# Nanoscale Materials and Devices for Future Communication Networks

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## ABSTRACT

New discoveries in materials on the nanometer-length scale are expected to play an important role in addressing ongoing and future challenges in the field of communication. Devices and systems for ultra-high-speed short- and long-range communication links, portable and power-efficient computing devices, high-density memory and logics, ultra-fast interconnects, and autonomous and robust energy scavenging devices for accessing ambient intelligence and needed information will critically depend on the success of next-generation emerging nanomaterials and devices. This article presents some exciting recent developments in nanomaterials that have the potential to play a critical role in the development and transformation of future intelligent communication networks.


## INTRODUCTION

During the last two decades, significant progress has been made in controlling and engineering new materials on the nanometer-length scale — at the level of atoms, molecules, and supramolecular structures. Many of these nanostructured materials have shown tremendous promise as building blocks for scalable, miniature, and energy-efficient electronics, photonics, magnetics, and electromechanical systems to transform computing and communication in the future. Key progress in all these areas will convincingly transform future communications links to facilitate faster data transfer rates for connections with ubiquitous intelligent ambient systems at home, in the office, and in public places. At present, these nanodevices for miniaturized processors, memory, circuits, interconnects, and possibly future self-powered computing systems with unprecedented intelligence, energy efficiency, and scalability are progressively posing an engineering and technological challenge rather than remaining as a field of fundamental research. A highly multidisciplinary endeavor and significant successes in the commercialization of nanomaterials and nanodevices will no doubt lead to strong potential for high economic impact comparable to the telecommunication technology of the 1990s and the information technology growth of the last decade.

In this article we give an overview of the anticipated profound impact of these innovations in nanomaterials and nanodevices in realizing this vision, and the range of factors that are critical to the success of the future communication technologies, computing, and intelligent sensor networks.

## NANOMATERIALS FOR COMMUNICATION DEVICES

### ON-CHIP, CHIP-TO-CHIP, AND FREE-SPACE INTERCONNECTS

Increased demand for seamless connectivity with intelligent ambient systems and unrestricted mobility requires faster data transfer rates, which leads to more memory and computing capabilities required in communication devices while ensuring small form factor and lower power consumption. For more than a decade, a great deal of work has been focused on improving the conventional interconnect technology for on-chip, chip-to-chip, and board-to-board communications by reducing the resistivity of conductors like copper (Cu) and reducing the dielectric constant of interlayer dielectric materials by using low-*k* polymers. As data rates approach 10 billion b/s, the dimension of copper wires approaches the mean free path of electrons in bulk Cu (40 nm at room temperature), resulting in excessive resistivity in the interconnects. This is largely due to the contribution of microscopic imperfections in the Cu wire, that signals traveling distances even as short as 50 cm are severely deteriorated, causing higher thermal dissipation. Consequently, interconnects are considered one of the most difficult challenges gigascale system integration faces. Currently, more than 70 percent of capacitance on a high-performance chip is associated with interconnects, and the dynamic power dissipation associated with interconnects is larger than that of transistors [1].

An additional issue with Cu wire interconnects carrying digital information has been that they are insufficient to provide the necessary connections required by an exponentially growing transistor count, thus impeding the advance of future ultra-large-scale computing. The parasitic resistance, capacitance, and inductance associated with Cu electrical interconnects are beginning to limit the circuit performance and have increasingly become one of the primary

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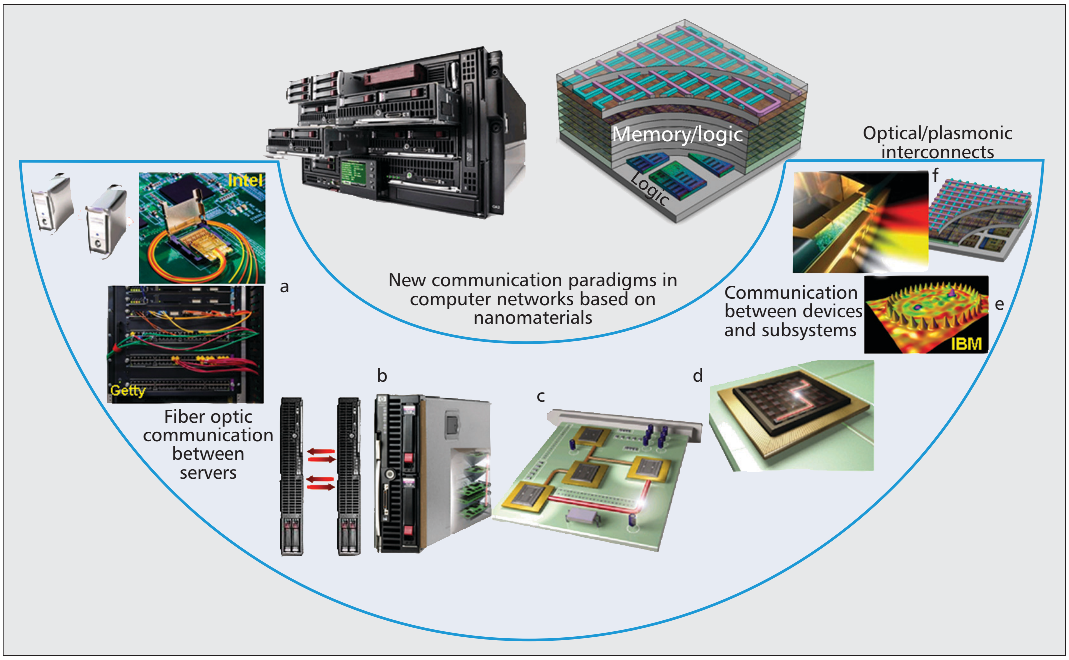


