GRAPHENE AS A DISRUPTER OF SILICON-BASED TECHNOLOGIES

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ABSTRACT

This paper discusses how the evolution of scientific knowledge has built upon previous discoveries, and how science has brought us to the point where we are able to manufacture tools on the nanoscale for use in circuits that have applications for every aspect of human activity. Today’s computer-component market is dominated by complementary metal oxide semiconductor (CMOS) technology. Four decades of research have gone into optimising the power consumption and performance of this technology. But CMOS is rapidly approaching its limits in terms of scalability. Nanomaterials – especially graphene, which has beneficial electric and physical properties – offer a solution that could catapult science into a new era liberated from the constraints of current technologies.

1. INTRODUCTION AND BACKGROUND

The history of science is punctuated by pioneering efforts in various disciplines. The names of savants and theorists such as Ernst Mach, Albert Einstein and David Bohm are as recognisable in tableside scientific discussion as the discovery of fire. But their contributions are not limited to the field of scientific inquiry. Owing to their achievements, these individuals have become well known in the academic and commercial fields.

For students of these fields, the evolution of knowledge, from relatively crude symbols recorded on cave walls to complex papers regarding the principles of atomic theory, is equally important. An understanding of the influence of Socrates on the work of Aristotle is as important as an understanding of Aristotelian physics. Similarly, an understanding of the influence of Mach's physics and philosophy is important in understanding Einstein's theory of relativity. As Mach noted:

> *"The historical investigation of the development of a science is most needful, lest the principles treasured up in it become a system of half-understood prescripts, or worse, a system of prejudices…"* (Mach 1883)

Accordingly, this paper begins by providing a brief history of scientific discipline, beginning with prehistory and leading up to the theories and principles that govern modern science. The paper will then continue to look into the futuristic field of quantum and nano-computing, asking what can be achieved using these emerging tools.

2. AN APPRECIATION OF THE HISTORY OF SCIENTIFIC INNOVATION

2.1 From prehistory to Egyptian Science

To accurately date back to the beginning of this field it is necessary to define what we consider to be science. We will call the first scientific era prehistoric science – the science used by our primitive ancestors in observing and classifying the environment in which they found themselves, even though these observations were only recorded to individual memory (Tylor 1871). The scientific knowledge we can establish that our primitive ancestors possessed included their perception that the world was flat and boundless.

A paramount manner to describe the development of the field from the days of our prehistoric ancestor would be to look at where the world's scientific "schools" developed. Early Egyptian science included the use of tools such as household utensils, potter wheels and bronze weapons. Later on, the Egyptians also had within their possession the art of writing, which enabled them to make records. (Lockyer 1894). The Egyptians also had within their possession, the art of writing which enabled them to make records. The Egyptians were also responsible for the Rhind mathematical papyrus, a handbook depicting the kind of mathematics they employed (Maspero 1895). This mathematics was designed for practical purposes such as obtaining value during the trading of commodities. It is, however, difficult to apply it to situations outside those of its original purpose. (Erman 1894: 44 - 357).

2.2 From Mesopotamia to Greece

The next scientific schools developed in Mesopotamia, Italy and Greece. In Mesopotamia, the Babylonians and Assyrians left us with a number of inscribed tablets, documents and terracotta cylinders (Abott 1850). Assyrio-Babylonian records contain a greater amount of accuracy concerning matters of chronology when compared to the

Egyptians. They also differed from the Egyptians in the relative importance they placed on celestial objects: the Egyptians focused on the sun, while the Babylonians focused on the moon. Perhaps the greatest advancement we can credit to the Babylonians is establishing the division of time. The divisions of time we use today are of Babylonian origin. Their week also consisted of 7 days, which they named after the planets; they also divided time by hours and months (Corey 1826).

The development of science in the Italian region is credited to Greek philosophers who went to live there. One of the most famous philosophers of this time is Pythagoras. Although Greek, Pythagoras spent most of his life in Italy, where he founded his Crotonian School of Philosophy. Pythagoras is said to have refrained from writing things down and relied only on teaching through word of mouth. This has made it difficult for historians to ascertain exactly what scientific advancements he was responsible for, but there seems to be consensus that Pythagoras:

- Conceived the idea of the music of the spheres;
- Propagated the doctrine of metempsychosis;
- Perceived the world to be a ball floating in space;
- Discovered the morning star and the evening star (termed Eosphorus and Hesperus, respectively);
- Introduced the concept of weights and measuring to the Greeks; and
- Argued that the human soul was divided into three parts – intuition, reason and mind – and that the animal soul was similarly constructed, apart from the mind.

A visionary who put forward a number of other scientific propositions, Pythagoras (Lewes, George 1888):

- Hinted at the idea of monads developing into more complex bodies and them being able to pass through stages in order to develop into complex bodies;
- Coined the idea of four elements – fire, water, earth and air – that formed the basis of all organisms;

- Put forward the concept of the earth being spherical; and
- Proposed that the air had a salubrious influence.

What Pythagoras' theories show is that he was a visionary in the field of science because he outlined some amazing scientific ideas.

The next school that developed is the one of Greek science in the early Attic period. Around the 5th century BC several philosophers/scientists emerged, such as Xenophanes, who, like Pythagoras, also had a number of students. One who stands out is Parmenides, who carried on with the work of his master within the same scientific lines, and also dabbled in the relationship between science and mysticism. Parmenides, like Pythagoras, is credited for his belief in the motion of the earth, although writings by the philosopher that demonstrate this have never been found (Gomperz 1905).

Another pre-Socratic philosopher worth mentioning of the Italic school is Empedocles, who was born around 494 BC. Empedocles, like Pythagoras, was a physician, who also led what we would call a cult today. Other categories which have been used to describe him include statesman, prophet, physicist, physician, reformer and poet. Some of the extraordinary knowledge he is credited with include his theories based on the pressure of air; he hypothesised that the pressure of air is able to sustain the weight of water in an inverted tube, that light has actual motion in space and that it is that motion which prevents the heavens from falling. He is also credited with the great hygienic achievement of a draining marsh, and the knowledge he possessed of medicine is considered to have been supernatural. We are able to judge Empedocles doctrines due to fragments of his writings that have been passed down through the years, along with Plato's references to him (William Bern 1898).

The next notable development in science came when famous philosophers such as Socrates established schools in Athens. We know that Socrates gathered among him a company of remarkable men, such as Plato. As great as he was, it seems he just could not escape the terrible fate that inevitably ended his life, after a public trial in which he was accused of “corrupting the youth”. In the era of metaphysics, it is evident that Socrates played a substantial role, but in terms of historian of science, he plays a less significant role (Lewes, George 1888).

Plato’s writings and teachings found the most traction. In some circles, he is credited as being the greatest thinker of all time. To comprehend him thoroughly, it is essential that the student of science recognises him as a thinker whose point of view is not essentially scientific. His teachings covered essentially the entire field of thought and he presented his ideas in a charming manner, resulting in successive generations of readers turning to them with persistent interest.

In most cases we are forced to estimate the teachings of Greek philosophers through hearsay, but Plato speaks to us directly. This great thinker did not bequeath a significant message for the physical sciences. He apparently had no defined opinions on the mechanics of the universe, nor did he have a clear conception of the origin of organic beings. He, instead, believed that his standards of ethics were the most fundamental and most reliable facts. Anaxagoras criticised him for having a tendency of deducing laws from observations. Modern society views this as criticism of the highest praise because it is in essence what differentiates the scientist who is a philosopher and the philosopher who has an indefinite idea of physical science (Ritter 1838).

The third great Athenian teacher worth mentioning is Aristotle, who was the complete opposite of Plato. His name, even thousands of years later, is regarded as synonymous with scientific inquiry, and throughout the Middle Ages, his words were regarded as the last words to any disputes concerning problems of nature. It is said that his followers had a preference for his mandates over their own senses. While there is no reason to believe that any of his teachings were his in origin, he does deserve credit for his notion of the earth being spherical. We have mentioned previously that this notion found its origins during the times of Pythagoras in Italy, but evidence shows that this doctrine had not yet made its way to Attica (Whewell 1847).

