 1. A cut-away cross section of high frequency beam-lead switching transistor.[1]

## EVOLUTION OF NANOELECTRONICS

By definition, the word nano simply refers to a nanometer or one billionth of a meter. A red blood cell measures ~5,000 nm while ten hydrogen atoms, lined up side by side, is equal to 1 nm. One thousand nanometers in any dimension has been accepted to represent nanotechnology. As the physical dimensions approach nano-scale, the material behavior and properties are governed by quantum physics. Examples of the discrepancy in material properties between macro- and nano-scale can be illustrated by gold, which appears yellow at the macro-scale and is seen as red at the nano-scale. Another popular example is carbon; at the macro-scale it is soft and malleable; it becomes harder, stronger, and more rigid than steel at the nano-scale. Further, at the macro-scale, carbon is a poor conductor of electricity. It is a better conductor of electricity than silicon or copper at the nano-scale.[4]

While nanoscience is pure research, nanotechnology is the application of research for the purpose of solving problems and manufacturing new materials.

From a historical point of view, Richard Feynman[5] first wrote about the potential for nanoscience in an influential 1959 talk "There's Plenty of Room at the Bottom." Feynman argued in support of studying concepts to build equipment needed to work at atomic dimensions. In 1981, in a paper titled "Molecular Engineering: An Approach to the Development of General Capabilities for Molecular Manipulation," Eric Drexler[6] built a framework for the study of devices that were able to move molecular objects and position them with atomic precision. In 1989, a scientist in IBM's Almaden Research Center moved individual xenon atoms to form the company's logo on a nickel plate.[7]

Since its inception just about six decades ago, silicon material, as well as device and circuit technology, has rapidly progressed, nearing the ultimate barrier in the micro-electronic and chip level of development. Thus, science has entered into the new era of the atomic realm. Nanotechnology is revolutionizing electronics through the development of nano-enabled systems. These systems incorporate novel nanostructures that integrate functional complexity directly into each individual nanoparticle, enabling the low-cost fabrication of revolutionary high-value, high-performance applications in a broad range of industries from life and physical sciences to information technology and communications to renewable energy to defense. These nanostructures include nanowires, nanorods, nanotetrapods, and nanodots formed from elemental and compound semiconductors. These devices, circuits, and systems exploit the fundamentally new and unique electronic, optical, magnetic, interface, and integration properties associated with materials on the nanometer scale. Possible applications include electronics and information technology, health care, environmental protection, energy, anti-terrorism, and homeland defense.[7]

Nanoelectronics refers to electronics at the sub-micrometer scale. Today, many integrated-circuit components in production already consist of device feature sizes at the nanoscale. Nanoelectronics also includes molecular electronics, which utilizes individual molecules in electronics. Recent advancements in nanotechnology with applications in electronics include carbon nanotubes that can be used in both electronic components and displays, and nanomaterials that can be used in films that make smaller, more flexible displays and improved hard disks.

Nanoelectronics holds promise for developing electronic components beyond silicon. But the impact of nanoelectronics will reach much further than