**Figure 1.** *Different interconnect technologies that could benefit from the rapid developments in the field of nanomaterials and devices. Images courtesy of a) Intel Corporation and Getty Images, e) IBM, and f) Nature Publishing Group.*

*Direct integration of an assortment of semiconductor nanostructures in devices and circuits on single crystal surfaces offers attractive opportunities in several areas of high performance communication electronics, optoelectronics, sensing, energy conversion and imaging.*

barriers to the progression of deep submicrometer ultra-large-scale integration (ULSI) technology. Primarily, the signal delay in interconnects has been increasing, becoming a substantial limitation to the speed of digital circuits and resulting in a slowing trend of clock speed in microprocessors. All these issues cannot be resolved with current technologies, and innovative methods and other novel techniques must be pursued to break the *interconnect wall*. One possible interconnect scheme is to use *active* photonic interconnects and free-space optical interconnects. Figure 1 depicts several different interconnect technologies that could benefit from the rapid developments in the field of nanomaterials and devices.

Photonic interconnects such as optical waveguides or fiber optic cables can carry digital data with three orders of magnitude capacity more than electronic interconnects [2]. Unlike electronic data, optical signals can travel tens of kilometers without distortion or attenuation. Furthermore, several dozens of channels of high-speed data, each with a unique wavelength, can be packed into a single fiber, in a technique known as wavelength-division multiplexing (WDM). Today, 40 separate signals, each running at 10 Gb/s, can be squeezed onto a hair-thin fiber. Despite all these attractive characteristics, the reasons photonic links are not widely accepted yet are the high cost of the components, large size, and difficulty of integration with complementary metal oxide semiconductor (CMOS) circuitry.

Current optical communication devices are specialized components made from Gallium Arsenide (GaAs), Indium Phosphide (InP), Lithium Niobate (LiN), and other exotic materials that cannot easily be integrated onto silicon chips. That makes their assembly much more complex than the assembly of ordinary electronics, because the paths the light travels must be meticulously aligned to micrometer precision. In a sense, the photonics industry is where the electronics industry was a half century ago before the breakthrough of the integrated circuit. The logical way for photonics interconnects to move into the mass market is to introduce innovative integration, high-volume manufacturing, and low-cost assembly. Fortunately, several nanomaterials and new nanofabrication methods can play a very important role in monolithically integrating different optical devices on a silicon platform, rather than separately assembling each from diverse exotic materials, as outlined in the following sections.

## Nanoheteroepitaxy for Optical Interconnects

Direct integration of an assortment of semiconductor nanostructures in devices and circuits on single crystal surfaces offers attractive opportunities in several areas of high-performance communication electronics, optoelectronics, sensing, energy conversion, and imaging. Beyond these applications, integration of a range of nanostructures on amorphous surfaces offers unlimited capabilities for multifunctional materials and device integration. In fact, the possibility of low-cost electronics and photonics based on such an approach would dwarf silicon photonics and other competing technologies. The key constraints in growing planar epitaxial thin film of a semiconductor on another single crystal substrate are lattice and thermal expansion coefficient mismatches, material incompatibilities, and differences in crystal structure [3]. These limitations can now be circumvented by growing semiconductor nano-heterostructures that can

