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Graphene and Communications Technology

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Abstract

The advances in communications technology depend on the development of tiny devices being capable of transmitting and receiving data at the highest possible data rates. The digital signal processing at gigabit-per-second rates is soon to be upgraded to the terabit-per-second range. Nanotechnology provides a variety of alternatives for the design of ultrafast nanoscale components. Graphene is one particular material which is considered for possible implementation due to its superior physical properties. This contribution is based on a selection of some foundation studies which explore the potential of graphene for emerging applications with an emphasis on communications technology.

Keywords: *Graphene, nanotechnology, network-on-chip, switching, terahertz band.*

Introduction

Nanotechnology steadily becomes an inseparable part of modern communications technology. The complexity of intended almost instant communication between heterogeneous digital devices using wired or wireless transmission media increases to such an extent that it challenges both the logical and technological capabilities of the human development. However, the maximum number of basic electronic components which can be used for the fabrication of an integrated circuit (IC) of a particular size is limited by the chosen semiconductor layout and the power consumption. Nevertheless, it is observed that the industry is capable of following some empirical trends which are also known as ‘technology laws’.

Technology Laws

Three so-called laws are frequently mentioned in relation to computers and transmission of information.

The Moore’s law was named after Gordon Earle Moore, the co-founder of Intel Corporation, Santa Clara, CA, USA, in 1968. Moore (1965) observed an initial trend in the 1960s which was used as a basis for the estimation that the number of components/ transistors in integrated circuits would double every year. Moore restated it in 1975 by correcting the duration to two years (Kanellos 2003). An alternative duration of 18 months is attributed to David House who was an Intel executive at that time (Kanellos 2003). The Moore’s law also implies a geometric progression for the reduction of the size of components/transistors until reaching a theoretical saturation point at atomic level. At present, the trend still continues with moderate fluctuations and it is worth estimating in advance the materials and methods for the ongoing transition from microelectronics to nanoelectronics.

The Metcalfe’s law is an assertion made by George Franklin Gilder and attributed to Robert Melancton Metcalfe which states that the usefulness, or utility, of a network equals the square of the number of users (Gilder 1993). Metcalfe developed the Ethernet protocol for computer networks in the mid-1970s and founded 3Com Corporation in 1979 (acquired in 2010 by Hewlett-Packard, Palo Alto, CA, USA). The Metcalfe’s law is linked to the combinatorial problem of fully interconnecting n distinct nodes resulting in

$n(n - 1)/2$ connections ($\sim n^2$ for $n \to \infty$). Although full connectivity cannot be achieved in all cases, a square relation is a good rule of thumb and modifications can take place depending on the constraints imposed onto the combinatorial problem.

The Gilder's law is a second assertion made by Gilder (1997) which states that bandwidth grows at least three times faster than computer power. Therefore, if computer components double every 18-24 months in accordance with Moore's law, then transmission bandwidth doubles every 6-8 months.

Two of the mentioned three laws are concerned with critical aspects of communications technology, bandwidth and connectivity, which points to the necessity of having a better understanding of the prospective nanotechnology approaches which would allow withholding the tendencies in said laws during the second decade of this millennium.

Both bandwidth and connectivity can be increased by utilizing the terahertz (THz) frequency band for reliable last-mile information delivery and also network-on-chip (NoC) wired and wireless communications. This requires giga- and terabit-per-second switching with reliable low-cost nanoscale components. Graphene is considered as a possible solution due to its two-dimensional (2D) structure and exceptional physical properties when compared to three-dimensional (3D) bulk materials. It is constructed of carbon (C) atoms and is the latest addition to a list of carbon-made materials discovered in materials science for the past three decades.

Fullerenes

The Discovery of Fullerenes

The systematic experimental research on molecules entirely made of carbon atoms started with the discovery by Kroto *et al.* (1985) of the buckyball consisting of 60 carbon atoms, also called buckminsterfullerene (C_{60}), by Sir Harold Walter Kroto (then of the University of Sussex, Brighton, England, UK), Richard Errett Smalley (1943-2005) and Robert Floyd Curl, Jr. at Rice University, Houston, TX, USA, and the Ph.D. students James Richard Heath and Sean Christopher O'Brien. Buckminsterfullerene is a technical word derived from the family name of the American architect Richard Buckminster Fuller (1895-1983) because the buckyball C_{60} molecule bears resemblance to the geodesic dome (sphere) designed by him (Kroto *et al.* 1985). This triggered the discovery of a new class of molecules made entirely of carbon atoms and forming a sphere (buckyball, like C_{60} and C_{70}), ellipsoid (elongated buckyball), cylinder (buckytube) or any other hybrid hollow structure. After the consequent discovery of other carbon-made molecules, the shortened term 'fullerene' was used to refer to such molecules. The suffix 'ene' comes from the term 'alkene' and stands for the in-plane double covalent bonds of a carbon atom with its three neighbors where a double bond involves two pairs of delocalized electrons of a conjugated system of overlapping orbitals (Smith and March 2007). The electrical, mechanical and thermal properties of fullerenes depend on the chemical bonding between carbon atoms. Since every carbon atom is connected to three neighboring carbon atoms, the resultant geometrical configuration is an atomic plane of interconnected hexagons which can be additionally bent to form a sphere, cylinder, or hybrid surface.

