22
Nanotechnology for Consumer Electronics

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22.1
Introduction

Advances in the cost and physical scale of computing power have enabled devices geared at a consumer market to carry considerable onboard processing capability. In turn, low cost has spurred mass adoption of handheld and smaller computing products. Many devices that started as box-like, single purpose devices – like landline phones, stereos, and televisions – have since evolved into lightweight, low-profile, and cross-functional products. We have already entered an age of ubiquitous smart consumer devices. Smartphones, nominally a replacement for landlines of old, offer the widest range of functions and services, though function-specific products with onboard computing are surging in popularity. Wearables, including fitness monitors, as well as smart sensors and controls for the home, such as automated thermostats, have seen shipment numbers more than triple year-to-year [1].

Innovations at the nanoscale will play a significant role in achieving future consumer devices: nanostructured systems offer electronic performance beyond what is possible with current very large-scale integrated circuits; even devices that do not require significant computing power stand to benefit from improved efficiency achieved using nanostructured materials. Moreover, by enabling the possibility of devices that are low cost and simultaneously flexible, transparent, and lightweight, nanostructured solutions are appealing to nearly any device system. For instance, the future of display technologies is in flexible, low profile, portable displays, many of which will be specifically designed for virtual reality. Interesting optoelectronic properties available at the limit of material thickness, including near-transparency and a direct bandgap, could be pivotal in realizing low-cost, high-performance virtual reality.

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What is nanotechnology? For the purposes of this chapter, we will use the definition, provided by the US National Nanotechnology Institute, that nanotechnology must involve one of the following aspects:

1) Research and technology development . . . in the length scale of 1–100 nm.
2) Creating and using structures, devices, and systems that have novel properties and functions because of their small size.
3) Ability to control or manipulate on the atomic scale.

Consumer devices both present and future rely on a few underlying technologies: most will contain some combination of processing electronics, energy storage, communications hardware, sensors, and displays. The future of processing electronics is covered in depth in other chapters. For other enabling technologies for future consumer electronics – communications, energy storage, displays, and sensors – we discuss the challenges associated with each, and explore ways in which nanoscale solutions may solve these problems and introduce new device possibilities.

First, we briefly introduce two-dimensional materials, one of the fundamental nanoscale elements that will influence the future of pervasive consumer electronics and sensors.

22.1.1
2D Materials and Flexible Electronics

The considerable appeal of nanoscale electronics for consumer applications stems from their potential to be both flexible and transparent without sacrificing performance.

Two-dimensional materials – single-to-few atom-thick layers which are covalently bonded in the plane – span ballistic conductors, such as graphene, direct bandgap semiconductors, including molybdenum disulfide (MoS_2), and dielectrics (hexagonal boron nitride, hBN). Also called van der Waals (vdW) materials, these materials may be stacked in sequence to form *heterostructures* of multiple two-dimensional materials, each with different properties, enabling familiar device technologies including transistors and diodes [2,3]. Not only are such all-two-dimensional-material devices merely nanometers thick, thus transparent and flexible, they also offer performance gains relative to conventional metal oxide semiconductor field effect transistors (MOSFETs), including ON/OFF current ratios of $\sim 10^6$ [2] and reduced short channel effects, such as leakage current, that plague silicon integrated circuit FETs due to ever-shortening channel lengths. For this reason, among others, two-dimensional materials are hailed as the future of transistors and a possible way forward for Moore's Law [4,5]. However, manufacturing challenges stand in the way of expansive industrial adoption of vdW materials.

By leveraging phenomena such as quantum tunneling that are uniquely available to low-dimensional materials, vdW material transistors may offer up to two orders of magnitude lower power consumption than silicon transistors [6].

Diminished cooling demands [7] compound the advantages of vdW transistors relative to silicon-on-insulator transistors.

Not only is energy efficiency desirable from a sustainability perspective but also for consumer devices, less power-hungry electronics mean greater life between charges and opportunity for a smaller onboard energy storage system. Thermal management has become a limiting factor in the performance of modern chips; by greatly reducing the need for heat sinks and onboard thermal distribution in consumer electronics, energy-efficient vdW electronics can enable new device form factors.

Further reading on two-dimensional materials may be found in Part Three of this book.

22.2 Communications

Communication links, particularly wireless links, are becoming essential for an ever-larger range of consumer devices. Smart phones, laptops, and tablets generally include a range of high data-rate wireless protocols, such as wifi, cellular, and bluetooth; other devices have wireless controllers or peripherals, or internet links for remote monitoring and control. Since almost all these devices are battery powered, low power consumption is a critical requirement, and the communication links are often one of the most power hungry functions. For many devices, size is also highly constrained, and as with all consumer devices, the ability to manufacture very large quantities at low unit cost is essential. Trends in wireless communications for consumer electronics include the use of higher frequency bands to increase bandwidth, the integration of increasing numbers of wireless protocols within single systems, multiple antenna systems for space division multiplexing, and the use of wireless optical (or infra-red) links. Nanotechnology is already inherent in communication modules through the ubiquitous use of low cost, highly functional silicon integrated circuits. However, nanoscale devices are also showing promise in other components of these systems.

All radio transmitter circuits, and all but the most primitive receivers, require oscillator circuits. For consumer devices, the radio carrier frequencies, and thus the required oscillator frequencies, are mainly in the 1–2.5 GHz range. High performance depends on these circuits having a high quality factor Q, which is essentially a measure of how precisely the oscillation frequency is defined. To achieve high Q, oscillators often incorporate quartz crystal mechanical resonators; however, these cannot be monolithically integrated, and thus add to cost, size, and complexity. It has for some time been recognized that MEMS (microelectromechanical systems) devices could provide the combination of high Q performance and integration potential. A well-known review by Nguyen *et al.* [8] proposed a range of functions in radio transceivers where micromachined components could offer advantages; besides resonators for frequency references, these included switches, filters, high Q inductors, varactors (variable capacitors), and antennas. High Q MEMS resonators have been successfully developed, but their size is excessive compared to the electronic components with which they are integrated, and achievable frequencies are limited. Further miniaturization to the NEMS (nanoelectromechanical systems) scale inherently reduces these limitations. By 2005, NEMS resonator frequencies, using silicon carbide structures, were reaching 1 GHz [9], well above what has been achieved with equivalent MEMS devices. However, achievable Q values were shown to drop with miniaturization, because of increased surface–volume ratio and consequent damping effects, and this was identified as a key challenge for NEMS.

