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## Visión Electrónica Más que un estado sólido

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VISIÓN ELECTRÓNICA

A CURRENT VISION

### Perspectives in nanoscience and nanotechnology

#### *Perspectivas en nanociencia y nanotecnología*

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#### ABSTRACT

This work is focused on reviewing the theoretical vision of the physicist Richard Feynman about nanoscience and nanotechnology, giving continuity to his ideas in the proper context of physics laws that has led nanoscience and nanotechnology to become robust and active sciences. Some implications of nanotechnology as a general-purpose foundational technology for all economic areas are discussed. Some aspects related to interactions between the fields of mathematics, high-energy physics and condensed matter physics that have allowed the remarkable development of new quantum material platforms for nanoelectronics are also analyzed.

#### RESUMEN

En este trabajo se revisa la visión teórica del físico teórico Richard Feynman acerca de la nanociencia y la nanotecnología dando continuidad a sus ideas en el contexto propio de las leyes de la física que ha llevado a la nanociencia y la nanotecnología a convertirse en robustas y activas ciencias. Se discuten algunas implicaciones propias de la nanotecnología vista como una tecnología fundacional de propósito general para todos los sectores de la economía. Así mismo se analizan algunos aspectos de la interacción entre campos de la matemática, la física de altas energías y la física de la materia condensada que han permitido el espectacular desarrollo de las nuevas plataformas de materiales cuánticos para la nanoelectrónica.

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## 1. Introduction

In 1959 theoretical physicist Richard Feynman gave a lecture entitled “There’s Plenty of Room at the Bottom, An Invitation to Enter a New Field of Physics” at the annual meeting of the American Physical Society in Caltech [1]. In this lecture, Feynman discusses the problem of manipulating and controlling things on a small scale, and begins by posing the following question: Why not write the entire 24 volumes of the “Encyclopedia Britannica” on a needle head? Moreover, Feynman proposes the idea of reproducing the 24 million volumes that the following libraries together hold: the Congress Library of the United States, the British Museum Library, and the National Library of France. Making simple calculations, Feynman concludes that an area approximately the size of 35 pages of the Encyclopedia would be needed, that is to say: all the information accumulated by humankind could be carried in a single brochure in one hand [1].

But Feynman took a step further by proposing that, instead of reproducing the information in its actual form, a code of dots and dashes could be used to represent each letter. Feynman then estimates that if one uses not only the needle head surface, but the inside of the material, then all the information that humankind has accumulated can be written on a cube made of material two-hundredths of an inch wide. So, how to read all this information? Feynman’s answer in 1960 was the following: to build better electron microscopes. Feynman emphasizes the importance of improving the electron microscope by stating that sciences such as biology would advance quickly if instead of using more mathematics, the electron microscope was improved a hundred times [1]. Regarding this, Feynman formulated the following challenge: Isn’t there a way to make the electron microscope more powerful?

As a final thought, Feynman proposed the following question: can we arrange atoms in any way we want?<sup>3</sup> What could we do with layered structures, with the right layers? What would be the material properties if we could really arrange atoms in any way we want?

The “There’s Plenty of Room at the Bottom, An Invitation to Enter a New Field of Physics” conference and their 1983 reformulation “Infinitesimal Machinery” [2], are now considered by some scientists to be the philosophical manifesto of nanoscience and nanotechnology.

However, from a practical point of view, the actual beginning of these fields of knowledge is considered to take place with three important scientific developments [3,4]: (1) the Scanning Tunneling Microscopy (STM) invention in 1981 by IBM scientists Gerd Binnig and Heinrich Rohrer [5]; (2) the Atomic Force Microscope (AFM) invention in 1986 by Stanford University scientists Gerd Binnig and C. F. Quate and IBM scientist Ch. F. Quate and Ch. Gerber [6]; and (3) the first manipulation of individual atoms on a surface, using STM to move thirty-five xenon atoms and create the IBM corporate logo, by Don Eigler and Erhard Schweizer of the IBM Almaden Research Center in California [7]. It was the first demonstration that mankind could move atoms one atom at a time. However, this demonstration is far from being an atomic scale model of a hard disk for data storage according to Feynman’s vision.

Following Feynman’s vision, the next sections provide a general overview of the development of nanoscience and nanotechnology, emphasizing in its multidisciplinary nature. Sections two and three are general descriptions of conceptual developments in these fields: controlled manipulation techniques of individual atoms using STM and AFM; challenges related to product regulation involving nanotechnologies or nanomaterials; and the development of new products that include nanotechnologies or nanomaterials. The fourth section describes key features of graphene nanomaterial physics as well as the technological projection of some two-dimensional materials.

## 2. Atom manipulation

The STM invention has been perhaps the main scientific development used in nanoscience and nanotechnology research. The STM is a type of electron microscope with a resolution at the atomic scale whose principle of operation is based on a quantum-mechanical phenomenon known as the tunneling effect [8, 9,10]. In STM, a sharp tungsten probe, approaching from a distance of 1 nm to a conductive sample, scans the surface by means of a scanner made of three piezoelectric rods that elongate on a nanometer scale when different voltage signals are applied. A voltage of 0.1 V is applied between the probe and the sample surface, causing a tunneling current that depends exponentially on the distance between the two metal surfaces. Thus, as the probe approaches a fixed distance of a few angstroms from the sample surface, the system controlling the STM registers

<sup>3</sup> So that they are chemically stable.

a reference tunnel current and marks the probe position. When the probe is moved to another position, the system detects the tunnel current variation and moves closer or further away the probe tip from the sample until the tunnel current reaches a reference tunnel current value. Then, the probe position is recorded, and it is moved again to another point of the sample. In this way it is possible to reveal three-dimensional images of surfaces, even at atomic level. The key feature of STM is the exponential dependence of tunnelling current on the distance separating two metallic surfaces: if the probe moves one atomic diameter towards the surface, the tunnelling current will increase by a factor of 100. It is this extreme resolution of STM that opened the door to the nanoworld, allowing not only atomic resolution imaging, but also the possibility of constructing objects at the nanometer scale.