The Discovery of Carbon Nanotubes

The cylindrical carbon molecules (buckytubes) are also known as carbon nanotubes. They were first synthesized by Iijima (1991) and Ebbesen and Ajayan (1992). Single-walled and multi-walled carbon nanotubes of different radius and length of the cylinder(s) can be produced for the practice. In communications technology, in addition to electrical nanoscale applications, carbon nanotubes can be considered as an alternative to the conventional optical fibers for network-on-chip optical interconnections because their small radius makes it theoretically possible to convey high energy X-ray electromagnetic signals (Dabagov 2011) of short wavelengths between different parts of optical digital circuits for all-optical signal processing.

The Discovery of Graphene

Among the hexagonal fullerenes, buckyballs are ‘zero-dimensional’ (0D) (closed surface) molecules and carbon nanotubes are ‘one-dimensional’ (1D) fibers. From geometrical perspective, there was a missing ‘two-dimensional’ (2D) surface which can logically be derived from the ‘three-dimensional’ (3D) bulk material known as graphite. The properties of such hypothetical carbon sheets were studied theoretically by Wallace (1947) and thin carbon foils were obtained experimentally by Boehm *et al.* (1962). The term ‘graphene’ was introduced by Mouras *et al.* (1987) and Boehm *et al.* (1994) to describe atom-thick sheets made of carbon atoms in graphite intercalation compounds (GICs).

The breakthrough in obtaining pure two-dimensional graphene was made by Novoselov, Geim *et al.* (2004) in collaboration between the University of Manchester, Manchester, England, UK, and the Institute for Microelectronics Technology (IMT) at the Russian Academy of Sciences (RAS), Chernogolovka, Moscow Region, Russia. The ideal graphite is composed of layers of graphene sheets and the hexagonal carbon rings of adjacent sheets are bound together due to weak interlayer interactions (Brown *et al.* 2008). The researchers initially applied sticky Scotch tape on the surface of graphite and realized that it was possible to peel off thin graphite layers. Then they realized that this technique can be repeated many times in obtaining extremely thin layers and, eventually, an atom-thick layer. The properties of graphene were studied systematically in subsequent publications (Novoselov *et al.* 2005a, 2005b; Geim and Novoselov 2007).

Nobel Prizes

The Nobel Prize in Chemistry 1996 was awarded jointly to Robert F. Curl, Jr., Sir Harold W. Kroto and Richard E. Smalley “for their discovery of fullerenes” (RSAS 1996).

The Nobel Prize in Physics 2010 was awarded jointly to Andre K. Geim and Konstantin S. Novoselov “for groundbreaking experiments regarding the two-dimensional material graphene” (RSAS 2010).

Physical Properties of Graphene

The chemical bonds between the carbon atoms in graphene are the result of orbital hybridization. The chemical element carbon (C) belongs to element group 14 of the Mendeleev’s periodic table (non-metals) of chemical elements and has atomic number 6. Its stable isotope carbon-12 (^{12}C) contains six positively charged protons and six neutrons in its nucleus which is surrounded by six negatively charged electrons attracted to said protons as a result of the interaction between them due to the electromagnetic force. The electronic structure of carbon atoms is given as $C = 1s^2 2s^2 2p^2$ and shows the existence of two electronic shells. The pair of electrons in the single orbital of the internal (inner) shell ($1s^2$) usually does not participate directly in chemical bonds. The external (outer) shell ($2s^2 2p^2$) has one *s* subshell with one orbital and one pair of electrons and one *p* subshell with 3 orbitals and two electrons. The two electrons in the *p* subshell are placed in two distinct orbitals and remain unpaired which makes carbon slightly paramagnetic. Carbon is tetravalent because four electrons are available in the external shell ($2s^2 2p^2$) to eventually form shared pairs of electrons (covalent chemical bonds) with adjacent atoms (Smith and March 2007).