Later, resonators based on suspended graphene diaphragms were demonstrated [10]. The graphene structure provides strong electromechanical coupling, and an oscillator Q of ~4000 was achieved, although at a frequency of only 50 MHz. (A radio oscillator is a resonator incorporated into an amplified feedback loop, and typically has much higher Q than the resonator itself). The device's structure also allows oscillator tuning, and a tuning range of 14% was demonstrated. Bartsch *et al.* [11] reported monolithic integration of a NEMS tuning fork resonator with a FET receiver circuit. They demonstrated electromechanical demodulation of frequency modulated signals at >100 MHz, using the high Q (800) of the NEMS oscillator at near atmospheric pressure, with low power consumption (<1 mW).

A specific communication capability that has added greatly to the functionality of consumer electronics is the GPS (global positioning satellite) receiver for location determination. Early portable GPS receivers, developed for military applications in the 1980s, weighed over 20 kg; orders of magnitude size reduction have been achieved largely through two advances: the clock speed of silicon microprocessor units increased to the point where the GPS signal processing could be done digitally, allowing the use of silicon integrated circuits, and replacement of the GaAs MMIC (monolithic microwave integrated circuit) analogue components with Si also became possible [12]. Further miniaturization and power reduction will depend on the same advances as for the other radio receivers and digital processors in consumer electronics, and thus are likely to benefit from advances in nanoscale components and materials. For example, performance improvements in GPS radios have been demonstrated by the use of MEMS resonators [13], although frequency stability was insufficient for practical application. The use of NEMS devices in this application would decrease size and power consumption, and could make temperature control more practical, helping to overcome the frequency stability problem.

Antenna sizes are largely determined by operating wavelength, and for current and anticipated radio frequencies these are not going to be at the nanoscale. However, nanoscale materials can offer performance benefits in antenna structures, particularly for antennas on flexible substrates. One of a number of reports of the use of carbon nanotube (CNT) materials in patch antennas is found in [14]. They developed CNT bundle-based patch antennas for wearables. The advantage is reduced weight, as well as increased flexibility, compared to metal structures. Significant polarization dependence was seen according to the

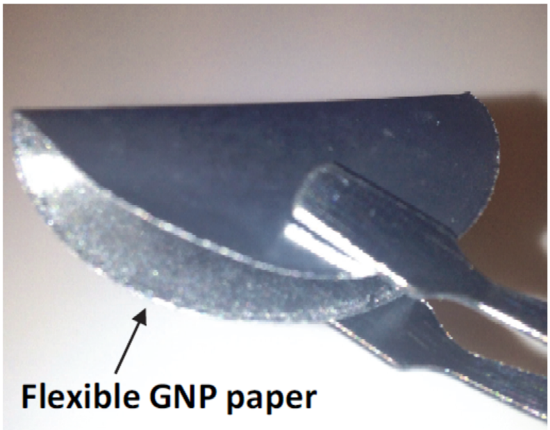

Figure 22.1 Photograph of a 47 mm diameter sheet of graphene nanoplatelet paper (GNP) held in tweezers, after annealing and compression processes, illustrating its flexibility [15].

orientation of the nanotubes, which may offer some additional design flexibility. The antennas were for X-band operation (10 GHz); this is well above most present-day requirements, but future consumer systems are likely to exploit ever-higher frequencies. Gain was still less than for an equivalent copper antenna, but this was attributed to the limited CNT thickness that could be achieved (about 5 um) compared to the Cu thickness (17 um) and the electromagnetic skin depth at the operating frequency.

A related application is RF (radio frequency) shielding. The use of nanomaterials impregnated into flexible substrates can provide shielding between different RF modules, or screening from external interference, in a format compatible with wearables and other flexible devices. In Ref. [15], the use of graphene loaded paper, shown in Figure 22.1, was reported to achieve high conductivity for flexible RF shielding material. Good shielding effectiveness was measured (≈55 dB) for frequencies up to 18 GHz.

In addition to the peripheral components and systems discussed above, nanotechnology is also showing promise for RF circuits based on nonconventional transistor technology. For example, CNT-based thin film transistors (TFTs) can be useful for flexible circuits. In Ref. [16], semiconductor-enhanced CNTs are used to produce high performance TFTs with cut-off frequencies as high as 170 MHz, indicating the potential for at least some RF applications. More recently, flexible graphene transistors with cut-off frequencies up to 3 GHz were reported [17], and these were used to implement a mechanically flexible, primitive frequency modulation transmitter operating at 2.5 GHz. The reported system, illustrated in Figure 22.2, also used a graphene speaker for audio output at the receiver.