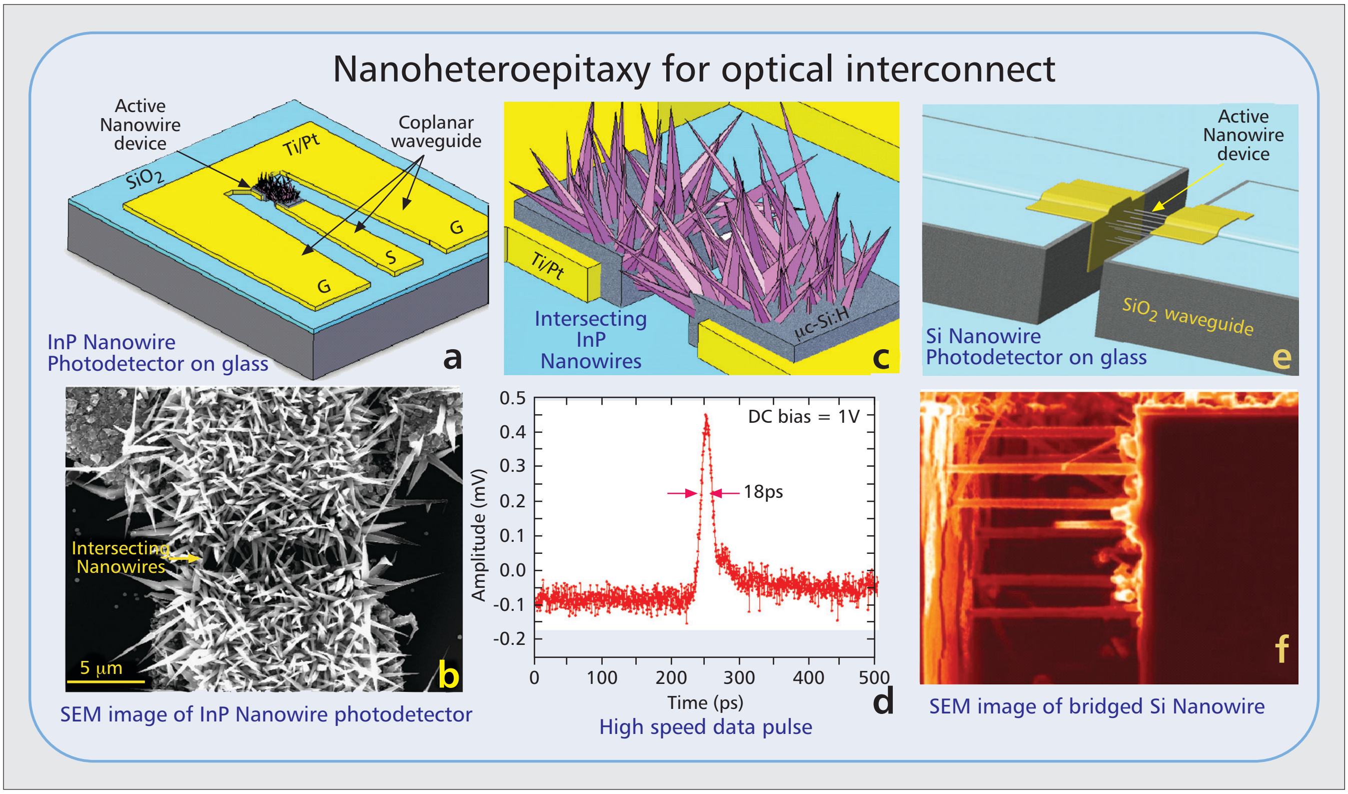


**Figure 2.** *InP nanowire photodetector on a glass substrate: a) schematic diagram; b) SEM image; c) schematic close-up; d) 30 GHz high-speed data pulse generated by the device [6]; e) bridged axial silicon nanowires on an optical waveguide; f) bridged silicon nanowires between a pair of silicon electrodes.*

accommodate large mismatch due to their small crystallite dimensions. Recently, a number of highly crystalline III-V nanowires were grown on wafers with lattice mismatch as high as 8.1 percent [4]. The ability to grow dissimilar materials with large lattice mismatches on a single substrate removes the integration related constraints of incorporating photonics with electronics, and therefore an associated challenge of on-chip electronic-to-optical (E/O) and optical-to-electronic (O/E) conversions for communication and information processing primarily using electrons and the majority of the information transfer using photons. Semiconductor nanostructures with direct bandgap grown on silicon can offer high gain for designing laser diodes as well as superior absorption characteristics needed for high-speed photodetection on a silicon surface.

Yi and coworkers recently reported the heteroepitaxial growth of highly aligned InP nanowires on silicon substrates [5]. More recently, VJ, Kobayashi, and coworkers introduced a new method of synthesizing III-V nanowires on a *non-single crystalline* surface that directly relaxes any lattice mismatching conditions and demonstrated a device for high-speed photodetection based on InP nanowires grown in the form of nano-bridges between prefabricated electrodes made of hydrogenated microcrystalline silicon as shown in Fig. 2a–d [6]. The device was fabricated on an amorphous glass surface and was measured to have a bandwidth above 30 GHz. Grego and coworkers reported the integration of bridged nanowires between a pair of vertically oriented non-single crystal surfaces etched into rib optical waveguides to design nanowire integrated waveguide photodetectors on amorphous surfaces (Fig. 2e and 2f) [7]. These capabilities offer opportunities for ultra-fast low-cost free-space optical interconnect for future computers and servers. Heteroepitaxially grown optically active materials such as III-V and II-VI for integration with mainstream Si technology may enable low-cost, and highly integrated ultra-fast devices due to their high carrier mobilities and optical absorption coefficients. This opens opportunities for a wide variety of applications including intrachip, interchip, and free-space communications. The capabilities of generating and detecting photons by direct bandgap materials on Si substrate, which is known for its low efficiency in electron-to-photon conversion, will bring about a myriad of challenges along with revolutionary opportunities that will impact a large sector of the high-tech industry. Several barriers still remain that impede this technology transition from the laboratory to real-world applications.

## Out-of-Plane Optical Interconnects

Optical pillars and wires along with microphotonics technology were employed to demonstrate external optical interconnects that can connect different parts of electronic chips via air or fiber cables at the expense of a bulky configuration [8]. Unfortunately, optical devices (laser, modulators, and detectors) and light guides are ~1000× larger in physical dimensions than electronic components, and it is very challenging to combine these two technologies on the same circuit. State-of-the-art electronic devices are fabricated with feature sizes in the range of tens of nanometers, and emerging electronic devices such as single electron transistors are designed with sub-nanometer dimensions. On the other hand, optical devices can reach a theoretical size limit on the order of the wavelengths ($\sim$1 μm) if sophisticated techniques such as photonic crystals are used.

## Photonic Crystals

The concept of photonic bandgap crystals has been around for more than two decades. A line defect within a two-dimensional photonic bandgap crystal provides efficient spatial confinement of light, and works as a building block in a variety of routing and processing schemes of light. In contrast, silicon in the form of the CMOS technology platform has been the core driver in microelectronics. Silicon nanophotonics, which allows CMOS platforms to handle light, thus would offer a wide range of photonic functions required for CMOS platforms to push further progress in high-speed data transfer rates. Nanophotonic implementations of wavelength multiplexers and demultiplexers by employing photonic crystals or non-periodic nanophotonic structures offer greatly reduced footprints and enhanced robustness to fabrication tolerances and temperature variations. While the photonic bandgap crystal and silicon nanophotonics are still subject to the diffraction limit of light, photonic devices that use surface plasmon polaritons (SPPs) and/or energy transfer mechanisms relying on optical near-field interactions would pave the road toward ultimate photonic integration beyond the diffraction limit of light.