In fact, the first version of STM was used by Binnig and Rohrer in 1982 to describe the 7x7 silicon structure at atomic scale [11], thus solving one of the most complex problems in surface science. The importance of this achievement was recognized in 1986 when Binnig and Rohrer were awarded the Nobel Prize in Physics. Then, in 1989 Don Eigler built an STM such that the uncontrollable variation of the distance between the probe and sample was only 2 picometers (or 1/100th of a typical atomic diameter), producing the first instrument able to perform controlled manipulations of individual atoms [7]. The creation of the IBM corporate logo by Don Eigler and Erhard Schweizer, using its STM to position thirty-five xenon atoms proved two things: (1) that atoms can be manipulated; (2) it showed that atoms can be seen as object building blocks at nanometer scale.

Atom manipulation by an STM takes place in two basic modes [12]: moving the particles along the surface without lifting them; or transferring an atom from the surface to the STM probe, repositioning the probe and transferring the atom to a desired position. On the other hand, AFM (a sibling of STM based on measuring force between the sample and probe, rather than tunneling current) has also been shown to allow manipulation of individual atoms even at room temperature [13,14]. Modern atomic resolution microscopy techniques now integrate AFM and STM capabilities, simultaneously measuring both force and current.

Following Eigler and Schweiter's work, many manipulations of individual atoms on a surface such as atomic corrals of Fe or Co on Cu (111) have been performed [15]. In 2016, researchers at Delft University

of Technology in the Netherlands developed a new method under ultrahigh vacuum for atom manipulation using an STM [16]. This technique consists of evaporating copper chloride powder on a crystalline copper surface to deposit a monolayer of chlorine atoms. Later they wrote a binary code by modifying the relative positions of the chlorine atoms and vacancies on the surface in such a way that a vacancy placed above a chlorine atom represents a 0, while one placed below a chlorine atom indicates a 1.

Using this data storage technique, the researchers encoded one of the passages of Feynman's conference, "There's Plenty of Room at the Bottom, An Invitation to Enter a New Field of Physics".

The results obtained in this work showed that it is possible to encode 8000 bits of data at 502 terabits per square inch, which implies a storage capacity 500 times greater than any existing hard disk to date. Although these results were encouraging, there is still room for improvement in aspects such as reading and writing data speed. For the scientific community this work constituted a real breakthrough in the atom manipulation and is an important step in Feynman's vision of storing information at atomic scale. Although the processes involved in atom manipulation are too slow for practical applications, Feynman's vision has been demonstrated to be feasible.

### 3. Nanoscience, Nanotechnology and Nanofiction

Nanoscience and nanotechnology are currently the core of disciplines such as quantum computing or nanomedicine and is perhaps the best example of mutual influence between science and engineering. However, nanotechnology has also often been presented in prophetic and fantastic terms. From the extreme of science fiction movie scripting in which the words "nano" or "quantum" are put in front of everything to break the laws of physics in fantastic ways, to scientific journal papers reporting on advances in nanotechnology and prophesying virus-sized nanomachines that will repair damaged human cells thus prolonging life or eventually annihilating death. Although such scenarios are not feasible at present, there is a common belief in the inevitability of future nanotechnology successes derived from ongoing work by techno scientists. According to Colin Milburn [17,18], representative texts of the popular and professional genre of writing about nanotechnology, often go beyond scientific speculation, setting out a

totalizing picture of the future in which nanotechnology has an almost messianic role in a radical metamorphosis of human life [17,18]. Milburn identifies this as one of the reasons nanotechnologies are characterized by some of its critics as “science fiction”. Driving this pseudo-scientific narrative are some representatives of social science and a humanistic scholarship who occasionally conduct critical reviews of the implications about nanotechnology by comparing them to future topographies envisioned by science fiction writers.

In reality, nanoscience and nanotechnology are highly multidisciplinary fields that involve experts in areas such as physics, chemistry, biology and engineering. The advances made by nanotechnology derived from basic research in nanoscience are innovative and have a high relevance in many areas. Despite this, there are common misconceptions about the scope of nanoscience and nanotechnology. In many areas, discussions related to nanoscience and nanotechnology are characterized by a significant lack of knowledge and reliable and updated information, starting from conceptual level. Therefore, governments have spent a lot of effort to define these disciplines, not only for regulatory purposes but also to understand their real impact on modern society.

The first definition of “nanotechnology” was introduced in 1974 by Japanese scientist N. Taniguchi of Tokyo University of Science in a paper entitled “On the basic concept of nano-technology” [19]. In that paper Taniguchi states that “Nano-technology mainly consists of the processing of separation, consolidation, and deformation of materials by one atom or one molecule” [19]. However, as the context in which nanotechnology is developed is so wide and complex, the different government agencies in each country have seen the need to develop different definitions of terms such as “nanotechnology” or “nanomaterial”, adapted to their purposes. For example, before 1999 nanotechnology definition emphasized ultra-precision engineering, ultra-dispersions or patterning of atoms and molecules on surfaces [20]. After 1999, the U. S. National Science Foundation (NSF) adopted the following definition of “nanotechnology” [20]:

“Nanotechnology is the ability to control and restructure the matter at the atomic and molecular levels in the range of approximately 1–100 nm [...]”