The next school which developed in the field was located in Alexandria. In terms of culture, Alexandria can be considered the successor of Babylonia because Ptolemy, following the Babylonian model, erected a huge museum and a library for collections. It is said that by the time he died, he had collected about 200 000 manuscripts there. He had also managed to collect a pronounced number of great teachers and founded a school of science, making Alexandria the cultural centre of the world. Even during its prime, Athens was unfamiliar with such structures. Such libraries existed in Babylonia for years, so now we say that the city of Alexandria had a Babylonian influence. The scientific trend during these times was focused on mechanics, which explains the great geometers that emerged. Their conceptions were applied to the creations of new mechanical contraptions and to the elaborations of theories on sidereal mechanics. The innovators responsible for these accomplishments may not necessarily have been born in Alexandria, but in general they came from territories of Alexandrian influence.

Plutarch is responsible for providing us with much of our knowledge about Archimedes of Syracuse. He described Archimedes as a man of profound learning who never wrote down the methods he used in making his warlike engines. Some remarkable discoveries Archimedes added to the field include the following:

- The state of every liquid when in a state of rest is spherical and the centre of that coincides with the core of the earth
- A solid body which is the same weight as a liquid, when submerged, will sink so that the surface of the body is even with the surface of the liquid, but no deeper
- Any solid body that is lighter than a liquid, if placed in the liquid will sink deeply enough to displace the mass of the liquid equal in weight to another body
- If a body which is lighter than a liquid is forcibly submerged in a liquid, it will be pressed up with a force which is equal to the weight of a like volume of water, less the weight of itself.

These prepositions are not challenging in demonstration after they have been conceived. But discovering them, combined with the discovery of statistics, showcases the superiority of Archimedes' inventive experiments.

2.3 From the Ancients to the Modern Era

Though the theories and discoveries of scientists during these times may seem foreign and even farfetched according to our modern notions of science, they form the foundation of what we term modern science. Without the ruminations of Plato and Aristotle, for example, we would not have arrived at the inventions of Popov and Bell.

The period known as the Industrial Revolution is touted as one of the great revolutions of human invention (Montagna 1981). Inventions such as the locomotive, the steam engine, and electricity are all part of this great age. The incredible inventions created during this age would not have been possible without the scientific contributions of the luminaries of that age.

The work of Newton, Descartes and Einstein provided the bedrock upon which pioneers such as Bell, Watt and Ohm were able to build their inventions. In order to appreciate the progression that has enabled these technologies, however, it is important to understand the histories of and contributions of the scientists who enabled these advances.

As we have discussed the early history of science in sufficient detail, we shall begin our focus from just before the time of the Industrial Revolution, with Isaac Newton. Born into a middle class family in 1642, Newtons training in scientific disciplines began while he was an undergraduate student at the Trinity College in Cambridge in the early 1660s. Interestingly, Newton did not excel in school and originally desired to study law. He was diverted to an interest in Mathematics, however, after picking up a book on the subject and not understanding the mathematical principles contained within (Whitlock 2013).

Newtonian contributions to science, especially regarding his work on gravitation, relationships between celestial bodies and the laws of motion are all well-known (Newton 2014, Westfall 1983, Mumford 2004). His influence is such that modern science still measures forces in newtons and considers his characterization of the law of universal gravitation as a fundamental force. Newton's work was not only characterized by leaps and bounds made in the branch of natural philosophy that is, today, known as science. But was also a serious student of subjects that are today relegated purely to the field of philosophy (Ameriks, Clarke, Janiak. 2004).

According to Ameriks, Clarke and Janiak, Newton's method in dealing with natural philosophy can be clearly seen in those we consider traditional philosophers today (Ameriks et al. 2004). Citing David Hume's 1739 *A Treatise of Human Nature*, Ameriks *et al.* argue that Newton's methodology prompted a number of philosophers to adopt his empirical methodology. In modern science, Newton is credited with being a precursor to the fundamental theory of relativity, which forms one of the building blocks of modern science.

The effect of Newton's work were far reaching in the realms of Science, affecting the work of another luminary of the age, Ernst Mach. Born February 18, 1838, Ernst Waldfried Josef Wenzel Mach was an Austrian physicist, philosophy and physiological psychology (Pojman 2008). Beginning his education in physics at the University of Vienna in 1855, Mach earned his degree in 1861 and continued on as a lecturer until 1864. Mach spent three years as a Professor of Mathematics at Graz, after which he became a full Chair at Prague.

During his tenure as a Professor at Graz, Mach collaborated with Gustav Fechner, discovering Mach Bands - a phenomena that relates the physiology effect of spatially distributed light stimuli to visual perception - in the process. Mach was a student of scientific history, and was an adherent of Darwinian evolutionary theory, which he used prolifically in his writings (Mach 1914).

Mach's work spans a number of fields including physics, philosophy and physiological psychology - all of which contain major contributions from himself. Mach was the first to systematically study super-sonic motion and is synonymous with the speed of sound travelling through a specific medium. Mach also helped in understanding of the Doppler Effect and is considered a major influencer of Gestalt psychology (Pojman 2008).

Einstein credited Mach with being one of the philosophical forerunner of relativity, saying that his work exhibited "extraordinary experimental talent" (Einstein 1916). Einstein's own Theory of Relativity which describes the relationships between macro, celestial bodies, has become foundational in modern physics. Einstein succeeded in creating a theory which united space and time - two forces considered fundamental in the universe, yet also the most mysterious. Einstein's theory combines space and time a way in which they cannot be unbound. By doing so, Einstein's relativity gives us an explanation of how the universe works. At the time, however, this theory challenged a number of long standing scientific traditions, calling for a major overhaul in the perceptions in truth at the time (Greene 2005).

Einstein argued that space and time were inextricably bound, even to the point of becoming one entity, which he called Space-time. As such, measurements of length and time were observer dependent; should the observer be moving at the speed of light, their perception of universal time would move slower or faster should they be moving slower than the speed of light. In this context, space-time was considered a fabric that was able to stretch and bend, with massive bodies such as planets or stars (Greene 2005).

While Newtonian physics were able to adequately explain the relationships and interactions in macroscopic objects, but did not adequately explain how these were held together. Einstein's Theory was not only challenged popular Newtonian notions of absolute space and time but also provided a unified theory showing how these all fit together.

Einstein's influence on scientists of his own and future generations cannot be underestimated, with many scientists taking their intellectual lead from his works. Despite detractors who posit that the Theory of Relativity is essentially incorrect (Gigov 2012) or contradictory to other fields of science such as Quantum Theory (Keepin 1993), it still holds sway over the scientific community. In this vein, Einstein has gone on to influence the intellectual direction of physics in our modern age, being a forerunner for many of the theories in use today.

Though the intellectual vigor of scientists of this age allowed for great leaps in fields such as physics and psychology, this is not to suggest that the age of revolution was purely theoretical. Rather, the theoretical contributions made by scientists, along with economic factors prevalent at the time, helped to inspire a new age of invention. Advances by James Watt, a Scottish inventor and mechanical engineer were fundamental to the industrial revolution. Watts work with early steam engines and later, the chemical experiments that helped produce effective ink solutions were vital in enabling early automation and information sharing respectively (Hills 2005).

The advances being made by Watt additionally don’t suggest that the Industrial revolution was localized to a single region. In addition to the advances being made by

Watt, Georg Ohm’s work with electricity allowed him to create Ohm’s Law, which is fundamental to understanding of electricity and electric currents today (Ohm 1827).

3. FUNDAMENTAL OBJECTIVES OF THE PAPER

This paper argues that the CMOS technology currently used in integrated circuits is rapidly approaching the limits of downsizing transistors on a chip. To overcome this problem, graphene is considered by International Technology Roadmap for Semiconductors (ITRS) to be the strongest candidate for post-silicon electronics.

As the industry try to extend silicon-based CMOS devices towards the end of the ITRS roadmap and beyond, the industry is confronted with several challenges that need to be mitigated with clever design, modelling and experimentation. This includes challenges arising from electrostatic effects such as diminishing gate control and quantum effects (Novoselov et. al., 2012:7). The fundamental concern is that the technology to produce graphene circuits is still in its infancy, and probably at least a decade of additional efforts will be necessary to avoid costly transfer from metal substrates.

However, in recent years, new prospects are starting to emerge from demonstration of high-speed graphene circuits offering high-bandwidth. This includes fundamental breakthroughs in research on graphene, especially the first two - dimensional atomic crystal, as well as a significant advance in the mass production of this material (Kosidlo et al., 2009:1). This emerging phenomenon within the digital electronics arena will have impacts on the next generation of low-cost smart phone and television displays.

Graphene may indeed be disruptive and cost - effective. In a similar view, Novoselov et al. (2012:2) also contends that the nanotubes have an impressive list of attributes. Nanotubes can behave like metals or semiconductors and can conduct electric current better than copper and also transmit heat better than diamond.