Finally, pressure on spectral availability and bandwidth is encouraging the exploration of alternative systems for wireless communications in consumer devices, such as visible or infrared communications. Nanostructures and devices

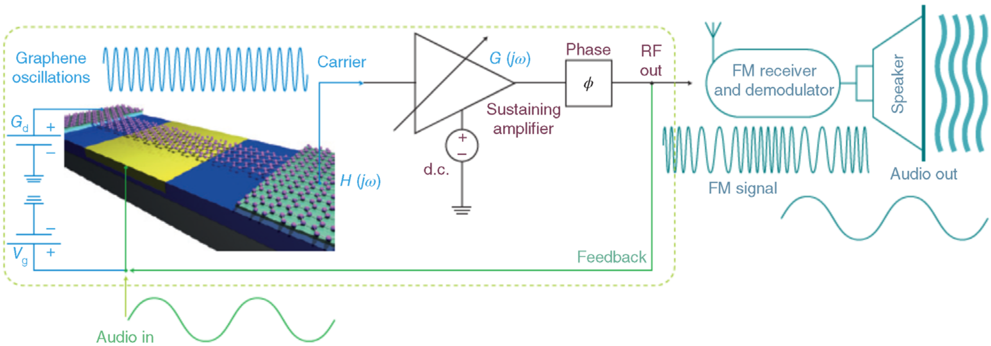

Figure 22.2 Schematic of graphene transistor-based modulator in radio transmitter module [17].

can enable many components for such systems. For example, Luzhansky *et al.* [18] reported a mid-wavelength infrared (MWIR) system for low weight, free-space communication. The source was a quantum cascade laser, a device in which nanostructuring is an essential requirement. The device demonstrated improved tolerance to atmospheric turbulence compared to conventional near-infrared systems.

As nanostructured elements become more integrated in communication systems, we can expect to see continued advantages in reduced power consumption through more efficient high Q oscillators, reduced weight using improved shielding and antenna materials, new operational frequency bands, and new modes of implementation, such as in flexible devices.

22.3 Energy Storage

Some amount of onboard energy storage is critical to any stand-alone powered device. Traditionally, batteries have been the exclusive means of onboard energy storage, and their high specific energy density enables long operation times between charges. However, batteries are subject to degradation at each charge/discharge cycle due to chemical modification of the electrodes. Recently, supercapacitors have attracted interest for their ability to deliver power densities of tens of kilowatts per kilogram, and tens of thousands of charge/discharge cycles without degradation, both orders of magnitude higher than batteries provide. Supercapacitors are potential storage solutions for applications in which the device largely sits idle but is subject to occasional and rapid power demands, for instance for incident sensing and data transmission. Such modes of operation are typical of Internet-of-Things devices, and have been enabled by recent advances in reducing the sleep-mode power consumption of communication circuits. While improvements to energy density and power density are boons to any application, the improvements in both that have been achieved using nanostructured devices are enabling new applications in the consumer device sphere that require energy densities and power densities previously inaccessible in a small form factor device. Recently, a boom in wearable electronic devices aimed at consumers – driven largely by the fitness market, and followed by accessory-scale mobile devices – has brought a commensurate demand for high-performance portable energy storage. In many devices, onboard energy storage need only power the device for a day, and may be rigid; in contrast, wearable devices require not only high energy density but also low profiles (to minimize invasiveness), flexibility (for ruggedness, form factor, and packaging considerations), and transparency (e.g., for displays). By offering inherent mechanical flexibility, limited optical absorption, and extraordinary surface-area-to-volume ratio, low-dimensional and nanostructured materials are attractive choices for electrodes and supercapacitors in consumer device-scale energy storage [19–21].

Nanoscale innovations have been able to contribute to battery performance with improved electrode materials. When considering electrode materials, the ability to host large numbers of ions is critical. In this regard, its high surface-area-to-volume ratio serves graphene well, as it is capable of hosting twice as many Li+ ions as bulk graphite [22]. However, in-use degradation of graphene cripples its feasibility as an electrode material. Ions must shuttle between electrodes in order to make the battery useful, and it is here that graphene suffers. Reduced graphene oxide – a form of graphene made by chemically expanding bulk graphite to facilitate exfoliation, and reducing the final graphene oxide product – undergoes a chemical reduction upon the initial implantation of lithium ions, becoming passivated and restricting ions from traveling between electrodes [23,24]. The ion-induced degradation limits the efficiency of the electrode, negating the value of its ion-hosting capacity. Thus, it is not believed that graphene electrodes will find widespread use [25], though many attempts are underway to architect the material in such a way that the issue of surface passivation is avoided [25].

Nanostructured materials benefit Li batteries by offering reversible intercalation and high charge/discharge rates due to their high surface area to volume ratio; Liu *et al.* conducted a thorough review of the use of carbon nanotubes in electrode applications [26]. To this end, Kim *et al.* [27] achieved a maximum discharge capacity of 1882 mAh/g using multiwalled carbon nanotubes in combination with silicon.

Silicon itself has a high theoretical charge capacity, but has found little use in Li battery anodes as it experiences a 400% volume change during lithiation that was mechanically untenable. Structuring silicon into nanowires allowed researchers to leverage silicon's theoretical charge capacity in actual application, reaching a maximum discharge capacity of 3193 mAh/g, without suffering the mechanical degradation that cripples bulk silicon [28]. A review of the benefits available by nanostructuring silicon and the mechanics of lithiation and delithiation in nanostructures may be found in Ref. [29].

Supercapacitors are fundamentally structured differently from batteries in such a way that enables rapid charge and discharge, which is equivalent to high power density. While batteries rely on chemical insertion and removal of ions from a material, supercapacitors take advantage of the creation of an electric double layer on a charged surface, meaning ions are only loosely, electrostatically adhered rather than chemically adhered. Though this mechanism limits the stored energy density of supercapacitors, it also allows supercapacitors to endure orders of magnitude more charge/discharge cycles than batteries without suffering material degradation. Successful supercapacitor systems must offer:

- high specific capacitance (hundreds of F/g),
- high specific power density (at least tens of W/g), and
- many recharge cycles (tens of thousands) with negligible loss of capacitance,

in addition to, ideally, being fabricable from readily available materials in low-cost manufacturing processes. A sample of properties offered by different supercapacitor and battery systems is given in Tables 22.1 and 22.2.

Ubiquitous and high-performance consumer electronics will need to leverage the improved energy densities which nanostructured materials are providing to both battery and supercapacitor systems. Hybrid storage systems could let device makers combine the benefits of long lifetime between charges in batteries and many charges per lifetime in supercapacitors. Moreover, both storage platforms will likely offer flexibility and facile mass production in the near future, for example, by printing methods as reviewed by Refs [39–42]. Challenges will come in finding cheaper and less-toxic materials for batteries, increasing the energy density of supercapacitors while reducing leakage current (about 10%/day [43]), and fine-tuning production techniques. Furthermore, the promise of environmental energy harvesting offers potential for fully self-powered consumer devices, with intermittent energy generation coupled to local storage. Already, consumer-device scale flexible lithium ion batteries have been coupled with onboard energy harvesting for a fully self-powered integrated approach to wearable electronics [44].