Since 2001 the U.S. Environmental Protection Agency (EPA) has promoted research into potential environmental and human health implications of

nanotechnology. In the document “Nanotechnology White Paper” document prepared for EPA by members of the Science Policy Board Nanotechnology Working Group of EPA’s Science Policy Board in 2007, nanoscience and nanotechnology are defined as follows [21]:

“Nanoscience: “the interdisciplinary field of science devoted to the advancement of nanotechnology”.

“Nanotechnology: “research and technology development at the atomic, molecular, or macromolecular levels using a length scale of approximately one to one hundred nanometers in any dimension; the creation and use of structures, devices and systems that have novel properties and functions because of their small size; and the ability to control or manipulate matter on an atomic scale”.

There is currently no internationally unified term such as “nanomaterial”, “nanostructure”, or “nanostructured material”, that meets the requirements for global legislation. Current definitions are based on intended applications in industry, research, or regulation [22-25]. Thus, there is a wide range of definitions of these terms, each of which is adapted to very specific sectors and activities.

According to International Organization for Standardization (ISO) a nanomaterial is any material with external or internal structures or surface structures at nanoscale [22]. On the other hand, as part of the discussions to assess the potential risks of nanomaterials and nanotechnology for quality of life in Europe, the definition adopted by the European Commission in 2011, is [23]:

“ ‘nanomaterial’ means a natural, incidental or manufactured material containing particles, in an unbound state or as an aggregate or as an agglomerate and where, for 50 % or more of the particles in the number size distribution, one or more external dimensions is in the size range 1 nm-100 nm [...]”

This approach requires specific analyses to determine the particle size ranges, considering that nanomaterials tend to agglomerate in fluids causing the loss of typical nanoscale properties. In general, most definitions of “nanomaterial” focus only on their size aspect (1-100 nm), and do not consider their various properties such as dimensionality and morphology;

chemical composition; complexity and functionality; and biological behavior [23].

In turn, the U.S. Food and Drug Administration (FDA) does not recommend adopting formal, fixed definitions for these terms until sufficient knowledge is known about interactions between nanomaterials and nanotechnology with biological and environmental systems. In this regard, FDA agrees that a definition that is appropriate in one area may be too narrow or wide to be useful in another area [26].

Thus, one of the main activities of the international associations is related to funding basic research on toxicological, ecotoxicological and epidemiological risks of nanomaterials and nanotechnology, to establish unified definitions, standards, nomenclatures, and databases to regulate the industry at a global level [22-26]. This, considering that lack of uniqueness is a source of ambiguity and confusion not only for the industry but also for legislators and public in general.

It is important to emphasize that now the interaction of nanomaterials and nanotechnology with biological systems and environmental systems is still under study, which implies that there is still a long way to go to understand the real scope of nanotechnology. Regarding this last issue, three stages of development are foreseen [27]: nanoscale phenomena research (2000-2010); nanoscale integration and creation of new products (2010-2020); and nanotechnology convergence with biotechnology, information technology, artificial intelligence, and cognitive science, i.e., NBIC integrated platforms (2020-2030). It has been estimated that only until 2030 a general-purpose technology will be available for all economy segments based on these platforms, with wide-ranging benefits for the improvement of life quality [27]. In this conceptual framework, nanotechnology has an important role in the convergence of science and technology, which stems from the fact that all physical systems' behavior is shaped by the scientific principles that underlie the nanoscale. This implies that several previously separate fields of science and technology are now tightly coupled to become so closely coupled that their boundary has become blurred.

Nanotechnology as a research area dedicated to solving emerging problems in engineering, science and technology represented in a wide spectrum of areas such as food, housing, transportation, health, water, clean energy, green manufacturing, among others, is currently facing a great challenge: the education and

training of a new generation of engineers, scientists, and skilled workers [28]. The lack of consensus on a nanotechnology definition has also impacted the educational communities, giving rise to diverse approaches because of different perspectives on what should be covered in the educational programs [28].

#### 4. Nanomaterials for nanoelectronics

Among a wide variety of nanomaterials used in human society, these can include all classes of materials such as: metals, ceramics, polymeric, composites, electronics, and biomaterials, if these exhibit a structural component at nanoscale or have one of its dimensions at nanoscale [29]. Nanomaterials are classified according to a number of dimensions that are not limited to nanoscale range (<100 nm), i.e.: zero-dimensional (0-D); one-dimensional (1-D); two-dimensional (2-D); and three-dimensional (3-D) [29].

Areas where nanomaterials are expected to have a considerable impact mediated by nanotechnology are electronics, optoelectronics, spintronics, and photonics, among others [29]. It should be noted that electronics is not necessarily considered a nanotechnology derivative, in the sense that the fabrication of electronic devices with structures smaller than 100 nm in size are the result of miniaturization techniques routinely used in semiconductor industry [24]. However, the integration of new two-dimensional nanomaterials into future electronic devices is expected to revolutionize the entire spectrum of applications in microelectronics.

In the framework of microelectronics applications, two-dimensional nanomaterials are a special case among nanomaterials due to their unique mechanical and transport properties [30-33]. The most well-known example of these nanomaterials is graphene, which was the first two-dimensional crystal found. It was first isolated in 2004 by a group of scientists at the University of Manchester led by Andre Geim [34,35]. Graphene belongs to a class of materials called "Dirac materials" characterized by the fact that the collective behavior of electrons is described by relativistic Dirac or Weyl equations. As a result, graphene exhibits pseudo relativistic effects, which make it ideal for performing electrodynamics tests in a simple experimental situation without requiring large particle accelerators [36,37].