The purpose of this paper is to present a comprehensive, compelling insight on graphene and related dimensional materials, targeting a revolution in information and communication technology (ICT), with impacts and benefits reaching into most areas of the society.

The objective is to challenge the current thinking in ICT, revealing new physics and applications of scalable quantum simulators for ICT-based semiconductor materials. This includes applications already used in real-life electronic and optoelectronic devices.

The key question is how technological innovations can overcome challenges related to graphene-based circuit’s production in a post-CMOS era. Other areas of interest include the uses of nanotechnology in information technology – specifically, fabricating structures consisting of individual atoms, molecules or macromolecular blocks in the length scale of 5nm and beyond. This similarly comprises the study of quantum effects to determine operational principles of graphene quantum dots-based devices. The long-term view is that having a strong and realistic simulation capability will provide a strategic tool to support product development in all fields of applications.

4. MODERN AND EMERGING CONCEPTS IN MATERIAL SCIENCE

Technology and economies usually advance incrementally. To be economically disruptive, a technology needs to improve by a dramatic order of magnitude. This could involve scaling the size and number of transistors on a chip, or it could require a quantum leap similar to the transition from vacuum tubes to semiconductor technologies (Smith, 1998: 19).

Disruptive technologies usually involve universal, versatile applications that change multiple aspects of societies from every aspect of human existence. Roco and Bainbridge (2007: 50) note that, in the medium term, disruptive technological progress is relatively independent from economic cycles. For example, in the past 40 years Moore’s Law – which states that the number of transistors in a dense integrated circuit doubles about every two years – has not wavered in the face of dramatic economic cycles. Google engineering director Ray Kurzweil’s extension of Moore’s Law, which applies the same principle to other technologies like computational capability and storage capacity, also shows an uninterrupted exponential growth curve in technological development over the past 100 years, again without perturbation during the Great Depression or the world wars. Similar exponential behaviour can be seen in internet connectivity, medical imaging resolution, the mapping of the human genome and the prediction of 3D protein structures. Roco and Bainbridge concluded that the level of analysis should be not on products or companies, but basic technological capabilities.

Rather than a specific new area of science, nanoscience – the study of materials and their application at the scale of nanometres, or a billionth of a metre (10−9m) – should be regarded as a new way of thinking. Nanoscience’s revolutionary potential lies in the fact that it continues to be developed by, and has applications in, many different disciplines including physics, chemistry, mathematics, the life sciences and engineering.

Individual inorganic and organic nanostructures involve clusters, nanoparticles, nanocrystals, quantum dots, nanowires, and nanotubes, while collections of nanostructures involve arrays, assemblies, and superlattices of individual nanostructures (Hambali et al., 2014:2; Rao et al., 2003: 01).

This section of the paper discusses areas of nanoscience and nanotechnology applications as they relate to the industry and to society at large. In particular, it focuses on an area of fundamental importance for the information society of the 21st century – graphene material.

The aim is to present a collection of fundamental terms and most important supporting definitions taken from general physics and quantum mechanics, material science and technology, mathematics and information theory, organic and inorganic chemistry, solid-state physics and biology. As a result, this section covers fast progressing nano electronics and optoelectronics material, molecular electronics and spintronic, nano-fabrication and -manufacturing, bioengineering and quantum processing of information. This includes an area of fundamental importance for the information society of the twenty-first century – graphene material. Therefore, the sub-headings of this section comprises: post CMOS era, aggressive scaling of CMOS technology, replacing Si CMOS in microprocessors, graphene FETs in electronics and emergence of advanced graphene material.

4.1 Insights on the post complementary metal oxide semiconductor era

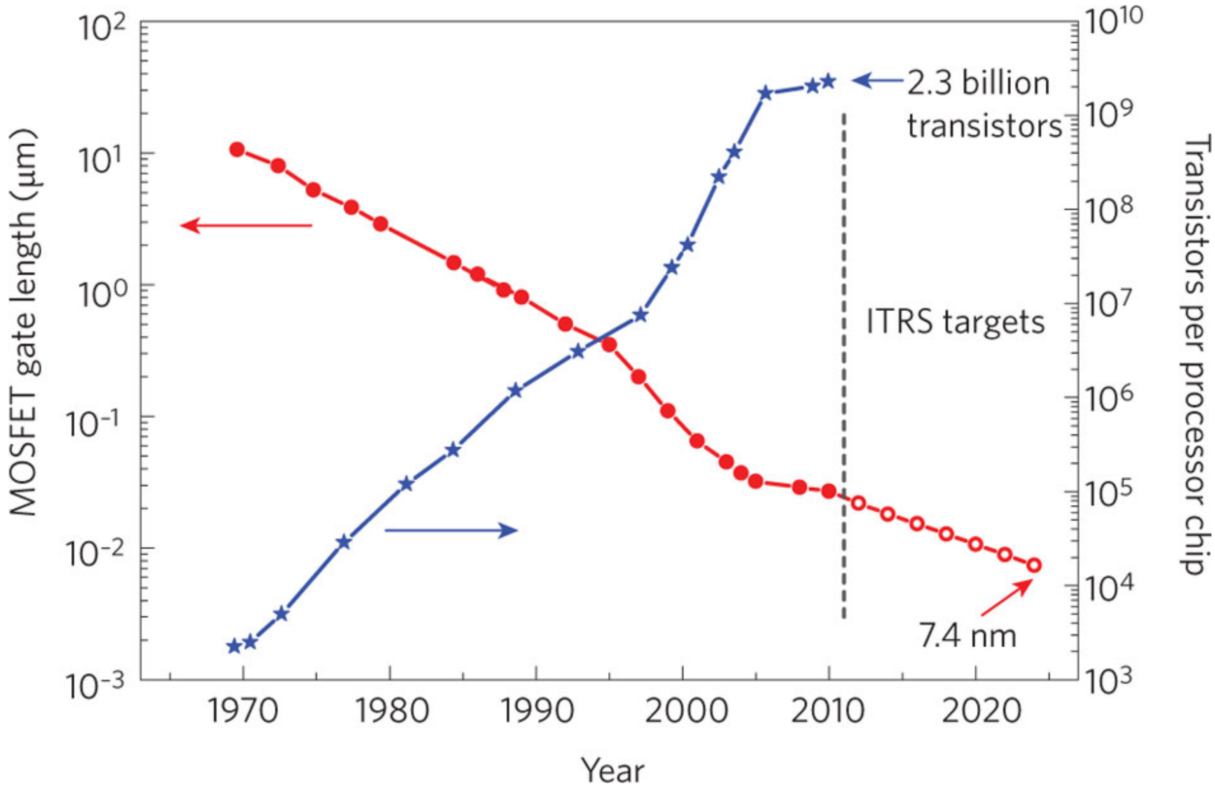
The complementary metal oxide semiconductor (CMOS) device is an integrated circuit, which uses a combination of p-channel metal oxide semiconductor transistors and n-channel metal oxide semiconductor transistors.

CMOS was initiated by technical investigations in the 1940s and started as an industry in the late 1960s. CMOS circuitry dominates the current semiconductor market because of the astonishing power of silicon electronic integration technology on a single chip. CMOS technology has distinguished itself by the rapid improvements in its products, in a four-decade history to be precise. Roco and Bainbridge (2002:87) also argue on the fact that the objectives for enhancing electronic devices have been the basis for many nanotechnology programs. The nanotechnology efforts in programs such as molecular electronics have been pursued for decades with little impact on the electronics industry thus far.

The progress in digital logic relies in down scaling CMOS devices through the demand for low voltage, low power and high performance. This size scaling has permitted the complexity of integrated circuits to double every 18 months. The decrease of gate lengths corresponds to an increase of the number of transistors per processor chip.
However, processors containing two billion MOSFETs, many with gate lengths of just 30 nm, are in mass production nowadays. Iwai (2009) similarly agree and state that the down-scaling is still the most important and effective way for achieving the high - performance logic CMOS operation with low power segment of CMOS technology. Iwai (2009:1) stresses that the limit is expected to be at the gate length of around 5 nm because of the too huge off-leakage current in the entire chip. For instance, static (leakage) power dissipation in Si microprocessors has already reached more than one third of the total power, and is expected to increase further with the continuation of the aggressive scaling of CMOS technology. New materials like graphene are emerging as perfect fit to maintain these trends in technology space.