Energy harvesting converts ambient sources of energy (predominantly heat, motion, and light) into electric energy for devices. Heat harvesting via

Table 22.1 Characteristics offered by selected nanostructured supercapacitor systems.

Max Capacitance (F/g)	Max energy density	Max power density	Material	Retention	Reference
540	51 Wh/kg at a power density of 205 W/kg		ZnS-carbon textile	94.6% after 5000 cycles	[30]
234.2	0.72 mWh/cm^3	~0.4 W/cm^3	MnO_2/G-gel/NF	>98.5% after 10 000 cycles	[31]
267	17 Wh/kg	2520 W/kg	MnO_2	92% after 7000 cycles	[32]
222	106.6 Wh/kg	10.9 kW/kg	Single-walled carbon nanotubes with reduced graphene oxide	~99% after 1000 cycles	[33]

Table 22.2 Characteristics offered by selected Li-ion and nanostructured battery systems.

Energy density (Wh/kg)	Charge capacity (mAh/g)	Material	Retention	Reference
100–200	~150	Lithium ion state-of-the-art	—	[34,35]
~120	377	Na–S	—	[35]
—	4277	Silicon nanowires	~81% over 20 cycles	[28]
—	~2500	Multiwalled carbon nanotubes with silicon	~87% over 12 cycles	[27]
—	2725	Interconnected silicon hollow nanospheres	>92%/100 cycles, for 700 total cycles	[36]
60	40	$LiMn_2O_4$ cathode, $LiTi_2(PO_4)_3$ anode, and Li_2SO_4 electrolyte	82% over 200 cycles	[37]
—	—	Porous PDMS electrode, $Li_4Ti_5O_{12}$ anode and $LiFePO_4$ cathode	70% after 300 cycles	[38]

thermoelectrics has seen performance improvements using nanostructured materials [45]; however, because of the small temperature differences present in any (comfortable) consumer device environment, the main applications for advanced thermoelectrics are likely to be in waste-heat recovery applications with large temperature differences, such as in the automotive sector [46]. For motion harvesting, transduction is often achieved using piezoelectric materials, which directly couple mechanical strain and electric field. Nanostructuring is being investigated to enhance properties of these materials [47]; researchers are aiming to improve film thinness, ability to withstand high flexural strain, and defectivity of piezoelectrics. Complex material structuring methods have been deployed to construct flexible piezoelectric metamaterials at the macroscale using macrofiber-composites [48].

Harvesting from light, using photovoltaic cells, has been commercialized for low power consumer devices such as pocket calculators for several decades. Recent research in photovoltaics is mainly concerned with large-area applications, where cost per unit area is critical; for consumer devices, where area is highly constrained, energy conversion efficiency is a more critical parameter. Nanostructures have been widely investigated for increasing the efficiency of photovoltaics, as reviewed in Ref. [49], by increasing both light trapping and photoelectric conversion, achieving efficiencies as high as 37.9% using multijunction devices [50]. State of the art efficiencies are regularly updated by Green *et al.* in [50].

22.4 Sensors

Sensors that are currently integrated in consumer electronics are mainly motion and image sensors. In addition, some portable devices integrate biomedical sensors to measure pulse rate, electrocardiographs, glucose, or blood oxygen, intended for health monitoring but also sports applications. These systems have greatly extended the functionality of personal electronics, introducing convenient services such as personal navigation, activity logging, connected and tagged photography, and location-sensitive information. Nanotechnology has already played a very important role in this development in the on-chip integration of multiple sensor systems, advanced biochemical assay analyses and nanolenses. In return, the consumer electronics market has been driving the booming progress in motion and camera sensors of the last decade, with state-of-art high-performance sensors being regularly found in a range of personal electronic equipment. This large market creates demand for advances supplied by nanotechnology. In the following subsections, motion processing units, portable biomedical sensors, and imaging sensors are discussed along with relevant nanotechnologies, both current and imminent.

22.4.1
Motion Processing Units

Acceleration sensors are the most developed and widely applied type of MEMS sensor. They are based on an inertial mass that moves inside the sensor package in response to acceleration. Beyond the supporting CMOS (complementary metal-oxide-semiconductor) circuit, these require fabrication of planar and vertical profiles and interfaces at the nanoscale. MEMS accelerometers also require high quality nanoscale springs. At the device level, accuracy, sensitivity, noise, dynamic and spectral ranges, and response time are the main performance metrics. Nevertheless, the key element in the successful incorporation of motion sensors to consumer electronics is chip-level integration of multiple sensors into a CMOS system. This provides compactness, reliability, and connectivity benefits, and also enables the combination of multiaxis linear and rotational motion data, and thus more sophisticated motion-based applications. Such applications include detection of free-falling, gestures, display orientation, and tapping; image stabilization; step counting for athletic applications; and dead reckoning (navigation by integrating motion from a known location). System-level integration of such services is critical for efficient power management in portable devices.

Commercial examples of integrated motion processing units (MPUs) are the Invensense MPU-9250, the Bosch BMX055, and the ST LIS2DS12 microchips. All integrate a three-axis accelerometer and a three-axis gyroscope, and the first two also include a 3D orientation sensor. The sensors are integrated with analog-to-digital converters and a digital processing unit to provide interrupts for detection and counting of specific events such as tapping, dropping, stepping, and motion state change. A comparison of the technical features of these implementations is presented in Table 22.3. Predecessors of these models have been used in popular devices including the Apple iPhone 6 and the Google LG Nexus 5. This type of hybrid system-on-chip integration has recently enabled various features and services in consumer electronics, such as indoor navigation by dead

Table 22.3 Comparison of commercial motion processing unit chips.