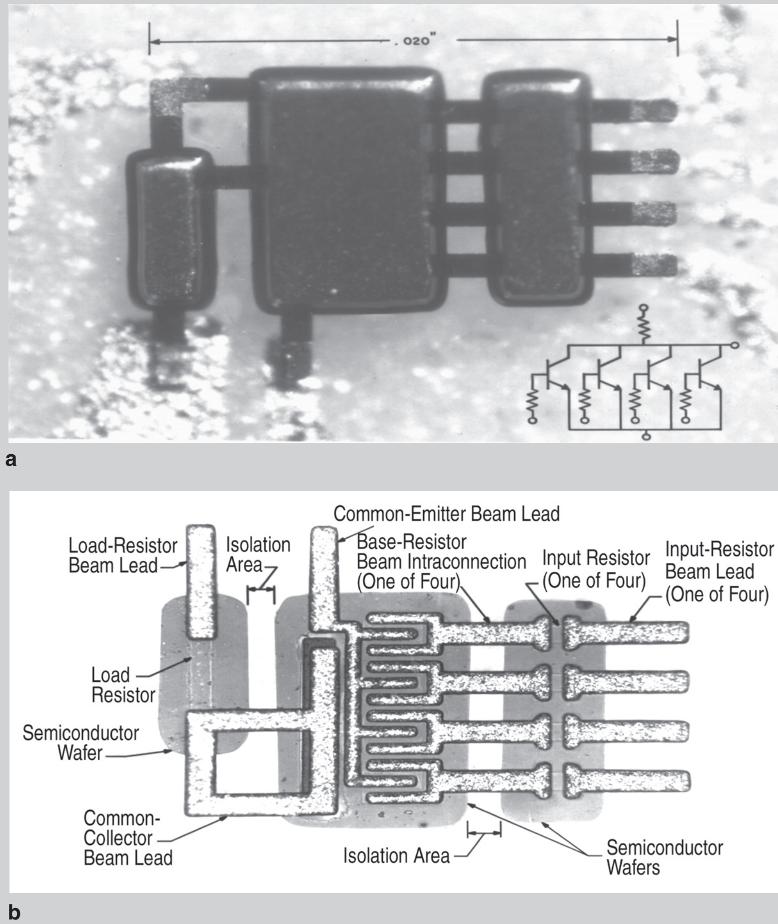


Figure 2. The top and bottom view of a four-input DCTL gate.[2]

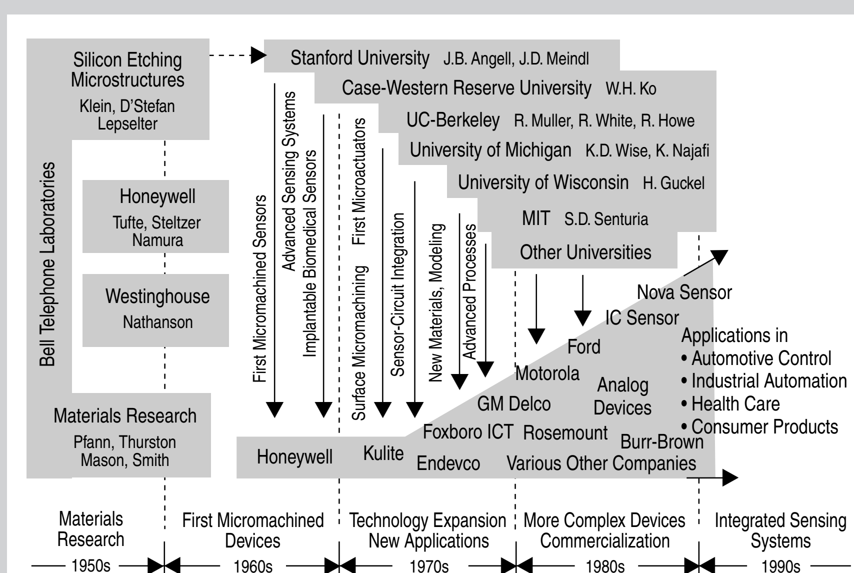


Figure 3. A summary of sensor development activities in the United States since their beginnings in the 1950s.[3]

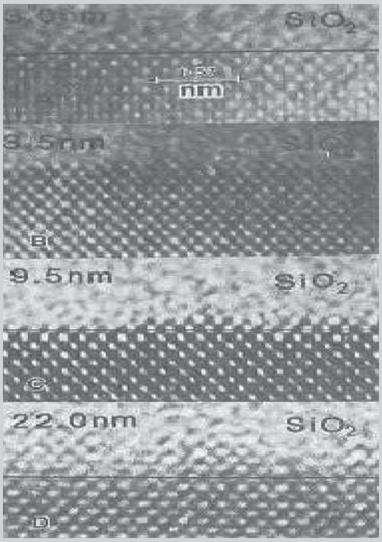


Figure 4. High-resolution transmission electron micrographs of the Si/$SiO_2$ interface for samples of different oxide thicknesses. The oxidation temperature is 800°C.[13]

the next-generation integrated circuits. It is the key to hard disks with large capacity; new forms of nonvolatile memory; smaller, more flexible displays; stronger batteries and power sources; more efficient networks; quantum computing; and more. The most commonly studied nanomaterial today is the carbon nanotube, which comes in both single-walled or multi-walled (tubes within tubes) varieties. Carbon nanotubes are tiny cylinders of carbon atoms. In addition to being stronger than steel, these nanotubes are excellent conductors of electricity. Many experts are of the opinion that photolithography, the process currently used to make chips, will be unable to keep up with the ever-decreasing dimensions of chip features. It is possible that an alternative to photolithography will be based on nanotechnology. Three competing technologies—x-ray lithography, e-beam lithography, and nano-imprint lithography—will allow the creation of patterns down to 100 nm.[8]