As per figure 4.1 below, the ITRS is targeting a gate length of 7.4nm in 2025. Alluded to the fact, figure 4.1 illustrates the evolution of MOSFET gate length in production-stage integrated circuits (filled red circles) and ITRS targets (open red circles). As gate lengths have decreased, the number of transistors per processor chip has increased (blue stars). Maintaining these trends is a significant challenge for the semiconductor industry, which is why new materials such as graphene are being investigated.

Figure 1: Trends in Digital Electronics



Source: Schwierz (2010)

To put matters into perspective, Kuphaldt (2009, 87) quite pertinent elucidates that the exception is the graphene single electron transistor, an allotrope of carbon, which does not have the rigid interlocking crystalline structure of diamond. Taking into account its unique properties, graphene transistors dissipate little power and switches at high speed, thus making it a replacement for silicon based transistors going forward.

Another concern points toward the fact that faster computing systems need access to the large amounts of on - chip memory and Si technology scaling limits create bottlenecks in realising high density memories (Meena et al., 2014:15). Therefore, this poses a significant challenge in the semiconductor industry – post Si CMOS age, with new materials such as graphene expected to play a major role going forward.

The outstanding thermal properties of graphene provide an extra motivation for its integration with CMOS technology, as well as beyond - CMOS, with the possibility to overcome Si and III-V semiconductor based high frequency field effect transistors (FETs) at the ultimate scaling limits. High mobility coupled with high thermal conductivity and high current density makes graphene an ideal replacement for CMOS technology beyond the 7.4nm node, which the ITRS expects to be reached in 2025.

4.2 Aggressive scaling of CMOS technology

Non-volatile memories are the most complex and advanced semiconductor devices following the Moore's law down to the 20nm feature size. Meena et al. (2014:1) put across and confessed that non-volatile memory technologies in Si-based electronics date back to the 1990s. For example, ferroelectric field-effect transistor (FeFET) was one of the most promising devices replacing the conventional flash memory facing physical scaling limitations at those times. The state-of-the-art non-volatile memories consist of floating-gate flash cells, in which the information is stored by charging or discharging additional floating gate embedded between the standard control gate and semiconductor channel of a MOSFET (Sun et al., 2007:4).

However, as noted by Chang (2003:1), technological advancements have been achieved over the past three decades primarily through the scale-down of device dimensions in order to attain continued improvement in circuit speed and reduction in size, particularly for lower unit manufacturing cost. The most important and fundamental building block of very-large scale- integrated (VLSI) circuits today is the metal-oxide-semiconductor field-effect transistor (MOSFET). Traditional scaling of CMOS technology has a negative impact on the reliability of non-volatile memories. The parasitic capacitances between the adjacent cells increase with scaling, leading to a cross-talk.

As the MOSFET channel length is reduced to 50 nm and below, the suppression of off-state leakage current becomes an increasingly difficult technological challenge - one that will ultimately limit the scalability of the conventional MOSFET structure (Chang, 2003:1). There is an urgent need to meet the high performance metrics of the ITRS beyond the 15 nm technology generation, in particular the need to reduce supply voltages (Thayne, 2012:1). For these reasons, alternative materials and storage concepts have been actively investigated by key leading organisations in the field, which include implementation of graphene in non-volatile memories.

4.3 Replacing silicon based CMOS in microprocessors

Kaul (2010:22) argue that silicon - based field effect transistors (FETs) have been the cornerstone of the integrated circuits (ICs) industry. This includes applications that range from microprocessors, solid-state memories or mobile phones. Carbon nanotubes for transistor could be considered as viable materials for CMOS applications, specifically as channel materials in FETs due to their exceptional electronic properties.

However, for the reasons already discussed previously, the long-term goal should be based on the graphene specification requirements for related industries. This is because graphene seem to be the main winner for the replacement of Si CMOS in future ubiquitous microprocessors in digital electronics. In a similar thought, Kaul (2010,22) also note that in order to overcome the performance limiting issues in highly miniaturised Si transistors, the focus research areas should include the use of nano-electro-mechanical-systems (NEMS) for microprocessor applications that are now gaining increasing attention. These arguments point towards physical isolation of conducting paths in NEMS to reduce leakage currents and power dissipation, which are difficult to constrain with increasingly miniaturized Si transistors with short source-drain channel lengths or ultra-thin gate oxides.

Furthermore, following on similar observations, in order to achieve the short-term goal, most organisations specialising in this field agree that it will be necessary to realise top-gated graphene field effect transistors (GFETs) with ultra-thin (< 4nm) gate insulators (Bonaccorso et al.,2012:74). This includes over - unity voltage gain, which has already been demonstrated in graphene devices with similar gate thicknesses (approx. 4nm). In the same way, Bonaccorso et al.,2014:134) further point out that the next step should be incorporation of such highly-efficient gate stacks in bilayer graphene field effect transistors (BLGFETs), in which perpendicular electric field opens a bandgap allowing large voltage gain in dual-gate configurations.

4.4 Graphene field effect transistors in electronics

Sordan and Ferrari (2013:1) reviewed the potential of graphene in ultra-high speed circuits and came to realised that most graphene field effect transistors (GFETs) to date have intrinsic gain much smaller than unity. This results in the inability to directly couple graphene electronic circuits. However, the main building block of analogue electronics is a voltage amplifier. For example, an electronic device capable of amplifying small alternating current (AC) voltage signals. For the same reasons discussed previously, in case of digital logic gates, AC voltage gain is usually much less than unity in graphene circuits.

The use of graphene field effect transistors (GFETs) in analogue electronics is currently limited to niche applications, such as analogue mixers, but even these require voltage amplifiers for signal processing. GFETs with a high intrinsic gain has remained elusive, meaning that graphene circuits and detectors should rely on Si FETs for signal amplification and processing. As Chauhan et al. (2012:1) alluded to this dilemma, the issues of the ultimate channel scaling, role of inelastic phonon scattering and performance potential of the unitary power gain frequency of graphene RF transistors, however, remains unclear. Therefore this makes GFET approach not recommended by key semiconductor industries, pointing towards such complicated and expensive hybrid technologies.

4.5 Emergence of advanced graphene FET materials

As alluded to earlier, the high frequency electronics is a cornerstone of today’s global economy leading towards running simulations for channel lengths down to 5nm. The continuous downsizing of components in ICT sustained the electronics industry for more than three decades. However, as already been highlighted, graphene as the material platform for both digital and analogue electronics could be used to create new economies and overcome most obstacles already identified in the technology space. This include scaling beyond the Si limits, which is possible with graphene because its unique properties (Chauhan, 2012:4).

Engelbrecht and Varlamova (2011:88) similarly discuss another ongoing international graphene project titled “Suspended graphene nanostructures” (RODIN, FP7) in which researchers of IPUT together with different institutions including Chalmers University of Technology, Aalto University, Technical University of Delft , University of Cambridge and Catalan Institute of Nanotechnology and industry players from Diarc - Technology Oy and Nokia Research Centre investigate suspended single - and few - layer graphene nanostructures and annealed diamond - like carbon films. This is evident that graphene is starting to emerge as an alternative to CMOS based transistors. This report by Engelbrecht and Varlamova (2011:88) sate that, in February 2011 the first high-quality chemical vapour deposition (CVD) graphene sheets (Miao et.al., 2011) with an area of several square centimetres were produced in a home-built reactor on copper foils.

Graphene will allow much higher operation frequencies for frequency doubling and mixer applications than possible with Si or Si/Ge, avoiding the disadvantages of III/V materials, such as high production costs, limited substrate size, toxicity and poor integrability into a cost efficient Si technology.

Graphene may favour not only a radical improvement of existing technologies, such as electronics and optoelectronics, but may also eventually enable the emergence of completely new technologies, hampered so far by intrinsic limitations of the employed materials and processes. The unique properties associated with graphene, being described by different physicians with respect to the other commonly used electronic materials, will permit the practical realisation of promising technological concepts, thus far only proposed by scientists, but never developed.

Taking these few patterns of unique physical phenomena into considerations, it is reasonable to expect the rapid development of many new applications due to the development of graphene technology, with a huge impact for ICT industry.