## Plasmonics for Interconnects

As discussed previously, to overcome the size limitation of photonic interconnects, researchers introduced devices and interconnects based on SPPs, which are electromagnetic waves that propagate along the surface of a conductor supported by the fluctuations in the density of electrons on a metal surface — which can absorb light, travel along the surface, and re-emit that energy. In this manner, plasmonics offers the synergistic bridge between nanophotonics and nanoelectronics. Initially, plasmonics was mainly focused on passive routing of light in waveguides with dimensions much smaller than the wavelength of the light. However, as the propagation length in such high-confinement SPP waveguides is limited to a few tens of micrometers, they have not been considered as a better substitute for high-index dielectric waveguides. It is important to note that the size of dielectric waveguides is limited by the fundamental laws of diffraction, which are orders of magnitude larger than the electronic devices on a chip. Plasmonic devices and their sub-wavelength dimensions are uniquely capable of reconciling this mismatch in size, bridging dielectric microphotonics and nanoelectronics. Plasmonic devices such as nanoscale lasers, modulators, and detectors offer the potential to generate, modulate, and detect optical signals while transporting them at the speed of photons through the same thin metal circuitry. This offers the ability to combine the superior technical advantages of photonics and electronics on the same chip. A big challenge to plasmon-based communication in computer chips is generating light from plasmonic lasers that are electrically biasable and compatible with silicon-based CMOS fabrication techniques. Recent demonstrations of plasmon-enhanced light source and detectors are significant steps toward this goal of realizing new generation of ultrafast nanoelectronics [9].

## Future Prospects of Nanophotonic Communication

Although the recent trend of using multicore processors is providing a temporary respite from stagnation of microprocessor clock frequencies, it has created daunting challenges to programmability, and ultimately drives today's system architectures toward extreme levels of unbalanced communication-to-computation ratios. Interior heat removal capability compounded with a huge deficit in chip input/output (I/O) bandwidth due to insufficient I/O interconnect density has stalled our high-performance gains. The excessive access time of a microprocessor for communication with the off-chip main memory is among the major hurdles holding back ultra-fast computing. Nano-photonics has the potential to offer a disruptive technology solution that will not only enhance the performance of communications and future computers, but will also contribute to a fundamental transformation in the field of computer architecture. Proven ultra-high throughput, minimal access latencies, and low power dissipation of nanophotonic devices remain independent of capacity and distance.

Although individual local interconnects are diminutive, their cumulative length is rather long, and their share in the delays of critical paths and power dissipation is large and growing. For instance, more than 50 percent of interconnect power is dissipated in local interconnects.

While for a distance exceeding a few millimeters energy efficiency for electrical signaling is typically $\sim$10 pJ/b (equivalent to $\sim$10 mW/Gb/s), photonic communication links based on nanophotonics have shown the ability to operate at 100 fJ/b, with potential to reduce the cost to the level of 10 fJ/b. The unique capability of photons for multiwavelength photonic interconnects in the DRAM I/O can continue the scalability advantage that semiconductor industry has been accustomed to in the last few decades. The emergence of multicore architectures and the ever increasing demand for information processing naturally make room for nanophotonics in the field of intrachip and interchip communications.

Unlike prior generations of optical technologies, nanoscale photonics offers the possibility of creating highly integrated platforms with dimensions and fabrication processes compatible with nanoelectronic logic and memory devices, and is expected to have a great influence on how future computing and communication systems will scale. *Nanophotonic interconnects* can potentially

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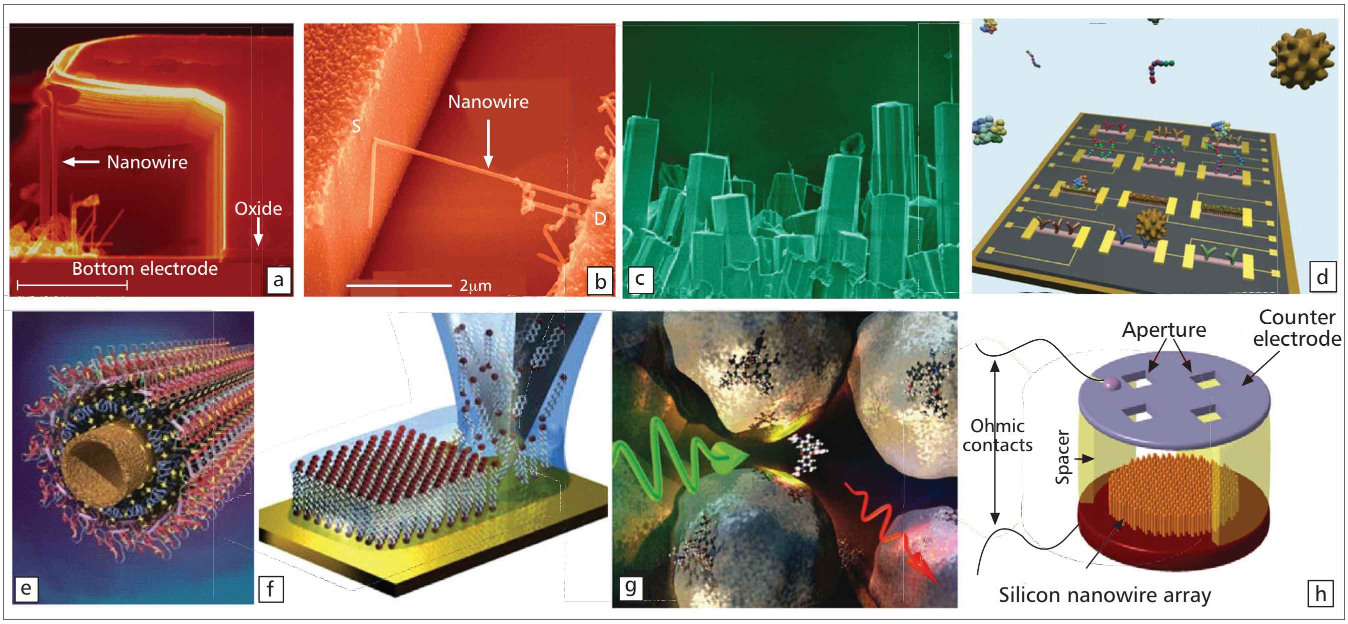