Graphene is a monoatomic layer of graphite with carbon atoms arranged hexagonally in a periodic lattice. The bonds in the carbon hexagonal lattice strongly

link the atoms to their first three in-plane neighbors. The bonds are perpendicular to the sheet surface and are much weaker than bonds, allowing many layers of graphene to be stacked to form graphite. Electrons in bonds are responsible for its electronic properties [38-41].

The hexagonal graphene lattice can be described as a triangular Bravais lattice with a base of two atoms A and B, i.e., graphene lattice is composed of two sublattices A and B which are Bravais<sup>4</sup> lattices [39-41]. In real space ( $r$ -space), basis vectors  $a_i$  of the triangular lattice can be chosen as  $a_1 = a(3/2, \sqrt{3}/2)$  and  $a_2 = a(3/2, -\sqrt{3}/2)$ , where  $a = 1.42\text{Å}$  is the distance between neighboring carbon atoms. The reciprocal lattice, which facilitates a Fourier analysis, is a set of all wave vectors  $k=(k_x, k_y)$  that produce plane waves  $e^{ik \cdot r}$  with the same periodicity as the Bravais lattice  $R$  [42]. So, under a translation  $T_R$  a plane wave  $e^{ik \cdot r}$  satisfies  $T_R e^{ik \cdot r} = e^{ik \cdot (r+R)} = e^{ik \cdot r} \Leftrightarrow e^{ik \cdot R} = 1$ , implying that the basis vectors  $b_i$  of the reciprocal lattice in momentum space ( $k$ -space) are given by the relation  $a_i \cdot b_j = 2\pi \delta_{ij}$ . Consequently, it can be chosen  $b_1 = b(\sqrt{3}/2, 3/2)$  and  $b_2 = b(\sqrt{3}/2, -3/2)$ , where  $b = 4\pi/3a$ .

On the other hand, the first Brillouin<sup>5</sup> zone  $\Gamma$  in  $k$ -space is a hexagon rotated by  $90^\circ$  with respect to the hexagons of the real graphene lattice in  $r$ -space [39,40]. At hexagon corners of the graphene first Brillouin zone there are high  $K$  symmetry points named Dirac points, which are responsible for the peculiar properties of graphene [39,40].

To derive the electronic band structure, it is necessary to solve the Schrödinger equation<sup>6</sup>  $H\psi(r,k) = E\psi(r,k)$ , which

<sup>4</sup> A Bravais lattice (2D), is an infinite matrix of discrete points determined by the lattice vectors  $R = n_1 a_1 + n_2 a_2$  where  $n_1$  and  $n_2$  are integers, and the linearly independent vectors  $a_1$  and  $a_2$  are the primitive vectors for the Bravais lattice [42]. Thus, the point  $\sum n_i a_i$  is reached by moving  $n_i$  length units in  $a_i$  direction for  $i=1,2$ .

<sup>5</sup> In Bravais lattice, a primitive cell called a Wigner-Seitz cell is defined as the surrounding region of a grid point that is closer to this point than any other point. The reciprocal cell of the Wigner-Seitz cell is called the first Brillouin zone [42].

<sup>6</sup> In order to determine the behavior of an electron in a crystal lattice, it is necessary to solve the time-independent Schrödinger equation  $H\psi(r,k) = E\psi(r,k)$  [42]. The Hamiltonian operator is given by  $H = -\frac{\hbar^2}{2m} \nabla^2 + V(r)$ , where  $V(r)$  is the "seen" potential by each electron in the lattice;  $\psi(r)$  and  $E$  are, respectively, the wave function and electron energy;  $\nabla^2$  is the Laplacian operator; and  $m$  the electron mass. The potential  $V(r)$ , which represents the electron interaction with all lattice atoms and with other electrons, is periodic and has the same translational symmetry as the lattice:  $V(r+R) = V(r)$ . So, according to Bloch's theorem, the electron wave functions in the crystal lattice are solutions of the Schrödinger Equation with crystal lattice periodicity, which implies that  $\psi_k(r+R) = e^{ik \cdot R} \psi_k(r)$  [42]. The periodic potential produced by individual atoms in crystal lattice causes electrons to move in waves called Bloch waves, where each one can be associated with a "quasiparticle" with energy  $E = \hbar\omega$ , where  $\hbar$  is Planck's constant and  $\omega$  is the wave frequency. Strictly speaking these quasiparticles are not electrons, but they are often given this name [42].

means: to obtain the eigenvalues of the Hamiltonian  $H$  as a function of the Bloch wavenumber  $k$ . In practice, only the solutions of the Schrödinger equation for a given  $k$  in the first Brillouin zone are calculated, since the solution elsewhere can be calculated from the first cell based on Bloch's theorem.

In the framework of a semiempirical tight-binding model with first neighbor<sup>7</sup> interactions approximation [38-41], solving the Schrödinger equation implies that in the electron wave function  $\pi$  of sublattice A or B, only the first three neighbors in the complementary sublattice B or A, respectively, are considered.

Thus, in this approximation the Schrödinger equation  $H\psi(r,k) = E\psi(r,k)$  for spinless quasiparticles in graphene becomes [40]:

$$H(k) \begin{pmatrix} \Phi_A \\ \Phi_B \end{pmatrix} = \begin{pmatrix} 0 & -\gamma_0 \alpha(k) \\ -\gamma_0 \alpha(k)^* & 0 \end{pmatrix} \begin{pmatrix} \Phi_A \\ \Phi_B \end{pmatrix} = E \begin{pmatrix} \Phi_A \\ \Phi_B \end{pmatrix} \quad (1)$$

where  $\alpha(k) = 1 + e^{ik \cdot a_1} + e^{ik \cdot a_2}$  and  $\gamma_0$  is a parameter.