Silicon microelectronics has transitioned to silicon nanoelectronics due to cost-performance correlations:[9]

- With decreasing feature sizes, the device cost decreases while its performance increases
- New markets are created by enhanced performance
- Research and development and capital investment are supported by reduced costs

Silicon enjoys natural abundance accompanied by a very mature and reliable technology in the semiconductor industry. The complementary metal oxide semiconductor field effect transistor (CMOS FET), which is the current basis of ultra-large-scale integration circuits, has begun to show fundamental limits associated with the laws of quantum mechanics and the limitations of fabrication techniques. The Semiconductor Industry Association's International Technology Roadmap for Semiconductors shows no known solutions in the short term for a variety of technological requirements including gate dielectric, gate leakage, and junction depth. Therefore, it is anticipated that entirely new device structures and computational paradigms will be required to augment and/or replace standard planar CMOS devices. Two promising beyond-CMOS technologies that each take a very different fabrication approach are molecular electronics and silicon-based quantum electronic devices.

Molecular electronics is based on bottom-up fabrication paradigms, while silicon-based nanoelectronics are based upon the logical continuation of the top-down fabrication approaches utilized in CMOS manufacturing. These two approaches bracket the possible manufacturing techniques that will be utilized to fabricate future nanoelectronic devices. In addition, electronic devices fabricated with organic materials form a dramatically emerging technology targeting applications such as printable large-area displays, wearable electronics, paper-like electronic newspapers, low-cost photovoltaic cells, ubiquitous integrated sensors, and radio-frequency identification tags. These applications are challenging to implement in conventional CMOS technology.[10] In addition, the primary difficulties facing nanodevice fabrication are making contacts to devices on a nanometer scale, interconnecting the nanodevices massively, and providing a means to input and read out data.[11]

## NANOELECTRONICS APPLICATIONS AND OPPORTUNITIES

Nanoelectronic devices being attempted today for logic and processing applications include nanotubes, nanowires, molectronics, spintronics, single-electron transistors, quantum cellular automata, quantum computing, and alternative architectures. For memory applications, magnetic drives and tapes, optical disks, holographic media, magnetic random-access memory (RAM), charge-driven phase change, molecular charge base memory, nanotube RAM, scanning probe systems, MEMS cantilever switch, ferroelectric RAM, and polymer memory are being

**Table I. A Summary of Funding Opportunities for Nanotechnology[15]**

| | Fiscal Year | | | | | |
|---|---|---|---|---|---|---|
| | **2000* Actual** | **2001 Enact/Actual** | **2002 Enact/Actual** | **2003 Enact/Actual** | **2004 Req./Enact** | **2005** |
| National Science Foundation | 97 | 150/150 | 199/204 | 221/221 | 249/254 | 305 |
| Department of Defense | 70 | 110/125 | 180/224 | 243/322 | 222/315 | 276 |
| Department of Energy | 58 | 93/88 | 91.1/89 | 133/134 | 197/203 | 211 |
| National Institutes of Health | 32 | 39/39.6 | 40.8/59 | 65/78 | 70/80 | 89 |
| NASA | 5 | 20/22 | 35/35 | 33/36 | 31/37 | 35 |
| NIST | 8 | 10/33.4 | 37.6/77 | 66/64 | 62/63 | 53 |
| EPA | — | — /5.8 | 5/6 | 5/5 | 5/5 | 5 |
| Homeland Security (TSA) | — | — / — | 2/2 | 2/1 | 2/1 | 1 |
| Department of Agriculture | — | —0/1.5 | 1.5/0 | 1/1 | 10/1 | 5 |
| Department of Justice | — | — /1.4 | 1.4/1 | 1.4/1 | 1.4/1 | 1 |
| **TOTAL** | **270** | **422/465** +72% | **600/697** +50% | **770/862** +24% | **819/961** | **982** |

* All in millions of dollars

attempted. Key industry players focusing on the development of nanoelectronic devices include IBM, Intel, Interuniversity Microelectronics Center, Hewlett-Packard Company, Motorola, Leti, STMicroelectronics, Microelectronics Technology Laboratory, the French National Center for Scientific Research, Nanotube Manufacturers, Nanosys, Carbon Nanotechnologies, Helix Materials Solutions, and Nanodynamics.