**Figure 3.** *SEM images of sensors designed with: a) vertically bridged nanowires; b) laterally bridged nanowires; c) ultra-sharp Ga2O3 nanowire; d) nanowire FET chem-bio sensor (Image courtesy: Lieber et al. Harvard University); e) carbon nanotube bio-sensor (image courtesy: Pacific Northwest National Laboratory); f) molecular functionalization of sensors using dip-pen lithography (image courtesy: NanoInk Inc.); g) Surface Enhanced Resonant Imaging (SERS) of biomolecules (image courtesy: Royal Society of Chemistry); h) schematic of a nanostructure-based gas ionization sensor.*

revolutionize future computing and communication by bringing parallelism, immense interconnection bandwidths, and wavelength routing capabilities without electrical impedance or crosstalk limitations.

## Nanosensors for Embedded Ubiquitous Intelligence

### Sensing Ambient Intelligence

Future communication infrastructure with embedded intelligent and autonomous devices will be equipped with a large number of robust sensors to ensure seamless connectivity with ambient and intelligent networks. In the recent past, researchers have been actively developing nanoscale sensors, instigating a new era of *ubiquitous nanosensors*. Nanosensors were realized based on the amazing progress in the synthesis of nanomaterials with rationally predictable size, shape, and surface properties resulting in extraordinary sensitivity [10].

When reduced to nanoscale dimensions, many materials reveal new properties that can be desirable for a variety of sensing applications. These attractive characteristics can stem from high surface-to-volume ratios at the nanoscale along with changes in optical properties (reflectivity, absorption, and luminescence), volumetric or surface diffusivity, thermal conductivity, heat capacity, mechanical strength, and magnetic behavior. Many of these effects can be harnessed to develop new sensitive detection techniques. Examples include utilizing the inherent ultra-high specific surface areas of materials structured (or porous) at the nanoscale to enhance the reaction rate or overall reactivity with a desired analyte. A single nanosystem will be able to identify many analytes, in a wide range of backgrounds, with great sensitivity. It is anticipated that in the not-too-distant future, nanosensors will become part of our everyday intelligent environment, collecting and transmitting enormous amounts of information about our health and wellness, life, and environment, bringing a host of benefits to our lives. Potential applications include safe driving systems, smart buildings and home security, smart fabrics or e-textiles, manufacturing systems, transportation, and rescue and recovery operations in hostile environments. Indeed, the inundation of a number of nanosensors is predicted to transform the way we interact and communicate with the environment and our surroundings. The abundance of inexpensive omnipresent sensors and their potential marriage with biotechnology and information technology will radically change human lives and communication with the environment. Emerging research in nanosensors continues to be among the broadest and most dynamic areas of science and technology, bringing together numerous researchers in biology, chemistry, physics, biotechnology, medicine, and many areas of nanoengineering. However, the widespread applications of nanosensors may also bring about a myriad of challenges in processing and analyzing the sensor data, and interpreting the information in an efficient manner.

Integration of various components into sensor systems will be a significant technical challenge. The real challenge in nanosensors now is to create the integrated nanoelectronic and micro-electronic circuits in the form of a universal platform that will allow speedy deployment as new needs emerge, and new intuitions and understanding for rapid transmission and processing of colossal sums of data. Practical meth-