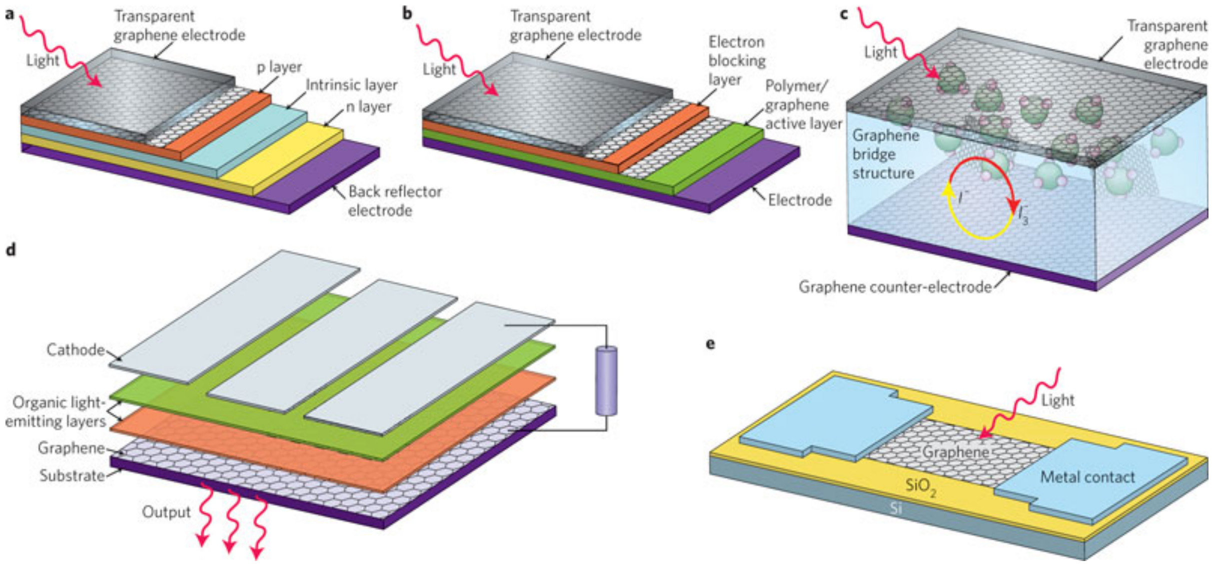
5. DISRUPTIVE TECHNOLOGICAL CHANGE MODELS IN SCIENCE

It is not unexpected that new nanomaterials will have a disruptive impact on current optoelectronics devices based on conventional materials. One advantage of graphene is well articulated by Bonaccorso et al.,(2012:46) on the basis that, unlike other nanomaterials, it can be made on large and cost-effective scale by either bottom up (atom by atom growth) or top-down (exfoliation from bulk) techniques. This is going to happen not only because of cost or performance advantages, but also because nanomaterials can be manufactured in more flexible ways, suitable for a growing range of applications.

However, Bonaccorso et al. (2010) contend that modern human interface technology requires the development of new applications based on printed and flexible electronics and optoelectronics, such as stretchable displays, touch-screens, light emitting diodes, conformal biosensors, photodetectors and new generation solar cells. Such components are depicted as schematics in figure 5.1: a–c, Schematics of inorganic (a), organic (b) and dye-sensitized (c) solar cells. I− and I−3 are iodide and tri-iodide, respectively.

The I− and I−3 ions transfer electrons to the oxidized dye molecules, thus completing the internal electrochemical circuit between the photoanode and the counter-electrode. d, e, Schematics of an organic LED (d) and a photodetector (e). The cylinder in d represents an applied voltage.

Figure 2: Graphene-based Optoelectronics



Source: Bonaccorso, Sun, Hasan & Ferrari, (2010: 214).

Following on the similar line of thoughts, it can be argued that graphene is emerging as a viable alternative to conventional optoelectronic, plasmonic and nanophotonic materials. Graphene has decisive advantages such as wavelength-independent absorption and tuneability via electrostatic doping. This includes large charge-carrier concentrations, low dissipation rates, extraordinary electronic properties, and the ability to confine electromagnetic energy to unprecedented small volumes.

This section covers important milestones of this subject under study. It addresses critical issues related on science models in different industries and the impacts on society moving forward. This section provides a significant shift in technology space as a whole towards creating 21st century science models.

The aim is to present a compelling argument and position graphene as the 21st century material in science models. Unique characteristics and properties of graphene structure are discussed. This provides absolute evidence to differentiate graphene from other existing materials in the technology space as a whole.

5.1 21st century material – graphene

The 2010 Nobel Prize in Physics has already acknowledged the profound novelty of the physical properties that can be observed in graphene. These arguments are based on its unique characteristics, structure and properties compared with other electronic materials such as traditional semiconductors. Therefore, it is not a question of if, but rather how many applications will it be used for, and how ubiquitous will it become.

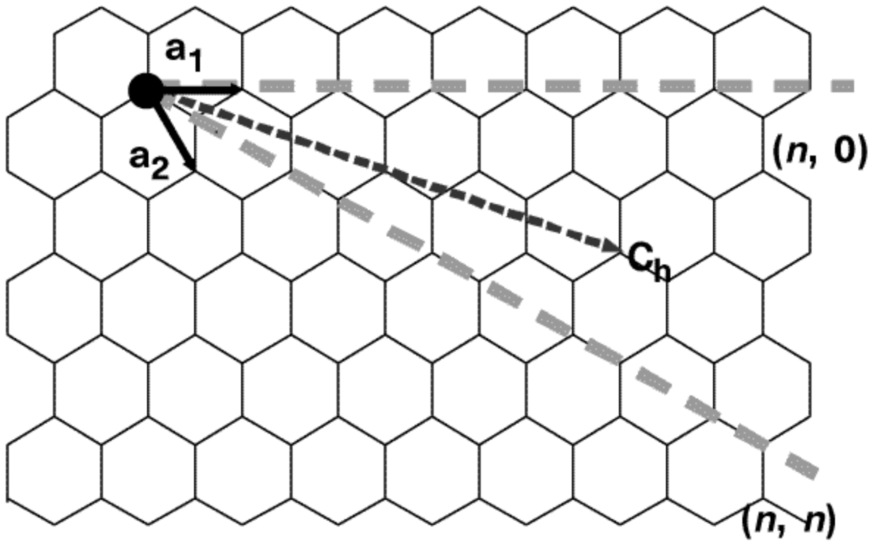
However, the main challenge facing most industries today is to use materials with stronger but lightness designed components in a way that such materials reduces global failure rates and life-cycle cost (Roco & Bainbridge, 2002:364). This can be achieved by developing smart materials which, while being lighter and stronger than the previous ones, shall also allow easy, possibly real-time sensing and monitoring for mechanical failure or leakage.

The big question: are the properties of graphene so unique for this material to be seen as the next disruptive technology and make it the material of the 21st century? As already stated, in terms of its properties most key players in the field agree that graphene is certainly has potential to become the next big thing in the 21st century.

In a similar view, naturally self-organized nanostructure in the form of a tube composed of carbon atoms with completed bonds comprised two general forms. This includes single-wall and multiwall nanotubes. In this instance, a single-wall carbon nanotube can be considered as a single sheet of graphite, which is called graphene (Hutchby et.al., 2002:09).

The resulting nanotube can have metallic or semiconducting properties depending on the direction in which the sheet has been rolled up. Within its context, graphene is a two-dimensional honeycomb net made up of sp2 bonded carbon atoms (Gavrilenko, 2013:08) as illustrated in Figure 5.3.

Figure 3: Schematic of a two-dimensional graphene sheet illustrating lattice vectors a1 and a2, and the roll-up vector: $c_h = na_1 + ma_2$. The limiting cases of (n,0) zigzag and (n,n) armchair tubes are indicated with dashed lines. As represented here, the angle between the zigzag configuration and c_h is negative.



Of further significance in this regard is the fact that the electronic properties of single-wall nanotubes may be understood when those of graphene are analysed. This includes electronic band structure of graphene as determined by electron scattering from the carbon atoms (Kuphaldt, 2009:87). As a result, only electrons with certain energy can propagate in this direction. This includes the material, which shows an energy gap similar to the one in a semiconductor. Such fundamental band gap in semiconducting nanotubes is in the range of tenths of eV to about 1 eV (Gavrilenko, 2013:09), being dependent on small variations in the diameter and bonding angle. In general, the band gap decreases with an increase of the tube diameter (Adam et.al.,2007:164).

As a result, there is a notable quantum confinement (Gavrilenko, 2013:09) in the radial direction of the tube provided by the monolayer thickness of its wall. In fact, single-wall nanotubes behave as one-dimensional structures and as such electrons can travel along the tube for long distances without being backscattered. Similarly, metallic carbon nanotubes have been found to behave like quantum dots (Engelbrecht & Varlamova, 2011:347).