Brand/model	Bosch/BMX055	Invensense/MPU-9250	ST/LSM6DSL
Year	2013	2014	2015
Packaging	3 × 4.5 × 0.95 mm, LGA	3 × 3 × 1 mm, QFN	2.5 × 3 × 0.86 mm, LGA
MEMS area	—	~2.5 mm^2	—
Accelerometer range, sensitivity, RMS noise	±2 g to ±16 g, 1 mg/LSB, 150 μg/$\sqrt{\text{Hz}}$	±2 g to ±16 g, 62 μg/LSB, 300 μg/$\sqrt{\text{Hz}}$	±2 g to ±16 g, 61 μg/LSB, 90 μg/$\sqrt{\text{Hz}}$
Gyroscope range, sensitivity, RMS noise	125–2000°/s, 0.0038°/s, 0.01°/s/$\sqrt{\text{Hz}}$	250 to 2000°/s, 0.0076°/s, 0.01°/s/$\sqrt{\text{Hz}}$	125–2000°/s, 0.0044°/s, 0.0045°/s/$\sqrt{\text{Hz}}$
Orientation magnetometer range, sensitivity	X,Y: ±1.3 mT, Z: 2.5 mT, 0.3 μT/LSB	±4.8 mT, 0.4 μT/LSB	—
Active/sleep mode power	18 mW/20 μW	9 mW/20 μW	1.2 mW/5.4 μW
Event recognition	Any motion, high magnetic field, low-g/high-g, new data, tap.	Any motion, step detector/counter, programmable interrupts.	Free fall, motion change, step detector/counter, tap.
Connectivity	SPI and I^{2}C	SPI and I^{2}C	SPI and I^{2}C

reckoning, gesture recognition, motion-based power saving, stable minidrones, and augmented reality systems.

The implementation of motion sensors in the nanoscale using conventional concepts of operation is challenging because of the requirement for a substantial proof mass. While new device concepts using 1D and 2D materials have been proposed, these are at an early stage of development [51,52]. Further information about emerging nanoscale motion sensor technologies can be found in Chapter 8.

22.4.2
Nanosensors for Biomedical Applications

Portable, personal biomedical devices have been expanding rapidly in usage and variety in recent years, supported by new sensor types and by low-power sensor, processing, and communication electronics [53]. The electronic personal glucometer, in commercial use since 1971, has been particularly successful: it has allowed a profound improvement in the quality of life for hundreds of millions of people globally [54]. The sensors in these systems are typically either electrochemical, based on measuring the electric current of glucose oxidation through glucose oxidase, or optical, mainly using tissue spectroscopy and fluorophore techniques [55]. Extensive research has focused on the improvement of these methods using nanostructures. Nanoparticles can improve the selectivity, stability, and sensitivity of electrochemical sensors by enhancing glucose absorption and improving electron transfer. Gold nanoparticles are the most popular in such studies, and they have also been shown to improve the sensitivity of optical glucose sensors, by serving as fluorescence quenchers. Nanowires, nanotubes, and nanocomposites have also been used in glucose sensors, mainly to improve the interface area and the selective absorption of glucose molecules. Nanotechnology-enhanced glucose sensors are expected in commercial glucose monitoring systems in the next few years. They may be particularly beneficial in continuous monitoring systems, where sensors are required to be minimally invasive. A review of nanotechnology research for glucose sensors can be found in Ref. [56].

Other personal biomedical devices that have been in commercial use include pulse oximeters, portable electrocardiogram systems, optical heart rate counters, breath analyzers, respiratory monitors, and fertility monitoring systems [57]. These systems have been given a dramatic boost by the advances in handheld personal devices, mainly smartphones and tablets, which offer a platform with a pre-existing display, stored power, and onboard computing capability. While systems such as pulse oximeters or electrocardiographs are fully optical or electrical, a number of personal biomedical sensors involve measuring an analyte through an assay procedure. In these cases, nanoparticles and nanostructures already play a critical role: nanoparticles are used to provide an optical output to selective reactions, in order to be measureable by a camera, which is typically available in the host personal electronic device. Gold nanoparticles in the size range 5–200 nm are often used; applications include the detection of antibiotics in food samples [58]. In the near future, such capabilities may become available to consumers as a smartphone-hosted service. An example of a gold nanoparticle-based assay system implemented as a smartphone sensor is the NutriPhone lab-on-a-chip, which can measure the level of vitamin D in a sample. An image of this prototype device describing the process of absorption enhancement by gold nanoparticles is shown in Figure 22.3 [59]. Quantum dots have also been used as a photoluminescence source for improved assay analysis in smartphone-based point of care biomedical sensors [60]. An overview of

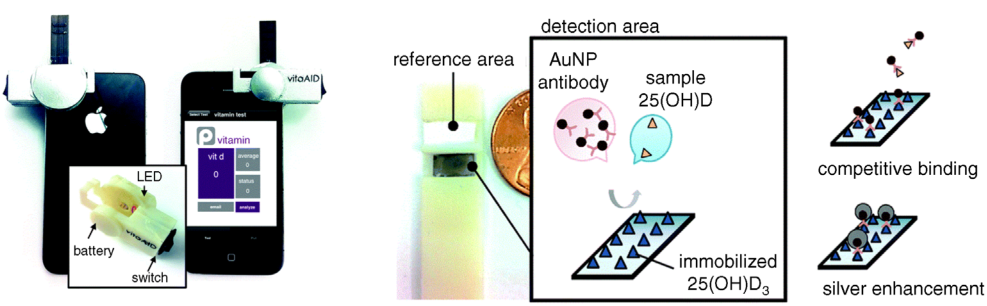

Figure 22.3 The gold nanoparticle based NutriPhone lab-on-a-chip for measuring vitamin D levels using a smartphone. (From Ref. [59].)

the role of nanoparticles in personal diagnostic devices has been recently published in Ref. [61].