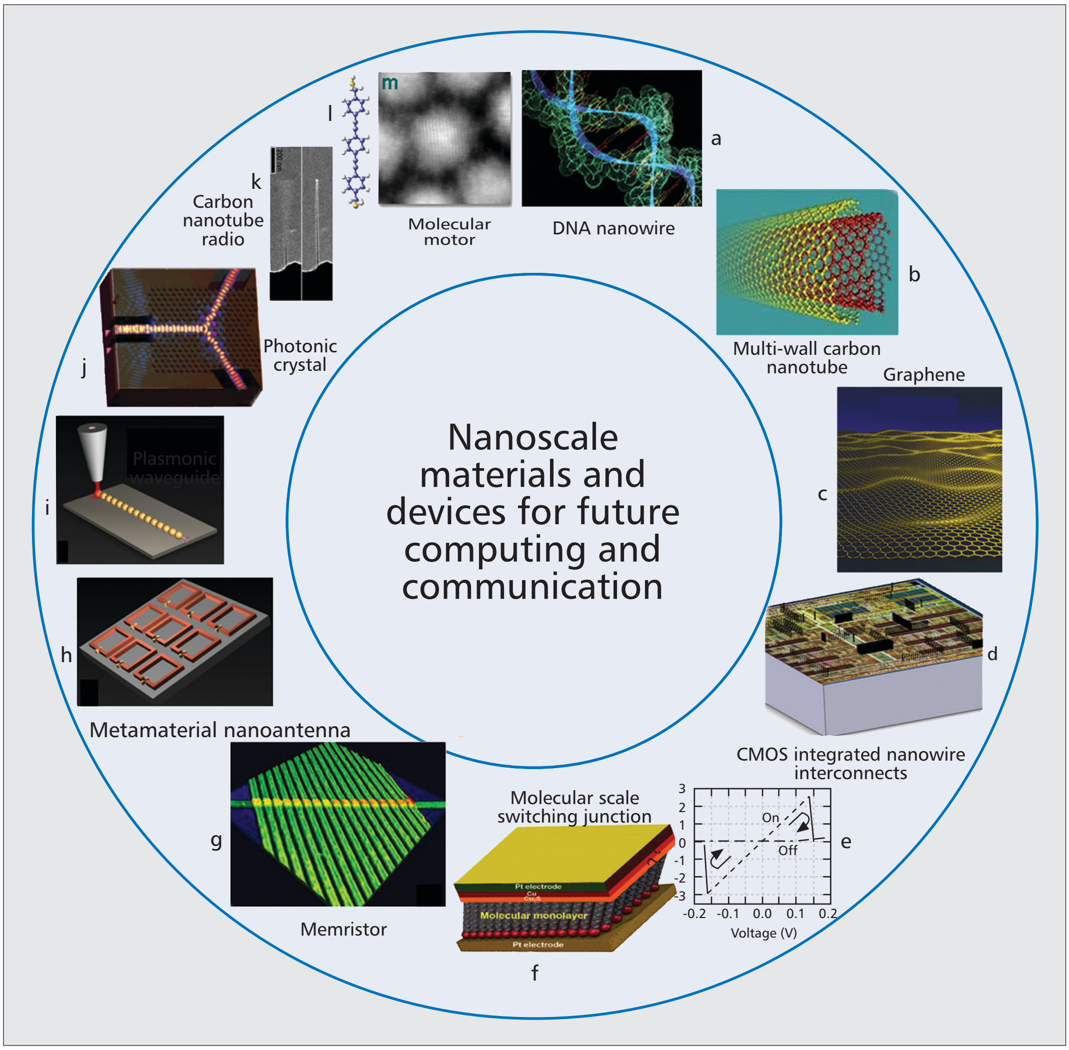


**Figure 4.** *Various emerging nanomaterials based communication devices and components: a) DNA can be used as a computing device as well as scaffolds to generate highly organized and complex superstructures through self-assembly; b) CNTs; c) graphene has the highest mechanical strength, enormous intrinsic mobility, zero effective mass, and an electron can travel for micrometers evading scattering at room temperature; d) metal catalyzed nanowires can be used to connect two chips by growing them in the shape of vertical bridges; e–f) molecular electronic switching junctions and their current-voltage property; g) an array of 17 purpose-built oxygen-depleted titanium dioxide memristors [12]; h) nano-antenna based on metamaterials; i–-j) plasmonic and photonic crystal waveguides capable of confining light to sub-10-nm dimension; k) a nanoscale CNT radio; l–m) molecular scale machines: molecular motors. Image courtesy: A. Zettl, University of California at Berkeley.*

*At the time of writing this review, major theoretical fundamentals have been laid and numerous experiments have been performed, placing the field of nanosensors on a sound technological footing.*

ods for integrating dissimilar materials and devices on a substrate need to be developed. Monolithically integrated nanoscale semiconducting materials, with diverse bandgap and electrical and optical properties, could offer the ultimate range of capabilities in nanosensors. The realization of a ubiquitous nanosensor with low-powered and self-powered computing networks could enable a vast number of novel applications and possibilities of ultra-low-power wireless sensor networks that have not been possible before. Although many of the exciting developments are only recent, the basic conceptual issues have now been widely debated and reasonably clarified. At the time of writing this review, major theoretical fundamentals have been laid and numerous experiments have been performed, placing the field of nanosensors on a sound technological footing. Figure 3 presents some of the nanomaterials-based sensors demonstrated by the research community in the recent past.

## Nanomaterials for Computing

### Materials for Computing Logic and Memory

In order to miniaturize devices beyond the ultimate limit for conventional CMOS devices, new concepts such as molecular scale electronics [11], memristors [12], low-dimensional semiconductors, and organic structures and single-electron transistors are being developed as replacements to Si-based technologies to address the ever increasing communication speed that requires

A direct byproduct of research in molecular electronics is the demonstration of a new electrical element called the memristor that not only behave like a resistor, which simply resists the flow of electric current, but also display the capability to remember the last current it experienced.

increasing computational capability with limited power. Consequently, nanoelectronics beyond CMOS will take very different approaches in both active device structures and interconnects. This will require new nanomaterials and interconnect innovation, fabrication techniques, and, most important, fundamental understanding of the interface with devices, low-/high-frequency carrier transport properties, and long-term device reliability.