5.2 Graphene quantum dots

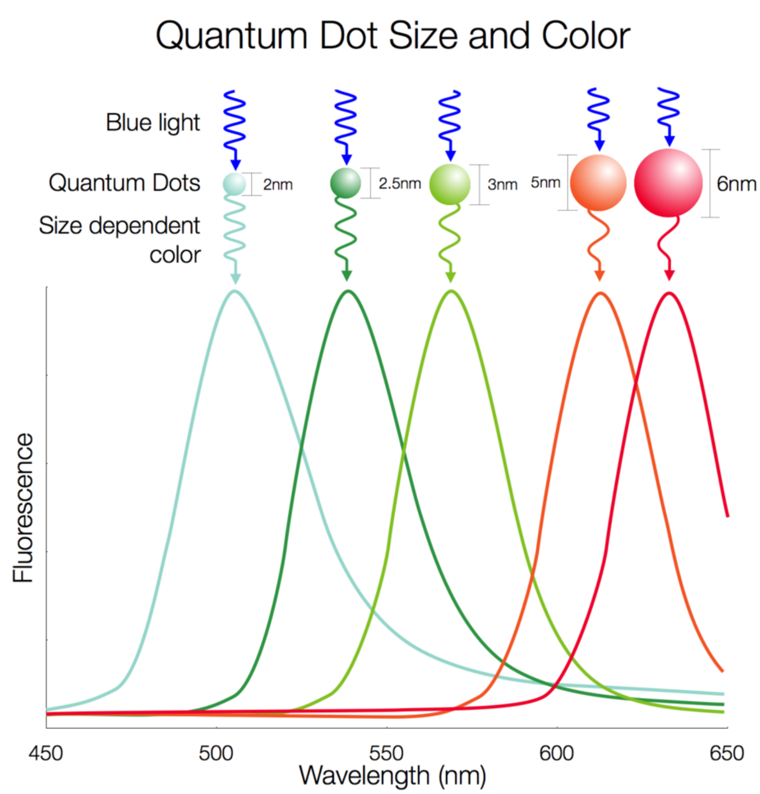
Meena (2014:24) attest that the memory made from tiny islands of semiconductors - known as quantum dots - could fill a gap left by today's computer memory, allowing storage that is fast as well as long lasting. Researchers have shown that they can write information into quantum dot memory in just nanoseconds. However, generally speaking, quantum dots are defined as semiconductor nanocrystals with particle dimensions range of 2 - 10 nanometres (10 - 50 atoms).

Quantum dots comprise a new class of material that can be tuned to emit any colour of light very efficiently by simply changing the material's crystallite size. Quantum dots have unique properties and can be used for LEDs and solid-state lighting, displays, photovoltaics, transistors, quantum computing, medical imaging, biosensors, among many others. Unlike other conventional materials, quantum dots, which are just nanometres in diameter, can be fabricated to convert short-wavelength light such as blue light to nearly any colour in the visible spectrum. Kuphaldt (2009:87) put all matters into perspective and state that graphene quantum dots within a transistor "this small" serve as single electron transistors.

The spectral output of a quantum dot is determined by its size. Bigger dots emit longer wavelengths, while smaller dots emit shorter wavelengths. In a similar sense Chen, Hardev and Yurek (2013) also elucidate that the best dots available today emit light with over 90% efficiency and with very narrow spectral distribution of only 30 - 40 nm at full-width at half-maximum.

For example, ranging in size from 2 to 6 nm, quantum dots made from the same material emit light in the visible spectrum at different wavelengths based upon size. Gavrilenko (2013:4) conclude by contending that the quantum dots are often referred to as artificial atoms. Therefore, the position of the energy levels of quantum dots can be changed by varying the size of the quantum dots. As per figure 5.4, quantum dots absorb high energy or shorter-wavelength light and down-converts the light into lower-energy or longer-wavelength light. The smallest dot represented here, at 2 nm in diameter, absorbs the light from a 450-nm blue source and emits light at 500-nm green wavelength while a larger 6-nm-diameter dot emits at 630-nm red wavelength. Precise control of quantum dots at manufacturing enables the dots to emit light at any wavelength in the visible spectrum (Chen, Hardev & Yure, 2013:3).

Figure 4: Quantum Dots of different sizes with corresponding output wavelengths



Source: Chen, Hardev & Yurek (2013)

6. FUNDAMENTAL METHODOLOGIES FOR GRAPHINE CREATION

There are several methods of mass-production of graphene (Gavrilenko, 2013:20), which allow wide choices in terms of size, quality and price for any particular application.

The industrial exploitation of graphene related 2d crystals and hybrids will require large scale and cost-effective production methods, while providing a balance between ease of fabrication and final material quality.

For example, the methods used for the production of graphene material consist, namely:

Micromechanical cleavage (MC) – used for research and proof of principle devices and is ideal for making prototype devices and will always be essential to investigate both new physics and concept devices.

Anodic bonding - used in microelectronics to bond Si wafers to glass. Makes it possible to apply micromechanical cleavage on a larger scale, while still giving high quality samples. This technique can produce larger samples than micromechanical cleavage.

Photo exfoliation - could be used to detach intact single layer graphene (SLG) from a graphite surface, one at a time, in principle free of contaminants and defects, at a high rate, both on wafer and in liquid. This technique can be an alternative and complementary technique to photo exfoliation.

Liquid phase exfoliation – offers many advantages in terms of cost reduction and scalability. It is used for coating, paint, batteries, super caps, solar cells, composites, sensors, photonics flexible electronics and optoelectronics and bio applications. This methodology paves the way to a large-scale production of patterned graphene.

Growth from SiC (Epitaxial graphene on SiC) – Used for sensors, RF transistors and other electronic devices. Different techniques can be used for the characterisation of epitaxial graphene such as Raman, X-ray photoelectron spectroscopy (XPS), spectroscopic and ellipsometry. Precipitation from metal substrate - devoted to the use of relatively inexpensive metals such as Ni and Co.

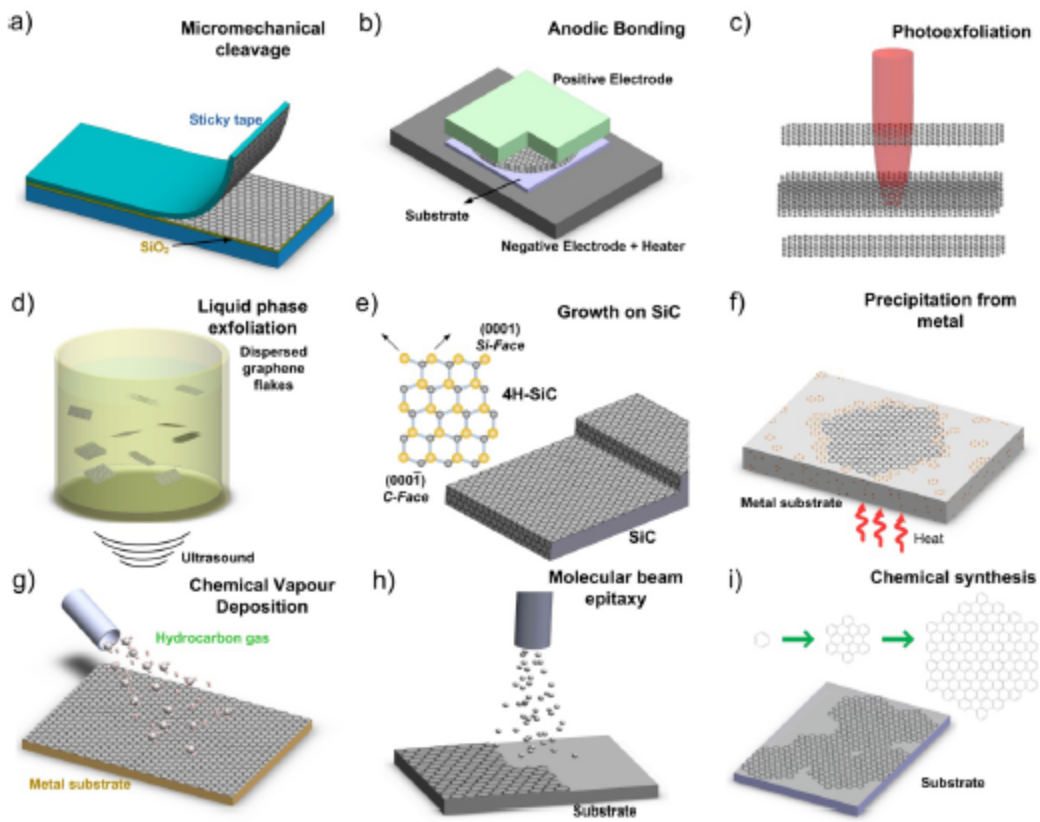
CVD process – used for photonics, nano electronics, sensors and bio applications Molecular beam epitaxy (MBE) - is an Ultra-High-Vacuum (UHV)-based technique for producing high quality epitaxial structures with monolayer control. Mostly used for epitaxial layers of metals, insulators and superconductors, both at the research and the industrial level. Can use a wide variety of dopants compared to CVD epitaxial techniques. It can also be used to grow carbon films directly on Si. Will have applications in RF, THz electronics and heat management.