22.4.3
Optical Sensors

The development of solid-state image capturing devices, initiated and mainly driven by charge coupled device (CCD) array technology, has led to the availability of low-cost, high-end sensors. Solid-state imaging is now ubiquitous in standalone cameras, and integrated into smartphones, tablets, and other personal electronic devices. An image sensor is comprised of an array of cells, each one having a semiconductor channel within which charge is accumulated by the absorption of incident light. The image resolution is defined by the number of rows and columns of cells. In CCD sensors, charge is measured at one side of the array by sequentially forwarding the accumulated charge from one cell to the next, using electrostatic gating. In CMOS image sensors, each pixel is individually addressable and so requires one or more additional transistors as well as further wiring. Both technologies now yield similar performance in terms of image quality, with CMOS being generally lower cost and more compatible with monolithic integration with other electronic functions. Hence, CMOS image sensor technology currently owns a much higher share of the imaging market. The size range of a typical sensor array is in the range of 10–100 mm^2, with larger arrays being beneficial for better sensitivity, because of larger pixel area, larger depth of field, and field of view specifications. The resolution typically found in high-end commercial devices is in the range of tens of megapixels, corresponding to a pixel pitch of 1–2 μm. This means that for typical consumer imaging applications, although the feature sizes of components within each pixel are in the submicron range, they can be fabricated by conventional CMOS methods, rather than requiring bespoke nanotechnological processes.

Nevertheless, advances in nanotechnology could soon play a significant role in the evolution of optical sensors for consumer electronics. With the rapid proliferation of applications related to 3D imaging, subpixel optical processing may become highly desirable in next-generation optical sensors especially in combination with high precision motion sensing. With subpixel processing, information about the direction of incoming light can be captured, allowing the reconstruction of a 3D image, in what is called light-field or plenoptic cameras [62]. Advances in nanolens arrays may play an important role; gold nanowire-based nanolenses have already been demonstrated that achieve imaging resolution beyond the Abbé diffraction limit [63].

An important and widely experienced limitation of current image sensor technologies is the poor performance in low light environments. Si-based sensors are not sensitive enough to capture images in dark environments at short exposure times, leading to either dark or blurry pictures. New materials such as monolayer molybdenum disulfide have proven promising for a dramatic increase in sensitivity, with the additional benefit of using only a subnanometer-thin and effectively transparent active area layer [64]. Such materials have not been integrated to device level yet.

Top-down nanoscale fabrication and chip integration techniques will be increasingly important as on-chip sensor integration becomes essential and is expanded to new sensor types such as breath or environmental gas analyzers, indoor localization, and radiation exposure. Silicon nanowires have been identified as a likely successor to state-of-the-art finFET CMOS technology, and nanowire-based sensors, either electrode- or beam-based, could benefit in cost, availability, and compatibility from sharing material and fabrication techniques, just as silicon MEMS benefitted from Si integrated circuit technology in the 1990s. Self-assembly and the fabrication of bulk materials from nanostructures are also expected to play an important role in consumer electronics, especially in optical surface processing layers and transparent conductors for displays, but also in communication components, as discussed elsewhere in this chapter.

22.5 Internet-of-Things Applications

In the Internet-of-Things (IoT) paradigm, a wide range of objects are given intelligence in the form of computation, communication and, typically, sensing capability [65]. IoT will allow such objects to be monitored and potentially operated remotely, either by human users or by automated systems. While "IoT" implies interconnection over the Internet, the concept can be extended to interconnection using other networks, such as private networks in the case of applications with high security demands. For consumer products, the most prevalent IoT products in the market currently are for "smart home" applications. These include Internet-enabled climate control systems and appliances, enabling such functions as control of room temperature and lighting, washing machine operation, or appliance status checks, from any location, using smartphone apps. In fact, IoT functionality will make electronics significant in a much larger range of household objects, including small electric appliances such as toasters and shavers.

The role that nanotechnology can play, for example, in improved energy storage, or novel antennas, discussed in Sections 22.2 and 22.3, will clearly apply in the IoT domain, as will their respective challenges. IoT applications also have particular challenges in terms of form factor, social acceptance, and distributed network communications and data processing.

The range of consumer products for which some IoT functionality is conceivable is vast, but in practice the range of applications will be constrained by the balance of cost, broadly defined, versus perceived benefit. For example, if the use of a product becomes dependent on its IoT functionality, then the IoT components must have high reliability, ruggedness, and long lifetime, as well as being cheap to manufacture and to incorporate into the object. In most IoT applications the electronics will be battery-powered, and therefore long battery lifetime, or the use of battery alternatives such as energy harvesting, will be essential. Minimizing power consumption for the computation and communications components is imperative for long battery lifetime.

One approach to overcoming the power consumption problem, which is suitable for some IoT applications, is that used in radio frequency identification (RFID). RFID tags typically hold stored information about the tagged object that can be interrogated by a reading device. While active RFID tags contain their own power supplies, passive tags gain the required power from the incident RF signal transmitted by the reader, and so have no on-board energy storage requirement. Permanent identity tagging is not a true IoT function, but the RFID platform can be extended to communicate nonstatic information such as the output of an on-board sensor [66]. For example, in Ref. [67], a strain sensor is reported, which uses a resonant L–C (inductor–capacitor) circuit implemented on a flexible substrate, so that the resonant frequency varies to indicate the strain state of the device. Since the tag is entirely passive, no memory is provided and the strain can only be known at the moments when the device is interrogated. Silver nanoink, comprised of silver nanoparticles suspended in an organic solution, is used to achieve the flexible conductors from which the circuit components are fabricated.

More ambitious application of nanotechnology to IoT has also been proposed. In the Internet-of-Nano-Things concept [68], the intelligence is implemented by devices that are themselves at nanoscale. Realization of this concept will require nanoscale sensors, and communication approaches that are compatible with nanodimensions. The latter requirement makes the use of THz frequencies attractive because of the short wavelengths involved, although these are still in the μm rather than nm range. Alternatively, the use of biomolecules as methods of communication between nanodevices [69], particularly within the body, has also been proposed, although this remains far from commercial realization.