Diagonalizing the Hamiltonian  $H$  the following dispersion relation of energy<sup>8</sup> are obtained [39-41]:

$$E_{\pm}(k) = \pm \gamma_0 |\alpha(k)| = \pm \gamma_0 \sqrt{1 + 4 \cos \frac{\sqrt{3} k_x a}{2} \cos \frac{k_y a}{2} + 4 \cos^2 \frac{k_y a}{2}} \quad (2)$$

Negative energy band  $E_-$  corresponds to a valence band and positive energy band  $E_+$  to a conduction band. These bands approach in the form of cones at the six corners of the first Brillouin zone by touching at the Dirac points  $K$  and  $K'$ , where  $E_{\pm}(K) = E_{\pm}(K') = 0$  [39-41]. As a result, the Fermi<sup>9</sup> level  $E_F$  is the zero-energy reference, and the Fermi surface is the finite and discrete set of points  $K$  and  $K'$  [39-41].

The electronic band structure of graphene consists of three main parts [48-50]: a fully occupied lower bands of the  $\sigma$  system, which are energetically far below the Fermi level  $E_F$  and do not participate in electron conduction; the  $\pi$  system bands, where the lower  $\pi$  band is occupied, and the upper  $\pi^*$  band is not occupied; finally (3) bands far above the Fermi level  $E_F$ . Electrical conduction occurs when electrons are excited from  $\pi$  band to  $\pi^*$  band.

<sup>7</sup> The tight binding model is an approach to calculate the electronic band structure using an approximate set of wave functions given by the superposition of wave functions of isolated atoms located at each atomic site. This approximation can be performed at first neighbors, second neighbors, and so on [42].

<sup>8</sup> The dispersion relation is an expression of the energy in terms of wave vectors  $k$  [40,41,42].

<sup>9</sup> The Fermi level is the highest energy level that an electron can occupy at  $T=0^\circ K$  [40,41,42].

In low energy approximation (around Dirac  $K$  points, where  $E < 1eV$ ), the Schrödinger equation becomes a relativistic Dirac-Weyl-like equation [39,40]:

$$\mathbf{p}_F \cdot \boldsymbol{\sigma} (-i\hbar \nabla) \psi(\mathbf{r}) = E \psi(\mathbf{r}) \quad (3)$$

where the Hamiltonian  $H$  turns to be a Dirac<sup>10</sup> type Hamiltonian [39,40]

$$H = v_F \boldsymbol{\sigma} \cdot (-i\hbar \nabla) = \begin{pmatrix} 0 & k_x - ik_y \\ k_x + ik_y & 0 \end{pmatrix} = v_F (p_x \sigma_x + p_y \sigma_y) \quad (4)$$

with  $\hbar = h/2\pi$  the reduced Planck's constant;  $p_i = \hbar k_i, i=x,y$  electron momentum components;  $\sigma = (\sigma_x, \sigma_y)$  Pauli<sup>11</sup> matrices; and  $v_F \approx 0.86 \times 10^6$  m/s the Fermi velocity<sup>12</sup> in graphene [39,40]. In this approximation, the energy dispersion relation becomes linear,  $E_{\pm}(k) = \pm \hbar v_F |k|$  [39,40], implying that effective electron mass<sup>13</sup> in the vicinity of a Dirac point  $K$  is zero [43,44].

In terms of electronic properties, graphene is a semiconductor material with a zero-energy gap, where the collective behavior of electrons can be described by the Dirac-Weyl-like equation [39,40], in other words, the charge carriers in graphene behave as relativistic particles with zero rest mass (massless Dirac fermions, originally predicted in high-energy physics), where the speed of light  $c$  is replaced by Fermi's speed  $v_F \approx c/300$  [39,40]. These peculiarities make graphene exhibit several electronic properties such as an anomalous quantum Hall effect and superconductivity [39,45]. It is important to highlight the differences between the Dirac-Weyl equation in graphene and elementary particle physics contexts [46]: the fact that the non-relativistic Schrödinger equation describing electron transport in graphene becomes the Dirac-Weyl equation in low-energy approximation is a direct consequence of graphene lattice symmetry; the pseudospin substitutes the role of spin in the usual relativistic energy spectrum of massless Dirac fermions; unlike relativistic particles, low-energy excitations in graphene have a Fermi velocity that is 300 times slower than the speed of light.

However, the Dirac fermion is not the only concept from elementary particle physics that has been used to describe graphene physics. Another concept, originally proposed in high-energy physics, has also been successfully used to describe the graphene behavior, supersymmetry. Indeed, the deep connection between supersymmetry and the Atiyah-Singer index theorem is expected to allow understanding a variety of unconventional Quantum Hall Effects that occur in graphene [47,48,49]. In this framework, the application of the index theorem to the Dirac-Weyl differential equation governing graphene physics has also provided a relationship between zero-energy modes and the topology of the graphene sheet, for example, in fullerene and carbon nanotube molecules [49].

Graphene is currently one of the most promising nanomaterials because of its exceptional transport properties. In addition, graphene can be arranged to form tubes, ribbons, wires and multilayers, with almost unlimited applications in a wide spectrum ranging from nanoelectronics to optoelectronics, sensors and nanomedicine. While graphene's zero energy gap is a disadvantage for its use in field-effect transistors, bandgap engineering techniques have made it possible to create and control a forbidden electronic bandgap. Thus, graphene, which is normally a semimetal capable of conducting electrons at extremely high speeds, also behaves like a semiconductor under certain conditions [50]. This makes it a potential candidate to replace silicon in CMOS systems used in today's computing.