It is anticipated that nanoelectronics will play a major role in the development of the following devices/subsystems: logic/processing, memory/storage, interconnects, thermal management, and displays. In the end-user market, the following sectors seem to be of importance: mobile computing, home computing and consumer electronics; enterprise computing and telecommunications; cell phones, global positioning systems and other communication devices; portable recording and display/playback devices; control systems and embedded computing; sensors, smart cards, radio frequency identification, and other disposable products; and military and homeland security.

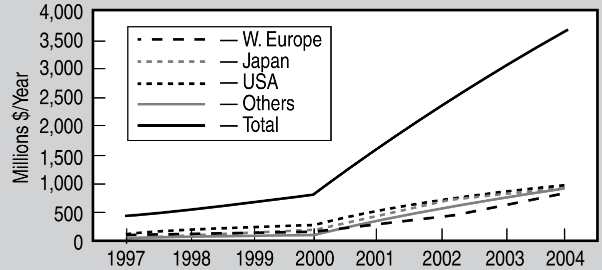


Figure 5. Past government investments for nanotechnology.[15]

Biological and biomedical applications will continue to deploy nanotechnology in drug delivery systems and imaging applications. An example of a revolutionary approach to imaging is being utilized by Given Imaging. Given Imaging[12] is redefining gastrointestinal diagnosis by developing, producing, and marketing innovative, patient-friendly products for detecting gastrointestinal disorders. The company's technology platform is the Given® Diagnostic System, featuring the PillCam™ SB video capsule, a disposable capsule that

**Table II. Possible Device Applications of Nanotechnology[11]**

| Device | Possible Applications | Advantages | Disadvantages | Remarks |
|---|---|---|---|---|
| Single-Electron Transistors (SET) | Logic element | Small size, low power | Sensitive to background charge instability. High resistance and low drive current. Cannot drive large capacitive (wiring) loads. Requires geometries <<10 nm for room-temperature operation | Use of Coulomb blockade in nanocrystal "floating-gate"-type nonvolatile memory demonstrated. May improve retention time. |
| Quantum Dot (Quantum Cellular Automata) | Logic element | Small size | Multiple levels of interconnection across long distance difficult. Room-temperature operation difficult. New computation algorithms required. Method of setting the initial state of the system not available. Single defect in line of dots will stop propagation. | Devices demonstrated at low temperatures. QCA architectures extensively investigated |
| Resonant Tunneling Diode (RTD) | Logic element dynamic memory | Small size | Tunneling process sensitive to small film thickness (tunneling distance variation, leading to process control difficulties. Requires direct current bias, large standby power consumption. Multivalue logic sensitive to noise margin. Speed of RTD circuits likely to be determined by the conventional devices required in the circuit. | Small- to medium-scale circuits demonstrated. Most demonstrations on III-V compound semiconductors |
| Rapid Single-Flux Quantum (RSFQ) Device | Logic element | Very high speed possible | Requires liquid helium temperature. Lacks a high-density random-access memory. Requires tight process tolerance. | Very-high-speed (THz) circuits demonstrated. |
| Two-Terminal Molecular Devices | Logic element memory | Small size | No inherent device gain. Scaling to large memory size may be difficult without gain. Placement of molecules in a circuit difficult and not yet demonstrated. Temperature stability of organic molecules may be problematic. | Sixteen-bit cross-point memory demonstrated. |
| Carbon Nanotube FET | Logic element | Ballistic transport (high speed) small size | Placement of nanotubes in a circuit difficult and not yet demonstrated. Control of electrical properties of carbon nanotube (size, chirality) difficult and not yet achieved. | Device scaling properties not yet explored. Inverter circuit demonstrated. |
| DNA Computing | Logic element | High parallelism | Imperfect yield. General-purpose computing not possible. | |