The rapid advancements in the creation of nanometric devices will push the limit of miniaturization to unprecedented levels and possibly exhibit new properties stemming from coupling standard electronic components with unconventional electronic materials such as molecules, redox active proteins, semiconductor nanocrystals, nanotubes, grapheme, chalcogenides, and even organic materials such as DNA [13], to name but a few (Fig. 4). One interesting approach to device miniaturization is molecular electronics, which utilizes single molecules or small groups of molecules as components in electronic devices; with feature lengths as small as 1 nm, it holds the promise of allowing the next generation of device scaling into the nanoscale range. These new devices must be integrated into complex information processing systems with billions and eventually trillions of parts, all at low cost. Fortunately, these molecular-scale components lend themselves to relatively large-scale manufacturing processes based on chemical synthesis and self-assembly techniques. By taking advantage of these key tools of nanotechnology, it may be possible to put a cap on the amount of lithographic information required to specify a complex system, and thus a cap on the exponentially rising cost of semiconductor manufacturing tools.

## Memristors

A direct byproduct of research in molecular electronics is the demonstration of a new electrical element called the memristor that not only behaves like a resistor, which simply resists the flow of electric current, but also displays the capability to remember the last current it experienced. In the world of integrated circuits, this ability to remember the last current would usually require many different components. Williams and coworkers, inventors of memristors — the fourth fundamental circuit element along with capacitor, resistor, and inductor — believe that each memristor can take the place of 7 to 12 transistors and hold its memory without power [12]. In contrast, transistors require power at all times, so there is a significant power loss through the leakage currents. For decades, attempts to build an electronic intelligence that can mimic the amazing power of a human brain have seen little success because of this missing crucial electronic component — the memristor. By combining the properties of memristors with those of capacitors and inductors to produce compound devices called memcapacitors and meminductors, complex processors resembling the human cortex synapses can be developed with a packing density of about $10^{10}/cm^2$ — 10 times more than today's microprocessors can offer. It is now speculated that it would be possible to implement more than 50Gbytes of low-power memory in mobile devices in the near future based on memristors.

## DNA Electronics

Among a few other organic nano-materials, DNA is currently regarded as an ideal scaffold for directed organization of materials at the nanoscale, thanks to its intrinsic physico-chemical properties. For instance, its length and sequence can easily be defined by enzymatic and synthetic methods with nanometric precision as each base pair contributes about 0.34 nm to a linear DNA strand. Furthermore, the DNA sequence can be programmed to generate highly organized and complex superstructures through self-assembly. Lastly, the propensity of two complementary DNA strands to hybridize into a duplex even when removed from their native environment adds an important recognition element that can be exploited for guiding the interaction with surrounding objects. Kiehl and coworkers used DNA, peptides, and proteins as scaffoldings for self-assembling nanoparticles, carbon nanotubes, and molecules into electronic circuitry [14]. This approach could be used to integrate novel devices at densities far beyond those possible with lithographic techniques. Several studies on DNA exhibit a range of electron transport behavior, which is currently dependent on the experimental conditions. For instance, it has been demonstrated that DNA can act as an insulator, a semiconductor, a conductor, and even a superconductor — offering opportunities for future bio-compatible devices and circuits.

## Carbon-Based Nanomaterials

Carbon-based nanomaterials are currently considered among the wonder materials expected to have a profound impact on future electronics, photonics, biomedical, energy storage, and conversion devices. Carbon nanotubes (CNTs) are 10 times as strong as steel with one-sixth the weight. CNTs, which are rolls of one-atom-thick carbon sheets, show great potential in addressing some of the key interconnect challenges in future generations of technology, when copper conductivity will degrade substantially because of size effects, and thereby extend the lifetime of electrical interconnects. Some of the fascinating properties of carbon nanotubes include very large current conduction capacity, large electron mean free paths, resistance to electromigration, high mechanical strength, and stability. Graphene, which is a one-atom-thick carbon sheet, is the thinnest material known to date with the highest mechanical strength, enormous intrinsic mobility, zero effective mass, and an electron can travel for micrometers evading scattering at room temperature. This magnificent material can sustain six orders of magnitude higher current densities than copper, shows record thermal conductivity and stiffness, is impermeable to gases, and reconciles such conflicting qualities as brittleness and ductility. Relativistic electron transport in graphene makes it unparalleled in speed for applications in ultra-fast logic, detectors, sensors, and communication circuits.

Other nanodevices currently being studied include nanomagnetics for spintronics, nanomaterial-based phase-change memory, and cellular