The discovery of graphene has motivated a great interest in two-dimensional materials research [32,51,52]. There are now notable examples of 2D materials with electrical and optical properties of great relevance for microelectronics, spintronics applications and flexible electronics [30,31,32,33,53,54,55]. Some of these materials are black phosphorus<sup>14</sup> (phosphorene), hexagonal boron nitride (h-BN), and transition metal dichalcogenides (TMDs). Among these materials, hexagonal boron nitride and transition metal dichalcogenides such as n-type molybdenum disulfide and p-type tungsten diselenide have been considered for integration into FETs. On the other hand, the integration of MoS<sub>2</sub> has reached such an extent that a complete MoS<sub>2</sub>-based integrated circuit has been designed with the ability to amplify signals and perform basic logic operations [56].

<sup>10</sup> For the  $K'$  point, one has the Hamiltonian  $H' = H^T$

<sup>11</sup> The Pauli matrices in 2D are defined as usual:  $\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$ ,  $\sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$ .

<sup>12</sup> The Fermi velocity is the velocity associated with the Fermi energy, i.e.: the velocity of the electrons which occupy the Fermi level.

<sup>13</sup> For the "quasiparticles" associated with Bloch waves in a solid, its mass is called "band mass" or "effective mass", and is not necessarily the same as the mass of a free electron. The energy bands whose momentum dependence is linear describe quasiparticles with zero effective mass, while the energy bands whose momentum dependence is quadratic describe quasiparticles with non-zero effective mass. The effective mass of the "electrons" in a solid determines the material's electrical conductivity.

<sup>14</sup> In literature, the suffix "-ene" is an indication of single-layer 2D materials.

Another 2D material that has attracted a lot of attention from researchers is black phosphorus. This phosphorus allotrope has a direct band gap of 0.33 eV, which increases above 1 eV when arranged in monolayer form. Because of this and the high charge carrier mobility ( $100000\text{cm}^2\text{V}^{-1}\text{s}^{-1}$ ), black phosphorus has applications in optoelectronics and infrared photonics [57]. Table 1 shows the electronic properties of some 2D materials.

**Table 1.** Room temperature solid-state properties of selected 2D crystalline materials, [54].

| 2D material         | Optical       |           | Electrical  |   | Mechanical           |   | Thermal                         |                                    |
|---------------------|---------------|-----------|---|---|----------------------|---|---------------------------------|------------------------------------|
|                     | Band gap (eV) | Band Type | Device Mobility ( $\text{cm}^2\text{V}^{-1}\text{s}^{-1}$ ) | $v_{\text{sat}}$ ( $\text{cm/s}^{-1}$ ) | Young's Module (GPa) | Fracture strain (%) Theoretic (Measure) | $(\text{Wm}^{-1}\text{K}^{-1})$ | $\text{CTE}(10^{-6}\text{K}^{-1})$ |
| Graphene            | 0             | D         | $10^3\text{-}5\times 10^4$                                  | $\frac{1}{-5\times 10^7}$               | 1.000                | 27-38(25)                               | 600-5.000                       | -8                                 |
| 1L $\text{MoS}_2$   | 1.8           | D         | 10-130  | $4\times 10^6$                          | 270                  | 25-33(23)                               | 40                              | NA                                 |
| Bulk $\text{MoS}_2$ | 1.2           | I         | 30-500  | $3\times 10^6$                          | 240                  | NA                                      | 50(∥),4(⊥)                      | 1.9(∥)                             |
| 1L $\text{WSe}_2$   | 1.7           | D         | 140-250   | $4\times 10^6$                          | 195                  | 26-37 NA                                | NA                              | NA                                 |
| Bulk $\text{WS}_2$  | 1.2           | I         | 500   | NA                                      | $\frac{75}{-100}$    | NA                                      | 9.7(∥),2(⊥)                     | 11(∥)                              |
| $h\text{-BN}$       | 5.9           | D         | NA  | NA                                      | 220 - 880            | 24(3-4)                                 | 250 - 360 (∥),2(⊥)              | -2.7                               |
| Phosphorene         | 0.3-2*        | D         | 50-1.000  | NA                                      | $\frac{35}{-165}$    | 24-32                                   | 10-35(∥)                        | NA                                 |

NA: not available. \* The precise value for the bandgap, which is a maximum for a monolayer is a matter of ongoing research. The symbol ∥ signifies the in-plane direction; ⊥ signifies the out plane direction.

In addition, both physical and chemical properties as well as electrical and magnetic properties of some 2D materials can be tuned by strain engineering or applying external electric and magnetic fields [57-60].

Examples of these tunable materials are arsenene and antimonene: normally semimetals, these materials become indirect semiconductors when reduced to an

atomic monolayer [58]. Applying a small biaxial strain to these atomic monolayers of arsenene and antimonene, can change their forbidden band character from indirect to direct [58]. On the other hand, in the case of silylene it is possible to create a forbidden band that can be tuned by applying a vertical electric field [59-61]. Table 2 shows some of the electronic properties that can be tuned in various 2D van der Waals materials [62].

**Table 2.** Examples of tunable materials, [62].

| Material  | Tunable Electronic Property            |
|---|--|
| 2H-TMDC<br>(2H- $\text{MoTe}_2$ , 2H- $\text{MoSe}_2$ , 2H- $\text{MoS}_2$ , 2H- $\text{WTe}_2$ , etc.)<br>+<br>Janus Structure<br>( $\text{MoSSe}$ , etc.) | Charge density, Exciton binding energy |
| h-Boron Nitride ( $h\text{-BN}$ )   | Charge density                         |
| MXenes ( $\text{Ti}_3\text{C}_2$ , etc.)  | Polarization                           |
| $\text{Fe}_3\text{GeTe}_2$  | Magnetization                          |
| III-VI compound family ( $\alpha\text{-}2\text{H-In}_2\text{Se}_3$ , etc.)  | Charge density                         |
| $\beta\text{-InSe}$   | Charge density                         |
| Silicene/Germanene  | Charge density                         |
| III-VI compound family ( $\alpha\text{-}3\text{R-In}_2\text{Se}_3$ , etc.)  | Polarization                           |