In graphene, the orbital hybridization results in three sp^2 bonds which are formed with every carbon atom. The hybrid sp^2 bonds involve one electron in the 2*s* orbital and the two electrons in two ($2p_x$ and $2p_y$) of the three 2*p* orbitals. One electron from the *s* subshell is placed in the third orbital ($2p_z$) of the *p* subshell. The three in-plane (*x*-*y*) sp^2 orbitals (lobes) of the hybrid bonds, formed by hybridization of 2*s*, $2p_x$ and $2p_y$ subshells, are equally spaced 120° apart. The weights of orbital hybridization are 1/3 for 2*s* involvement and 2/3 for 2*p* involvement (Bunch 2008). The hybrid sp^2 bonds are called double bonds because two pairs of electrons are effectively involved in each bond. However, every carbon atom shares only three electrons (2*s*, $2p_x$ and $2p_y$) which are delocalized to form a conjugated system. The low energy of the electronic bonds of the molecules in the conjugated system increases the strength and stability of graphene. The double covalent sp^2 bonds of the conjugated system in alkenes, like graphene and other fullerenes, are stronger and more stable than the single sp^3 covalent bonds in alkanes, like in the three-dimensional tetrahedral lattice of the diamond crystal (Smith and March 2007; Bunch 2008). The $2p_z$ orbital of the outer shell with the unpaired fourth electron becomes a perpendicular *pi* orbital (lobe) being present both above and below the planar structure of interconnected hexagonal carbon molecules. The sideway overlap of adjacent *pi* orbitals creates a global orbital which allows the electrons to move easily across the molecular plane which gives graphene its semimetal properties (Smith and March 2007; Bunch 2008). This also partially explains the semimetal properties of graphite which is composed of stacked layers of graphene. More specifically, graphene is a semimetal with zero bandgap energy and zero effective mass of the electrons and holes (Wallace 1947; Charlier *et al*. 2008) which have very high mobility (Chen *et al*. 2008; Akturk and Goldsman 2008) and behave as relativistic fermions (Charlier *et al*. 2008). The zero effective mass makes possible the observation of anomalous quantum Hall effect at room temperature (Novoselov *et al*. 2005a, 2005b) which is desirable in metrology for the low-cost calibration and traceability of the international standard of voltage. The low-energy electronic structure of the hexagonal (honeycomb) planar lattice of graphene affects its optical properties as it is almost transparent and absorbs only $\pi\alpha \times 100\% \approx 2.3\%$ of white light (Kuzmenko *et al*. 2008; Nair *et al*. 2008), where $\alpha = 1/137.035999074(44)$ is the fine-structure constant (CODATA 2010).

The distance between two adjacent carbon atoms of the two-dimensional (2D) graphene crystal is only 0.143 nm (RSAS 2010), shorter than the distance of 0.154 nm between adjacent carbon atoms in diamond and the distance of 0.341 nm between the stacked layers in graphite (Brown *et al*. 2008). Table 1 shows the numerical values of the density, Young's modulus, tensile strength, thermal conductivity, mobility, and specific surface area of graphene. The in-plane Young's modulus was estimated by nanoindentation in an atomic force microscope (Lee *et al*. 2008) and a molecular dynamics study (Jiang *et al*. 2009) to be ~ 1.0 TPa establishing it as the strongest material ever measured. The estimation of Young's modulus by Raman spectroscopy (Lee *et al*. 2012a) is even higher. The thermal conductivity exceeds the range of $0.9\text{-}2.3 \times 10^3$ W m^{-1} K^{-1} known for diamond (Wei *et al*. 1993) and is dominated mainly by phonons (lattice excitations of energy) rather than free electrons (Balandin *et al*. 2008).

Alternatives to graphene are also being studied. For example, silicene is the silicon equivalent of graphene and consists of a hexagonal mesh of silicon atoms arranged in a slightly distorted plane having ripples (Aufray *et al*. 2010; Lalmi *et al*. 2010).

Table 1. Some physical characteristics of graphene.