22.6 Display Technologies

Display technology has been revolutionized since the late 1990s with the introduction and widespread use of various new types of flat panel displays. These have allowed more compact, higher quality, and more efficient stationary display devices, while simultaneously equipping handheld devices with powerful graphics, paving the way for handheld computing, including various new services such as localized information and augmented reality. The key underlying scientific advancements are the invention of the InGaN quantum well blue LED [70] and bright solid-state lighting, progress in LCD and the semiconductor technology including MEMS microreflector technologies, the development of polymer semiconductors (organic, flexible LEDs) and improved performance of transparent conductors.

22.6.1 Self-Illuminating Displays

Liquid crystal displays (LCDs) employ a liquid layer containing longitudinal molecules that tend to align in a common direction. This type of liquid, called a nematic liquid crystal, is interposed between two patterned surfaces, which guide the crystals to a rotation gradient, thereby rotating the polarization of passing light. By using two orthogonally aligned polarization films, the multilayer is transparent only when the crystals are in the rotational orientation. Hence, the intensity of passing light can be controlled by electrostatic distortion of the crystal rotation. A grid of transparent electrodes allows control of individual pixels. A white LED source is used as backlight, and color is achieved by using multiple cells per pixel and filtering. Other liquid crystal geometries and alignment modes, such as in-plane switching (IPS) and vertical alignment (VA), are described in Refs [71,72]. The IPS-LCD is currently the most widespread display technology for consumer electronics, used in the vast majority of flat panel monitors and televisions as well as smartphone models such as the Google Nexus, the LG G-series, and the Apple iPhone 6.

The light transmission efficiency of LCD displays is below 10%, due to the large number of optical layers required. As energy consumption becomes increasingly important, especially for portable devices, methods for better light management have been proposed. These include the use of polarized light sources to reduce loss from the bottom LCD polarizer, sequential coloring in place of color-filtering, dynamic LED backlight, and reflective polarization using grid polarizers. Nanowire grid polarizers have been proposed and implemented to achieve significant light recycling [73]. Nanowire fabrication techniques that have been used include laser-interference lithography [74], nanoimprint technology [75], and self-assembly, such as block copolymer pattern transfer [76]. Advances in the manufacturability of polarization nanostructures should play an important role in light management for power reduction of displays in the near future.

Organic light-emitting diode (OLED) displays consist of an array of organic semiconductor devices which can be individually lit by application of an electric current, using bottom and top transparent electrode grids to address each pixel. The application of a voltage across an organic semiconductor material results in the injection of electrons from the cathode and holes from the anode, which recombine, emitting a photon. Depending on whether each pixel contains a transistor for switching support or not, OLED displays are subdivided into active matrix (AMOLED) or passive matrix (PMOLED) displays. AMOLED has the advantage of requiring considerably lower current for the same illumination. The photon emission at recombination depends on the spin combination of the two carriers, which leads to a triplet exciton at 75% in three out of four recombinations. These excitons cannot directly decay, delaying transmission and leading to an efficiency of around 25% for simple small molecule organic materials. Implantation of organometallic molecules with heavy metals, such as iridium, assists in the exploitation of phosphorescence from triplet excitons. Commercial OLED devices leverage this technique for red and green emitters, but use a conventional fluorescent small molecule LED for deep blue, due to reliability concerns for blue phosphorescent layers [77]. Commercial OLED flat panel display products include models from most major TV and monitor makers as well as smartphones such as the Samsung Galaxy series.

Nanotechnology is expected to play a significant role in the technology evolution of OLED devices. Nanoscale surface modification of OLEDs has been shown to reduce plasmon-trapping of emitted light, thereby improving the out-coupling efficiency of the device [78]. The reduction of roughness of OLED material layers has been demonstrated by using nanoparticle-based electrospray deposition methods [79]. The use of graphene and other nanomaterials as transparent conductors for OLED devices has also been proposed [80,81]. Transparent conductors are discussed separately later in this section.

Field emission displays (FED) have been also proposed and studied, as a type of illuminating display technology that combines the brightness and contrast benefits of the old cathode ray tube technology with the compactness and low power of modern flat panel displays. In this display architecture, an array of field emission tips is used to emit electrons and excite photons through a color phosphoric panel. This type of display could benefit substantially by employing efficient nanoscale emitting structures such as self-assembled nanoscale tips or carbon nanotubes [82]. Industrial interest in FED technology has declined in recent years, mainly due to the requirement for high vacuum integration and structural reliability issues related to ion impact damage of the nanoscale tips.

22.6.2
Reflective Displays

Reflective displays address the markets of electronic reading, smart windows, dimmable mirrors, large-scale screens, and signing. Electronic readers (eReaders), currently the most widespread application, are typically based on the electrostatic migration of light- and dark microparticles. Such devices are known as electrophoretic displays. Particles of both types are encapsulated in microcontainers. The light reflection from each container is controlled by applying an electrostatic field, which can bring to the surface either the light or the dark particle population. This microencapsulation technique was first introduced by Comiskey *et al.* [83], and is used in the eReader products of E-Ink, currently supporting popular commercial products such as the Amazon Kindle. The main benefit over LCD displays is the absence of backlighting, which means lower eye stress and power consumption. While the “inks” in reflective displays are monochromatic, recent studies have proposed the use of electrophoretic nanoparticles, including organic molecules [84], pigment-silica composite nanoparticles [85], phthalocyanine nanoparticles [86], and block copolymers [87], as color electronic inks. Furthermore, front-lit displays (which enhance reading in dark environments) can operate with a single LED light source, by using nanoimprinted light guides along with an array of holes to evenly disperse light across the screen.