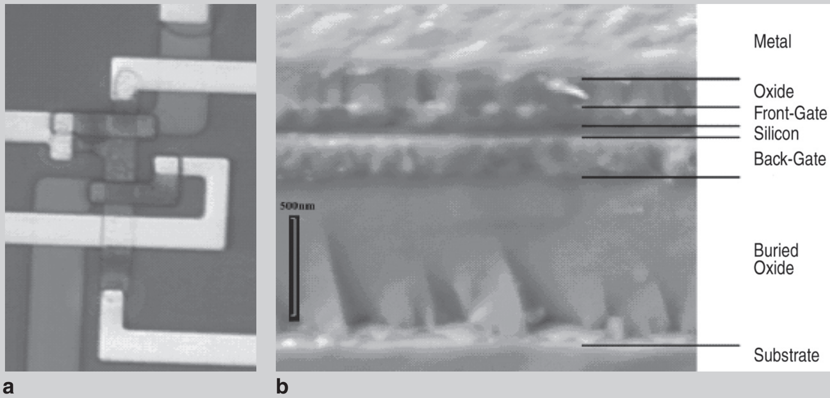


Figure 6. (a) An optical microscope photograph of a signal inverter circuit fabricated with a silicon crystal layer of nanoscale thickness and with control gate electrodes fabricated both above and below the active silicon layer. (b) A scanning electron microscope image of the silicon wafer from which the circuit shown in (a) is fabricated. The electronically active part of the structure is the thin silicon layer sandwiched between the back-gate and front-gate layers in the image.[16]

captures video after it is ingested by the patient. The PillCam SB video capsule is the only naturally ingested method for direct visualization of the entire small intestine. It is currently marketed in the United States and in more than 60 other countries and has benefited more than 122,000 patients worldwide. The company is developing a complete line of PillCam video capsules for detecting disorders throughout the gastrointestinal tract. The PillCam ESO video capsule for visual examination of the esophagus is currently under review by the U.S. Food and Drug Administration, and capsules for visualization of the stomach and colon are under development.

A well-known example of the use of films of nano-dimensions is illustrated in Figure 4. In this figure, high-resolution transmission-electron micrographs of the $Si$-$SiO_2$ interface for various oxide thicknesses in the 2 nm to 20 nm range are presented.[13] Another well known example of devices of nano-dimensions has to do with shallow junction formation in CMOS technology. The Nanoelectronic Device Metrology (NEDM) project of the U.S. National Institute of Standards and Technology[14] is developing metrology for three specific areas of nanotechnology: silicon-based quantum electronics, molecular electronics, and organic electronics. In addition to this project, various federal agencies have committed funds to support research in nanotechnology. A summary of these funding opportunities is presented in Table I. Past worldwide government investments in nanotechnology are illustrated in Figure 5. As can be seen in this figure, the United States has invested as much as many of the countries in the world.

A summary of various possible device applications of nanotechnology is presented in Table II. The challenges posed by each of the device applications are also described in the table. In Figures 6 and 7, some of the examples of silicon nanoelectronic devices are illustrated.

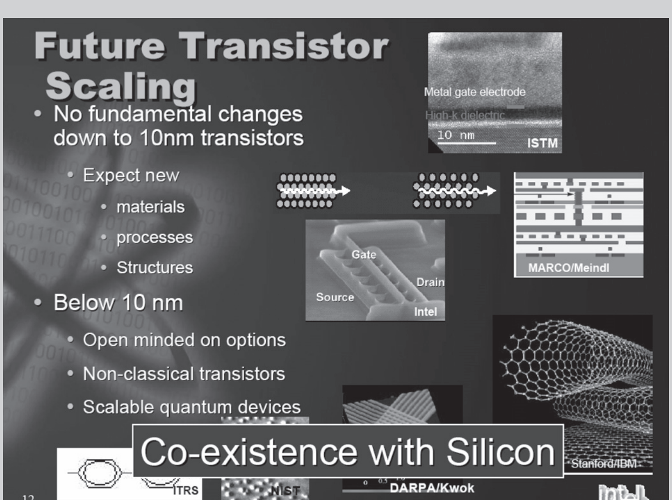


Figure 7. Future transistor scaling.[9]

## CONCLUSIONS

Property-structure correlations will continue to drive nanotechnology. Health and biosciences will dictate the terms of growth in relation to betterment of human living conditions. In order for silicon nanoelectronics to thrive, it will have to seek compromise with other semiconductors. Free-standing nano devices would be difficult to manufacture due to limitations of materials stability, contact problems, and long-term reliability.

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