Graphene	
Characteristics	Numerical values
Dimensionality	2, two-dimensional (2D)
Density (RSAS 2010)	0.77 mg/m^2
In-plane Young's modulus (Lee *et. al*. 2008; Jiang *et al*. 2009);	~ 1.0 TPa
Raman spectroscopy (Lee *et al*. 2012a)	2.4 ± 0.4 TPa (mono-layer) and 2.0 ± 0.5 TPa (bi-layer)
Tensile strength (Lee *et. al*. 2008)	130 GPa
Thermal conductivity at room temperature (Balandin *et al*. 2008)	$(4.84 \pm 0.44) \times 10^3$ to $(5.30 \pm 0.48) \times 10^3$ W m^{-1} K^{-1}
Mobility, μ, of charge carriers at room temperature (Geim and Novoselov 2007);	15,000 cm^2 V^{-1} s^{-1}
Theoretical limit (Chen *et al*. 2008; Akturk and Goldsman 2008)	$< 2 \times 10^5$ cm^2 V^{-1} s^{-1}
Specific surface area (Kaneko *et al*. 1992; Stoller *et al*. 2008)	2,630 m^2 g^{-1}

Potential Applications of Graphene

The thorough investigations of the properties of graphene point to numerous potential applications (Choi and Lee 2012; Katsnelson 2012; Murali 2012; Raza 2012) some of which are discussed below.

Nanotechnology Alternative to CMOS Integrated Circuits

Even though the complementary metal-oxide-semiconductor (CMOS) technology (Wanlass 1967) dominated the design of integrated circuits for the past four decades and there is still room for improvement, it will reach soon a saturation point due to fundamental constraints at the atomic level. The simplest CMOS circuit is a complementary pair of *p*-channel and *n*-channel metal-oxide-semiconductor field-effect transistors (MOSFETs). A silicon MOS transistor has silicon dioxide (SiO_2) as an insulator between a polycrystalline-silicon conducting gate and a semiconductor channel within silicon substrate.

The applicability of the Moore's law in the near future depends on the timely introduction of alternative transistors having higher carrier mobility, better thermal conductivity and smaller size than silicon MOSFETs. The application of voltage to a dual-gate bilayer graphene FET can tune the bandgap energy of graphene up to 0.25 eV (4.95-μm wavelength) at room temperature (Zhang *et al.* 2009). Subsequent experimental studies on the design of graphene transistors grown on SiC (Lin *et al.* 2010) and sapphire (Fanton *et al.* 2011) showed promising results. The creation of the first graphene IC, a broadband radio-frequency mixer, was also reported by Lin *et al.* (2011).

Ongoing research addresses several technical issues:

- problematic single-layer deposition;
- small bandgap energy; and
- small voltage gain.

Due to obvious difficulties concerned with the manipulation of atom-thick layers, bilayers (double, or dual layers) are more commonly used although they have different properties compared to single layers (RSAS 2010). The small bandgap energy and small voltage gain are serious constraints for the creation of reliable transistors for digital circuits. Although the nanoscale transistor size could allow the use of very low voltages and quantum tunneling effects, it remains unclear to what extent graphene FETs will outperform the existing silicon FETs at room temperature. Nevertheless, the general expectation is that the use of the new material will allow the design of hybrid integrated circuits (Obeng and Srinivasan 2011). Presumably, the wired interconnections will be partially or fully replaced by wireless communications between different IC sections thus simplifying the wire layout and improving the fault-tolerance.

Graphene-Enabled Nanophotonics and Wireless Communications

The relativistic charge carriers in graphene have a linear energy - wave vector relation (linear energy dispersion) which enables ultrawideband tunability of visible and infrared light (Bonaccorso *et al.* 2010). Also, the application of magnetic field can tune the optical response of graphene nanoribbons in the THz frequency band (Liu *et al.* 2008). This is suitable for hybrid graphene-enabled wireless network-on-chip (GWNoC) communications (Abadal *et al.* 2012) for establishing both photonic and wireless interconnection networks within an integrated circuit.

Optical Modulators

At present, the silicon waveguides are the preferred option for optical communications. The effective on-off switching of light pulses depends on the modulators integrated with the waveguides. Liu *et al.* (2011, 2012) reported a double-layer graphene optical modulator which operates at 1 GHz. Xia *et al.* (2009) demonstrated a graphene photodetector at 40 GHz. These initial developments indicate that optical transmitter-waveguide-receiver systems for network-on-chip (NoC) communications can be implemented by modifying the existing electrically-wired CMOS integrated circuits and introducing silicon waveguides with graphene-enhanced signal processing at both ends.

Graphene Antennas (Graphennas)

The THz radiation is related to a portion of the electromagnetic spectrum within the frequency range from 0.3 to 3 THz with corresponding wavelengths from 1 mm down to 0.1 mm (submillimeter band). This band is in between the microwave band and the infrared light so that the wave-particle dualism of the electromagnetic signals is clearly demonstrated during physical experiments by observing high frequency waves or low energy photons (Jornet and Akyildiz 2011). The frequency is sufficiently high and the use of the standard antenna engineering and coherent modulation techniques are problematic. The generation of collimated beams as with the standard laser sources cannot be applied. Therefore, new devices for transmission and reception of THz signals are needed which should be able not only to detect the THz carriers but also to process the encoded information-bearing signal. The work in this direction is progressing with the development of techniques for THz wave switching (Lee *et al*. 2012b).