The use of electrochromic materials has also been proposed for flexible reflective displays. Such materials include metal oxides (e.g., WO_3, $Ir(OH)_3$), viologens, and polymers. Electrochromic materials are able to reversibly change their refractive index when they are oxidized or reduced, thereby allowing electronic control of light reflection. A transparent conductor such as indium tin oxide (ITO) is used to control each pixel. The use of mesoporous TiO_2 has been proposed [88] and used in commercial electrochromic products [89] to confine electrochromic molecules, resulting in contrast enhancement at the edges of displayed features. Color electrochromic displays have also been demonstrated, using multilayers of different materials or optical filters [90]. A review of electrochromic materials for display technologies can be found in Ref. [91].

Electrowetting, the modulation of surface tension by the application of an electric field, is also under investigation for reflective displays. In such devices, the intensity of a pixel can be controlled by forcing a light-absorbing liquid to alternately spread over the pixel surface area or to congest at a corner, through surface tension. Despite involving fluid motion, these devices have shown promise for faster switching in comparison with electrophoretic displays [92]. Color electrowetting displays could be implemented by using multilayers of oil-based materials. Controlling the hydrophobic and oleophobic properties of surfaces by surface engineering at the nanoscale is expected to play a critical role in electrowetting devices [93,94]. For example, the use of nanopillars has been shown to enhance the manipulation of liquids in the microscale [95]. An analysis of electrowetting and its applications can be found in [96]. This technology was initially proposed by Philips Research Lab, and subsequently developed through the Liquavista spin-out in 2005. Liquavista was acquired by Amazon in 2013.

22.6.3 Transparent Conductors

A common key technology behind these diverse approaches to making displays is the integration of a transparent conductor material. Such a material is required as an interconnection layer at the front side of the display, in order to allow individual pixel control. In addition, transparent conductors play a vital role in the integration of displays with complementary functionality such as touch-screens. The most common conductor material for these purposes is ITO, which has an absorption spectrum practically identical to that of glass, transparency in the range of 90% for typical film thickness, and an electrical conductivity of 10^4 S/cm [97]. ITO has been studied and used over several decades, providing mature fabrication and integration processes [98]. It holds over 90% of the billion-dollar transparent conductor market [99], with the rest mainly shared between fluorine doped tin oxide (FTO) and aluminum-doped zinc oxide (AZO). The rapidly increasing demand for transparent conductors has led to research for alternative materials, mainly because of low indium reserves and the need for flexible devices.

Figure 22.4 Demonstration of flexibility in a transparent display using metal nano-wire based transparent conductor, Lee *et al.* [105] (left); and comparison of transparency for a graphene based touch screen with 250 Ω/sq. sheet resistance (corresponding to around 10^5 S/cm) against an ITO implementation, Ryu *et al.* [106] (right).

To achieve a combination of high flexibility, transparency, and conductivity, various nanostructures have been considered, including carbon nanotubes, graphene, and metallic nanowires [100,101]. Nanowire conduction lines are usually deposited from a solution, allowing them to be printed or spread onto a surface. This is compatible with existing roll-to-roll production methods that are envisioned for flexible electronic devices. Nevertheless, dry deposition methods do exist, such as preparation of CNT sheets by pulling from vertically grown multiwall CNTs [102]. CNT transparent conductors exhibit over 80% transparency, and conductivity in the range of 10^3 S/cm, but are difficult to manufacture due to purification and separation challenges [100]. Graphene layers have been recently shown to exhibit similar electrical conductivity and optical transparency performance to ITO, over 10^4 S/cm at 80% transparency [103]. Extensive reviews on the prospects of graphene transparent conductors have been reported recently, including performance comparisons against other materials [80,104]. Examples of touch screen panels using metal nanowire- and graphene-based transparent conductors are shown in Figure 22.4.

Silver nanowires have been demonstrated to be over 90% transparent, with electrical conductivities over 10^4 S/cm [107]. They are considered a very promising alternative to ITO, due to the high conductivity of silver. Conductive lines are fabricated by deposition, as with CNTs, but require annealing to exhibit high sheet conductivity. Such annealing is not always compatible with CMOS integration, and significant effort has been devoted to developing alternative methods for improving nanowire interlinks, such as pressing [108]. In addition, the surface roughness on metallic nanowires is a significant factor, as it can lead to increased reflections. Silver nanowire-based OLED prototypes have already been demonstrated with very promising transparency and durable flexibility performance [109]. A review of the prospects of silver nanowires as a flexible transparent conductive material can be found in Ref. [110]. Various conducting polymers are also under investigation, such as the commercially available PEDOT: PSS with conductivity as high as 10^3 S/cm [111]. An overview of nanotechnology-based flexible conducting materials can be found in Refs [112,100].

The evolution of flat panel displays has already benefitted from various nanoscale optical technologies, such as grid polarizers, reflectors, and color filters, as well as from nanofabrication techniques. Nanotechnologies are of critical importance to the progress of LCD, electrophoretic, and electrochromic displays, all of whose operating principles fundamentally rely on nanoscaled structures. Nanomaterial-based transparent and flexible conductors, such as CNT bundle layers or silver nanowires, are expected to join ITO in display technology in the short term, enabling higher resolution and energy efficiency, denser functionality, and improved transparency and flexibility, which is expected to give rise to vastly different ways for users to interact with handheld electronics.

22.7 Conclusions

Nanotechnology is essential to the continuing advances in integrated electronics: increasing computational power, reducing device scale, and limiting energy consumption. In addition, as we have seen in this chapter, nanostructured materials are providing performance improvements and new functionalities in a range of associated technologies, such as nanomechanical devices, transparent and flexible conductors, display materials, and high capacity energy storage. These developments provide critical support to current trends in consumer electronics – in particular, increased functionality and battery life in smartphones and other handheld devices, rugged and comfortable wearables, wide area and flexible displays, and a wide range of sensing devices.

We anticipate a future where distributed devices, with specialized sensing capabilities and long-lasting energy supplies, are ubiquitous and well integrated into our environments and ways of living. By providing such devices with both the unique functionalities, including flexibility and transparency, and the required performance, nanoelectronics will be critical to realizing such a future.

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