Arrival of 2D materials allowed scientists to combine two or more single layer 2D materials to create van der Waals heterostructures, which are nowadays integrated in all functional nanoelectronic devices. One example of these heterostructures is rotated graphene, displaying new and surprising electronic and optical properties [63,64]. Rotated graphene is obtained from two overlapping graphene layers rotated at an angle of approximately one degree [63,64]. Around 2010, it was predicted that electron Fermi velocity in a rotated graphene structure would decrease to near zero, which would cause the Coulomb interaction between the electrons to modify the electronic properties of the material. It was only until mid-2017 that the new electronic properties of rotated graphene were experimentally demonstrated: an unusual type of insulating behavior.

Furthermore, by adding some charge carriers to this insulating state, a superconducting state is obtained that can be electrically controlled. It is now known that by superimposing two sheets of graphene and rotating one around the other, the periodic alignment and misalignment of the atoms creates a moiré<sup>15</sup> pattern that results in a grid of low and high energy sites throughout the material. As a consequence, the behavior of electrons in the material is strongly modified thus inducing new electronic properties in the material. This strange phenomenon is derived from the strong correlations between the electrons in the material and the topological configurations of the electronic bands.

Physics research on massless Dirac Fermions in materials beyond graphene has led to the prediction and subsequent experimental discovery of topological insulators or Quantum Spin Hall<sup>16</sup> states [64]. These materials are called “topological” since wave functions describing their electronic states span a Hilbert space that has a non-trivial topology. This fact is manifested as follows: in the two-dimensional case a topological insulator differs from ordinary band insulators by the presence of one-dimensional metallic states along its edge; whereas in three-dimensional case a topological insulator is insulating in its volume and presents exotic topologically protected metallic (conducting) states on its surfaces [64]. Thus, topological insulators are materials that are insulators in their bulk but are perfect conductors at their boundaries.

<sup>15</sup> A moiré pattern is an interference pattern obtained by superimposing similar but slightly offset or rotated stencils with respect to each other.

<sup>16</sup> The quantum Hall system is considered to be the first topological insulator known to physicists. Graphene was the first quantum spin Hall insulator (IQSH) material.

## 5. Conclusions

As stated before, there is currently no international consensus on many of the concepts and terms involved in nanoscience and nanotechnology. In addition, the extraordinary growth of basic research in these areas has blurred the boundary between nanoscience and nanotechnology to such an extreme that nanotechnologists in various industries see no difference between terms that denote nanoscience and terms that denote nanotechnology. In addition, the integration of nanotechnology with information technology, biotechnology, cognitive science, and artificial intelligence in Nano-Bio-Info-Cognitive (NBIC) platforms has posed formidable challenges in clarifying the purpose and nature of derivative products, as well as in establishing a common language [65], [66]. In this context it is necessary to speak of “nanotechnologies” as fields of knowledge related to controlled fabrication of nano systems or nanostructures at the 100 nm length scale in areas such as: materials science, information technologies, energy production and storage, food, water, and environment, among others. Regarding NBIC platforms, the creation of new fields of knowledge and new technological products is imminent and will radically modify lifestyles: from educational processes, through the rise of new professions and disappearance of many others, to the improvement of life expectancy [67], [68]. In conclusion, if new NBIC technological platforms bring with them something inevitable, it is not - for now - the annihilation of death, but a new industrial revolution.

## References

- [1] R. P. Feynman, “There’s Plenty of Room at the Bottom”, In *The Pleasure of Finding Things Out: The Best Short Works of Richard Feynman*, ed. by J. Robbins. Cambridge MA: Perseus, pp. 117-139, 1999.
- [2] R. P. Feynman, “Infinitesimal Machinery”, *J. of Microelectromechanical Systems*, vol. 2, no. 1, pp. 4- 14, 1993. <https://doi.org/10.1109/84.232589>
- [3] C. Toumey, “Reading Feynman into Nanotechnology: A Text for a New Science”, *Techné: Research in Philosophy and Technology*, vol. 12, no. 3, pp.133-168, 2008. <https://doi.org/10.5840/techne20081231>
- [4] C. Toumey, “Plenty of room, plenty of history”, *Nature Nanotechnology*, vol. 4, pp. 783-784, 2009. <https://doi.org/10.1038/nnano.2009.357>