Chemical synthesis - offers opportunities to control nano graphenes with well-defined molecular size and shape. Can be tuned to match the requirements for a variety of applications, not limited to, but ranging from digital and RF transistors, photodetectors, solar cells and sensors. It is suited for the formation of superstructures, whose physics is very rich.

However, Zhong et al.(2015:2) reiterate by contending that the mass production of graphene has main factors, which comprises production cost, scalability, reproducibility, process ability and the quality of the graphene products. Zhong et al.(2015:2) argue that considering the low cost and abundance of graphite flakes, the wet chemical approaches in exfoliation of graphite to graphene seem to fit all the requirements. Similarly, Zhong et al.(2015:2) conceal by cautioning that the definition on the quality of graphene or rather the efficacy of graphene is highly dependent on its application. For example, electro catalysis and storage of capacitive charges, it has been shown that the graphene edges are more superior compared to the graphene basal planes. Docherty et al.(2014:3) also discusses large-scale industrial production of graphene and presenting viable methods based “Ultrafast Transient Terahertz Conductivity of Monolayer” using CVD methodology.

Moreover, the schematic block diagram illustrating different methods used for the production of graphene material is depicted in figure 6.1. Such techniques include: (a) Micromechanical cleavage (b) Anodic bonding (c) Photo exfoliation. (d) Liquid phase exfoliation. (e) Growth from SiC. Schematic structure of 4H-SiC and the growth of epitaxial graphene on SiC substrate. Gold and grey spheres represent Si and C atoms, respectively. At elevated temperatures, Si atoms evaporate (arrows), leaving a C-rich surface that forms graphene. (f) Precipitation from carbon containing metal substrate. (g) CVD process. (h) Molecular beam epitaxy. Different carbon sources and substrates (i.e. SiC, Si, etc.) can be exploited and (i) Chemical synthesis using benzene as building blocks.

Figure 5: Schematic illustration of the main experimental setups for graphene production



Source: Bonaccorso, Ferrari, Falko & Novoselov (2012:46).

7. GRAPHENE OR QUANTUM APPLICATIONS – OPPORTUNITIES

As alluded to previously, potential electronics applications of graphene (Bae et al.,2012:3) include high-frequency devices and radio frequency communications, touch screens, flexible and wearable electronics, as well as ultrasensitive sensors, nano electromechanical systems (NEMS), super-dense data storage, or photonic devices. In the energy field, applications include batteries and super capacitors to store and transit electrical power, and highly efficient solar cells (Mao, Lu & Chen, 2014:2). The use of graphene as a transparent electrode in either quantum dots or dye-sensitized solar cells has proved highly beneficial (Novoselov, 2012:07). However, in the medium term, some of graphene's most appealing potential lies in its ability to transmit light as well as electricity, offering improved performances to light emitting diodes (LEDs), and aid in the production of next-generation devices, such as flexible touch screens, photodetectors, and ultrafast lasers.

Graphene's high electrical conductivity and large surface area per unit mass make it an interesting material for energy storage such as in advanced batteries and super capacitors. These could have a large impact on portable electronics and other key areas, such as electric cars. The prospect of rapidly chargeable lightweight batteries would give environmentally friendly transportation a push and advance the large scale implementation of electric cars as a key component in urban and suburban transport.

Strong and lightweight composites would also allow industries to build new cars, airplanes and other structures using less material and energy, and contribute directly to a more sustainable global economy. Figure 7.1 provides an overview of applications of graphene in different sectors ranging from conductive ink to chemical sensors, light emitting devices, composites, energy, touch panels and high frequency electronics.

Figure 6: Overview of Applications of Graphene in different sectors ranging from conductive ink to chemical sensors, light emitting devices, composites, energy, touch panels and high frequency electronics

Source: Ferrari *et el.* (2014:19).

8. CONCLUSION

Following on the interpretation of literature review analysis and supported arguments from various authoritative scientific research papers, it can be concluded that the stated objectives of the paper were met. Alluded to this, is the connection of views that existed between different key leading organisations currently investigating the future of technology in the field of science.

For example, graphene may favour not only a radical improvement of existing technologies, such as electronics and optoelectronics, but may also eventually enable the emergence of completely new technologies, hampered so far by intrinsic limitations of the employed materials and processes. The properties associated with graphene, being described by many physicians with respect to the other commonly used electronic materials, will permit the practical realisation of promising technological concepts.

Scientific papers have highlighted some graphene properties that are highly suitable for the development of novel spintronic devices and many research groups are now involved in such activity. Radically new technologies could be enabled by graphene. Taking these few examples of unique physical phenomena, it is reasonable to expect the rapid development of many new applications due to the development of graphene technology, with a huge impact for ICT industry.

Practical implementation of graphene requires understanding of its performance in real devices, as well as its durability under ambient and extreme conditions. A specialised effort will be needed to study the reliability of graphene-based devices, such as electric or thermal stress tests and device lifetime. To preserve device performance, it is likely that some protection of the graphene and the metals will be needed to minimize environmental effects.

The conclusive evidence identified during the literature analysis from previous sections can be interpreted as follows:

- The field of graphene related 2d crystals and hybrids are now rapidly evolving from pure science to technology;
- The incorporation of biomaterials into all of the different structural components of organic and nanomaterial based electronic devices has the potential to be applied towards a range of applications in medicine and point-of-care diagnostics;
- Future efforts will need to be focused on the development of new hybrid biomaterials integrated into electronic devices capable of being processed on flexible substrates;
- The overall progress of this research field will have enormous implications for both fundamental scientific discovery and technological development;
- The investigation of the interface of biomaterials and organic electronics could also lead to the realisation of new classes of electronically active medical devices for use in advancing human health;
- It is a milestone in chemical vapour deposition (CVD) history that the fabrication of sub-nanometre materials has been successfully achieved;
- Graphene is a unique crystal in the sense that it combines many superior properties, from mechanical to electronic; and
- More experimental work should be performed for graphene to be competitive on practical applications. This will be an extensive area of research in the near future with the intention to synthesize controllable number of graphene layers on arbitrary substrates with a reliable and reproducible method;

9. RECOMMENDATIONS

The key recommendations evolve around the need for a funding model focusing on University based research projects in the area of nanoelectronics for instance. This may include government funding models on business start-up, development, and commercialisation of nanotechnology based business ideas. The industry support and global research collaboration on nanotechnologies involvement is also needed.

Focus research programme will need to be incorporated with universities to maintain technology innovation on science. This is necessary for the development of talent pool of scientists and engineers in the field on science and technology. This may also include coordination between multi-university centres and other institutions including research innovation hubs. Private –public partnerships programmes will ensure the expansion of already existing centres and create new ones.

10. REFERENCES

Abott, J., 1850. History of Darius The Great, New York: Harper & Bros.

Ameriks, K., Clarke, D.M. & Janiak, A., 2004. Isaac Newton - Philosophical Writings 1st ed. K. Ameriks & D. M. Clarke, eds., Cambridge: Cambridge University Press. Available at: http://content.schweitzer-online.de/static/content/catalog/newbooks/978/052/183/9780521831222/9780521831222_Intro_001.pdf [Accessed March 6, 2015].

Bae, S., et al. 2012. Towards industrial applications of graphene electrodes. The Royal Swedish Academy of Sciences. doi:10.1088/0031-8949/2012/T146/014024

Bandaru, P.R& Kaul, A.B.2010. Electronic and Photonic Applications of One-Dimensional Carbon and Silicon Nanostructures. Encyclopedia of Semiconductor Nanostructures, American Scientific Publishers,2010 California Institute of Technology.