The graphene-based nano-antennas (graphennas) have resonant properties in the THz band due to the propagation of plasmon waves across the graphene lattice (Llatser *et al*. 2012a, 2012b). Such plasmons when coupled with a photon are called surface polaritons.

Graphene antennas for the THz band are made of 10-100-nm wide and 1-μm long nanoribbons (Murali *et al*. 2009). The transmission and reception of THz electromagnetic signals is established through interactions with the plasmons at the surface of the nanoribbon.

Typically, THz waves can be used at a distance of one meter up to 10 meters with possible data rates not exceeding 100 Gbps. The distance can eventually be increased even further resulting in a rapid reduction of the available data rate due to significant attenuation. It should be noted that long distance transmissions with THz waves are possible in free space between communication satellites. Jornet and Akyildiz (2010, 2011) calculated that at shorter ranges, such as a few centimeters, data rates of up to 100 Tbps are theoretically possible. The plasmon resonance effect in graphennas allows the tuning of the carrier frequency in the THz band by applying electroctatic bias (Llatser *et al*. 2012a, 2012b), magnetic field (Liu *et al*. 2008), etc. However, a fine tuning must be achievable for distinct transmitter and receiver units. Also, nanoscale approaches for the coding and modulation of the information signals are needed (Jornet and Akyildiz 2011). The main application of graphene antennas is considered to be for GWNoC communications at hundreds of gigabytes per second. Novel multiple assess techniques are required for avoiding signal interference. The attempt to interconnect wirelessly thousands of sub-processors for parallel processing in a multi-core chip poses an additional challenge in terms of data/cache coherence, consistency and synchronization (Jornet and Akyildiz 2011).

Mobile Platforms and Flexible Electronics

A variety of other components needed for the operation of platforms for mobile applications are currently developed with the implementation of graphene layers. The efforts in this direction lay the groundwork for the flexible electronics manufacturing of bendable, stretchable and wearable devices.

Electrodes and Touch Screens for Panel Displays

The straightforward application of graphene is in the production of transparent electrodes which can be used in touch-screen panels (Bae *et al*. 2010) for the replacement of the indium tin oxide (ITO) which has a tradeoff issue between conductivity and transparency. There is also uncertainty over the future availability of indium (POLINARES 2012).

Speakers

Thermoacoustic sound generation (Suk *et al*. 2012) from the surface of transparent graphene layers is considered for the replacement of the existing electromechanical loudspeakers. The high thermal conductivity of the material would allow fast contractions of the air being in contact with the surface which is subjected to repeated cooling and heating in accordance with the frequency of the applied signal.

Supercapacitors and Batteries

The large specific surface area of graphene (Stoller *et al*. 2008) is suitable for the production of supercapacitors (ultracapacitors) which can serve as energy storage in mobile devices due to the minimum discharge which occurs over time. Among other advantages, supercapacitors can charge much faster than rechargeable batteries.

Some Other Applications

RF NEMS

A nanoelectromechanical system (NEMS) is the nanoscale version of a microelectro-mechanical system (MEMS). Radio frequency NEMS (RF NEMS) can be used as resonators, switches, oscillators and filters in RF signal processing (Dragoman *et al*. 2008; Chen *et al*. 2009; Xu *et al*. 2010; Palacios *et al*. 2010).

Self-repair

Zan *et al*. (2012) reported experimental observations of the reconstruction of the graphene lattice after etching if there is a supply of carbon atoms. Although the hexagonal structure is not always perfectly reconstructed after significant damage, other polygonal ring structures, consisting of 5 to 8 carbon atoms, are formed instead (Zan *et al*. 2012). The ability of the hexagonal lattice to repair itself could possibly be used for the development of fault-tolerant components.

Conclusion

The potential implementation of graphene-based components for faster and more reliable transmission of information is anticipated to have a profound impact on communications technology. The utilization of the THz band and ultrafast switching pave the way for the universal interconnectedness of all electronic devices in real time. The price of mobile equipment could drop radically if the use of rare-Earth elements is minimized and graphene becomes the preferred material in nanotechnology. The tiny size, strength, and potential self-repair ability of digital graphene circuits are suitable for advanced design and manufacturing of fault-tolerant, reconfigurable and evolvable systems. Such systems must rely on communications technology using novel coding and modulation techniques for the exchange of information at both nanoscale and macroscale levels.

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