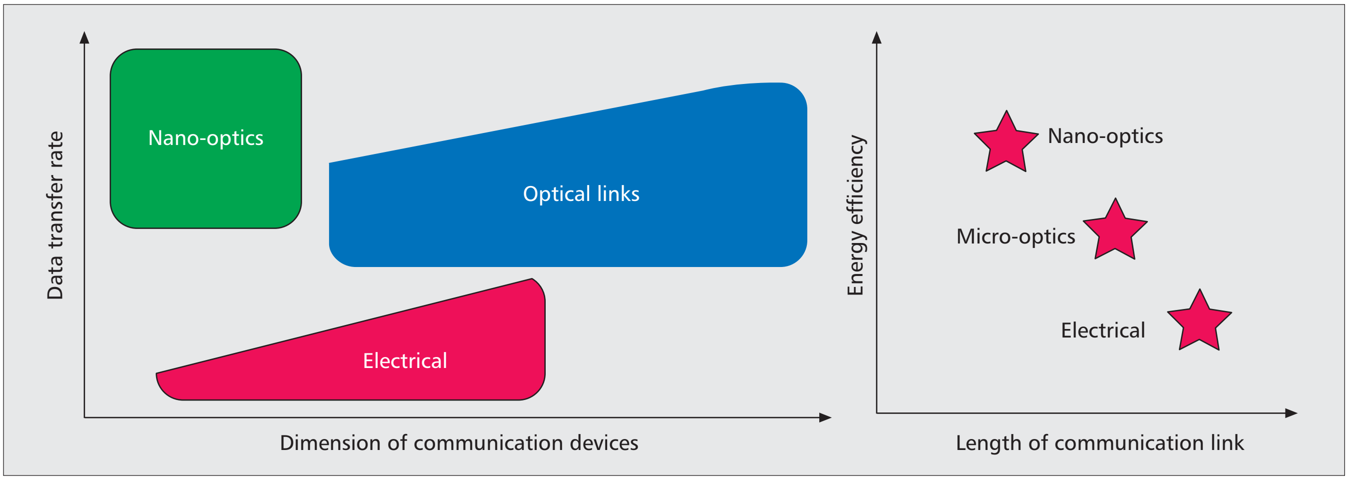


**Figure 5.** *Performance of communication links with current and emerging nanoscale devices and systems.*

automata realized with extremely low levels of electrical currents or charges. Nanomagnetics provide an opportunity to realize zero-energy switching logic gates and memory. Phase change memory (PCM) is considered one of the most promising candidates for next-generation non-volatile memory, based on its excellent characteristics of high speed, large sense margin, good endurance, and high scalability. *Nanoscale quantum dots*, *wires*, and *wells* in resonant nanophotonic structures can provide extremely strong modulation and switching effects with low power excitations. The combination of quantum confinement for electrons with the nanoscale confinement of photons may lead to very exciting possibilities in optical switching. Such switches could operate at very high speeds with energy cost per bit much lower than electronic approaches, enabling greater intelligence in the on-chip communication networks that are crucial for advanced computing architectures. Conventional semiconductor flash memory devices require relatively large program/erase voltages (exceeding 10 V); hence, the amount of energy required to store one bit of information exceeds 10 fJ, whereas the energy required to store one bit of information in a volatile memory (SRAM) cell (~1 V operation) is less than 1 fJ. Recently, nano-electro-mechanical memory (NEMory) cell designs have been proposed and demonstrated [15]. These can be very compact and operate with low voltages (less than 3 V) to achieve low program/erase energy (<1 fJ). The device is another strong candidate for future embedded non-volatile memory applications because it potentially offers a dramatic reduction (more than 100 times) in program/erase energy.

Computing today is facing a catastrophic power crisis that has stalled progress across all scales — from handheld devices and personal computers to supercomputing systems. Future advancement is simply too challenging with conventional semiconductor scaling, and breaking this barrier, the so-called *power wall*, will clearly require paradigm shifting innovations and transformative opportunities that can only be created by fundamental breakthroughs in nanoscale science and technologies. At the same time, to deal with the inaccuracies and instabilities introduced by fabrication processes and the tiny devices, future nanomaterial-based computer architectures have to be able to tolerate an extremely large number of defects and faults. This will lead to fault-tolerant architectures for the ultra-large integration of highly unreliable nanometer devices. A significant roadblock to wide-scale integration of functional nanomaterial-based devices is the difficulty in forming contacts to them, controlling their surfaces, and purifying them to ensure identical physical and electrical properties. In addition, in all practical devices, it is important to pattern nanoscale electrical contacts and interconnects and to fabricate low-resistance Ohmic interfaces to the devices. All these challenges are limiting the immediate applications of these materials and devices in current technology.

## Conclusion: A New Era of Nanomaterials

Nanomaterials — in both unrefined and more advanced and engineered forms — are the key to future technology development and industrial revolutions, and thus to better and more secure societies. The ages of ancient civilizations are known to be categorized by their materials. Different eras of history are named after the materials that defined them, for example, the Stone Age, the Bronze Age, and the Iron Age. Truly, the present age will be known as the Nanomaterials Age, as they should provide our society the necessary tools to address many pressing technological barriers. Indeed, in the last decade, nanoscience has reached the status of a leading science with fundamental and applied implications in all basic physical sciences, life sciences, and earth sciences, as well as engineering and materials science.

Several innovations based on nanoscale devices have the potential to play a unique and important role in enhancing the data transmission speed of future communication systems. Consequently, the performance of communication links is experiencing an impact as depicted in Fig. 5. This graph shows the map of energy efficiency and data transfer rate with the dimen-

Resolute effort on overcoming the roadblock to wide-scale and cost-effective integration of functional nanomaterials in communication systems, and understanding their environmental impact, are likely to keep the scientific community occupied in the next decade.

sions of different device technologies. In the past, devices were relatively slow and bulky. The semiconductor industry has performed an incredible job in scaling electronic devices to nanoscale dimensions. Unfortunately, interconnect delay time issues provide significant challenges toward the realization of purely electronic circuits operating above several gigahertz. In stark contrast, photonic devices possess enormous data-carrying capacity. Unfortunately, dielectric photonic components are limited in their size by the laws of diffraction, preventing the same scaling as in electronics. On the other hand, plasmonics and emerging quantum communication techniques offer precisely what electronics and photonics do not have at present: the size of electronics and the speed of photonics. While at this stage it is impossible to predict the eventual timeline of deployment and applications of new nanodevices in scalable commercial systems, resolute effort on overcoming the roadblocks to wide-scale and cost-effective integration of functional nanomaterials in communication systems, and understanding their environmental impact, are likely to keep the scientific community occupied in the next decade.

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