Bonaccorso, F., Ferrari, A., Falko, V.& Novoselov, K.2012. Coordination Action for Graphene-Driven Revolutions in ICT and Beyond: Coordination and support action - Scientific and technological roadmap for graphene in ICT. Graphene Flagship. Seventh Framework Programme, European Commission.

Chang, L., et al.2003. "Moore's law lives on [CMOS transistors]," Circuits and Devices Magazine, IEEE , 19(1), pp.35-42, Jan, doi: 10.1109/MCD.2003.1175106.

Chauhan, J., Liu,L., Lu,Y. & Guo,J. 2012. Assessment of High-Frequency Peformance Potential of Graphene Field-Effect Transistors. Department of ECE, University Florida. Florida, Gainesville, FL, 32611-6130, USA.

Chen, J., Hardev, V. & Yurek. 2013. Quantum-Dot Displays: Giving LCDs a Competitive Edge Through Color. Frontline Technology, Information Display 1/13.

Corey, L.P., 1826. No Title Ancient Fragments of Phenician, Chaldean, Egyptian, and Other Writers Second., London.

Docherty, C.J., et al.2014. Ultrafast Transient Terahertz Conductivity of Monolayer MoS2 and WSe2 Grown by Chemical Vapor Deposition. American Chemical Society, 8(11), pp.1-7.

Einstein, A., 1916. Ernst Mach. Physikalische Zeitschrift, 17, pp.101 – 104.

Engelbrecht,J. & Varlamova,G. 2011. Research in Estonia:Present and Future. Estonian Academy of Sciences, Tallinn.

Erman, A., 1894. Life in Anciant Egypt, London, New York: Macmillan.

Ferrari, A.C. et el. 2014. Nanoscale. Royal Society of Chemistry. DOI: 10.1039/C4NR01600A

Gavrilenko, V.P. 2013. Some Aspects of Nanophysics.Review Article. International Review of Atomic and Molecular Physics, 4 (1), January-June.

Gigov, E., 2012. Einstein or Newton, Bulgaria. Available at: http://www.rxiv.org/pdf/1208.0062v1.pdf [Accessed March 10, 2015].

Gomperz, T., 1905. Greek Thinkers: a History of Ancient Philosophy, New York.

Greene, B., 2005. The Fabric of the Cosmos: Space Time and the Texture of Reality 1st ed., New York.

Hambali,et al.2014. Synthesis of zinc oxide nanostructures on graphene/glass substrate by electrochemical deposition: effects of current density and temperature. Nanoscale Research Letters, 9:609

Hills, R.L., 2005. James Watt: The Years of Toil, 1775 - 1785 Illustrati., Landmark Publishers, 2005.

Hutchby, J.A., Bourianoff, G.I., Zhirnov, V.V., Brewer, J.E. 2002. "Extending the road beyond CMOS," Circuits and Devices Magazine, IEEE , 18(2), pp.28-41, Mar. doi: 10.1109/101.994856

Iwai, H. 2009. "Logic LSI technology roadmap for 22 nm and beyond," Physical and Failure Analysis of Integrated Circuits, 2009. IPFA 2009. 16th IEEE International Symposium on the , pp.7 - 10, 6-10 July. doi: 10.1109/IPFA.2009.5232710

Keepin, W., 1993. Lifework of David Bohm - River of Truth. , p.23. Available at: http://www.gaia.dk/international/externalarticles/bohm-lifework.pdf.

Kosidlo, U., et al. 2009. Production methods of graphene and resulting material properties. Sinuerop Nanoetch GmbH,Fraunhofer.

Kuphaldt 2009.T.R.2009. Lessons In Electric Circuits, Volume III – Semiconductors. Fifth Edition, Design Science License.

Laertius, D., 1853. The Lives and Opinions of Eminent Philosophers, C. D. Yonge's translation VIII., London.

Lewes, George, H., 1888. A Biographical History of Philosophy from its Origin in Greece down to the Present Day, New York.

Mach, E., 1883. Die Mechanik in ihrer Entwickelung 1st ed., Prague: F.A Brockhaus.

Mach, E., 1914. The Analysis of Sensations 1st ed., Chicago, London, Open Court Publishing Company. Available at:

https://www.marxists.org/reference/subject/philosophy/works/ge/mach.htm [Accessed March 6, 2015].

Mao,S.,Lu,G.&Chen,J.2014. Three-dimensional graphene-based composites for energy applications. The Royal Society of Chemistry. DOI: 10.1039/c4nr06609j.

Maspero, G., 1895. The Dawn of Civilization, Paris.

Meena,J.S.,Sze,S.M.,Chand,U.&Tseng,T.2014. Overview of emerging nonvolatile memory technologies. Nanoscale Research Letters,Springer.

Miao,C.,Zheng,C.& Xie,Y. 2011. Chemical Vapor Deposition of Graphene, Physics and Applications of Graphene. University of California, Los Angeles United States.

Montagna, J., 1981. The Industrial Revolution. Yale - New Haven Teachers Institute, p.1. Available at: http://www.yale.edu/ynhti/curriculum/units/1981/2/81.02.06.x.html [Accessed March 8, 2015].

Mumford, S., 2004. Laws in Nature 1st ed., Oxfordshire: Routledge 2 Park Square, Milton Park, Abingdon, Oxfordshire. Available at: http://samples.sainsburysebooks.co.uk/9781134386512_sample_521916.pdf [Accessed March 6, 2015].

Newton, I., 2014. The Principia: Mathematical Principles of Natural Philosophy 1st ed. B. Cohen & A. Whitman, eds., California: University of California Press, 2014.

Novoselov et al. 2012. A roadmap for graphene. Research Review, Macmillan Publishers Limited.

Ohm, G.S., 1827. The Galvanic Circuit Investigated Mathematically 1st ed., New York, New York, USA: Kraus Reprint Co.

Pojman, P., 2008. Ernst Mach. Available at: http://plato.stanford.edu/entries/ernst-mach/ [Accessed March 4, 2015].

Rao,K.S.,Senthilnathan,J.,Liu,Y.& Yoshimura,M.2003. Role of Peroxide Ions in Formation of Graphene Nanosheets by Electrochemical Exfoliation of Graphite. Sci. Rep. 4, 4237; DOI:10.1038/srep04237.

Ritter, H., 1838. The History of Ancient Philosophy, London.

Roco, M.C.&Bainbridge,W.S.2002. Converging Technologies for Improving Human Performance:Nanotechnology, Biotechnology, Information Technology and Cognitive Science. National Science Foundation, Arlington, Virginia

Schwierz, F. 2010. Graphene transistors. Nature Nanotechnology, 5, pp.487-47.

Smith,T.P.H. 1998. Navy Electricity and Electronics Training Series. Module 14 - Introduction to Microelectronics, Navedtra 14186.

Sordan, R., Ferrari, A.C.2013, "Gigahertz multi-transistor graphene integrated circuits," Electron Devices Meeting (IEDM), 2013 IEEE International , pp.1.1.1 - 1.1.7, 9-11 Dec. doi: 10.1109/IEDM.2013.6724538.

Thayne,I. et al. 2012. III-V MOSFETs for Sub-15 nm Technology Generation CMOS : Some Observations, Issues and Solutions. CS MANTECH Conference, April 23rd - 26th, Boston, Massachusetts, USA.

Tylor, E.B., 1871. Primitive Culture: Researches into the Development of Mythology, Philosophy, Religion, Art and Custom 2nd ed., London: John Murray.
Westfall, R.S., 1983. Never at Rest: A Biography of Isaac Newton 1st ed., New York: Cambridge University Press. Available at: http://www.maa.org/publications/maa-reviews/never-at-rest-a-biography-of-isaac-newton [Accessed March 6, 2015].

Whewell, W., 1847. History of the Inductive Sciences Volume 2., London.

Whitlock, L., 2013. Sir Isaac Newton. Starchild Publications, p.1. Available at: http://starchild.gsfc.nasa.gov/docs/StarChild/whos_who_level2/newton.html [Accessed March 6, 2015].

William Bern, A., 1898. The Philosophy of Greece Considered in Relation to the Character and History of its People, London.

Zhong,Y.L.,Tian,Z.,Simon,G.P.&Li.D.2015. Scalable production of graphene via wet chemistry: progress and challenges. Department of Materials Engineering, Monash University, Clayton, VIC 3800, Australia.