- [5] G. Binnig, H. Rohrer, "Scanning tunneling microscopy", *Surface Science*, vol. 126, no. 3, pp. 236-244, 1983. [https://doi.org/10.1016/0039-6028\(83\)90716-1](https://doi.org/10.1016/0039-6028(83)90716-1)
- [6] G. Binnig, "Quate and C. Gerber, Atomic Force Microscope", *Physical Review Letters*, vol. 56, no. 9, pp. 930-933, 1986. <https://doi.org/10.1103/PhysRevLett.56.930>
- [7] D.M. Eigler, E. K. Schweizer, "Positioning Single Atoms with a Scanning Tunneling Microscope", *Nature*, no. 344, pp. 524-526, 1990. <https://doi.org/10.1038/344524a0>
- [8] G. Binnig, H. Rohrer, "Scanning tunneling microscopy—from birth to adolescence", *Review of Modern Physics*, vol. 59, pp. 615-625, 1987. <https://doi.org/10.1103/RevModPhys.59.615>
- [9] G. Binnig, H. Rohrer, Ch. Gerber, E. Weibel, "Surface Studies by Scanning Tunneling Microscopy", *Physical Review Letters*, vol. 49, pp. 57-61, 1982. <https://doi.org/10.1103/PhysRevLett.49.57>
- [10] C. J. Chen, "Introduction to scanning tunneling microscopy", Oxford University Press, New York, 1993.
- [11] G. Binnig, H. Rohrer, Ch. Gerber, E. Weibel, "7 × 7 Reconstruction on Si(111) Re-solved in Real Space", *Physical Review Letters*, vol. 50, pp. 120-123, 1983. <https://doi.org/10.1103/PhysRevLett.50.120>
- [12] G. Meyer, "Atom manipulation with the scanning tunneling microscope: nanostructuring and femtochemistry", *Journal Superlattices and microstructures*, vol. 25, no. 2, pp. 463-47, 1999. <https://doi.org/10.1006/spmi.1998.0676>
- [13] S. Morita, "Atom world based on nano-forces: 25 years of atomic force microscopy", *Journal of Electron Microscopy*, vol. 60, no. 1, pp. S199-S211, 2011. <https://doi.org/10.1093/jmicro/dfro47>
- [14] O. Custance, R. Perez, S. Morita, "Atomic force microscopy as a tool for atom manipulation", *Nature Nanotechnology*, vol. 4, pp. 803-810, 2009. <https://doi.org/10.1038/nnano.2009.347>
- [15] S. Hla, "Single-atom manipulation mechanisms during a quantum corral construction", *Physical Review B*, vol. 67, no. 20, 2003. <https://doi.org/10.1103/PhysRevB.67.201402>
- [16] F. E. Kalf, "A kilobyte rewritable atomic memory", *Nature Nanotechnology*, vol. 11, pp. 926-929, 2016. <https://doi.org/10.1038/nnano.2016.131>
- [17] C. Milburn. "Nanotechnology in the Age of Posthuman Engineering: Science Fiction as Science", *Configurations*, vol. 10, no. 2, pp. 261-95, 2002. <https://doi.org/10.1353/con.2003.0017>
- [18] C. Milburn, "Just for Fun: The Playful Image of Nanotechnology", *Nanoethics*, vol. 5, pp. 223-232, 2011. <https://doi.org/10.1007/s11569-011-0120-4>
- [19] N. Taniguchi, "On the basic concept of 'nanotechnology'", in Proceedings of the International Conference on Production Engineering, pp. 18-23, 1974.
- [20] M. C. Roco, "The long view of nanotechnology development: the National Nanotechnology Initiative at 10 years", *Journal of Nanoparticle Research*, vol. 13, pp. 427-445, 2011. <https://doi.org/10.1007/s11051-010-0192-z>
- [21] U.S. Environmental Protection Agency, U.S. Environmental Protection Agency Nano-technology White Paper EPA 100/B-07/001, Washington, D.C., U.S. Environmental Protection Agency, 2007.
- [22] ISO/TS 80004-1:2015, "nanotechnologies—vocabulary—Part 1: core terms", Geneva Switzerland, 2007.
- [23] K. Savolainen, "Nanosafety in Europe 2015-2025: Towards Safe and Sustainable Nanomaterials and Nanotechnology Innovations", Helsinki: Finnish Institute of Occupational Health, 2013.
- [24] G. Lövestam, "Considerations on a Definition of Nanomaterial for Regulatory Purposes", Joint Research Centre of the European Commission, Ispra, Italy, 2010.
- [25] A. J. Bleeker, "Considerations on the EU definition of a nanomaterial: Science to support policy making", *Regulatory Toxicology and Pharmacology*, vol. 65, pp. 119-125, 2013. <https://doi.org/10.1016/j.yrtph.2012.11.007>

- [26] U.S. Food and Drug Administration, Nanotechnology: A Report of the U.S. Food and Drug Administration Nanotechnology Task Force, 2007.
- [27] M. C. Roco, "Overview: affirmation of nanotechnology between 2000 and 2030", in: *Nanotechnology Commercialization: Manufacturing Processes and Products*, First Edition., Ed. by T. Mensah, B. Wang, G. Bothun, J. Winter and V. Davis, John Wiley & Sons, Inc. 2018. <https://doi.org/10.1002/9781119371762.ch1>
- [28] S. E. Lyshevski, "Multidisciplinary undergraduate Nano-Science, Engineering and Technology Course", *Proceedings IEEE Conference Nanotechnology*, Cincinnati, OH, pp. 399–402, 2006. <https://doi.org/10.1109/NANO.2006.247661>
- [29] M. F. Ashby, P. J. Ferreira, D. L. Schodek, "Nanomaterials, nanotechnologies and design: an introduction for engineers and architects", Elsevier, Oxford, 2009. <https://doi.org/10.1016/B978-0-7506-8149-0.00003-9>
- [30] G. Fiori, "Electronics based on two-dimensional materials", *Nature Nanotechnology*, vol. 9, pp. 768–779, 2014. <https://doi.org/10.1038/nnano.2014.207>
- [31] M. C. Lemme, "Two-dimensional materials for electronic applications", *Materials Research Society Bulletin*, vol. 39, pp. 711–718, 2014. <https://doi.org/10.1557/mrs.2014.138>
- [32] M. Houssa, A. Dimoulas, A. Molle, "2D Materials for Nanoelectronics", CRC Press Taylor & Francis Group, Boca Raton FL, 2016. <https://doi.org/10.1201/b19623>
- [33] E. C. Ahn, "2D materials for spintronic devices", *2D Materials and Applications*, vol. 4, no. 17, 2020. <https://doi.org/10.1038/s41699-020-0152-0>
- [34] K. S. Novoselov, "Electric Field Effect in Atomically Thin Carbon Films", *Science*, vol. 306, pp. 666–669, 2004. <https://doi.org/10.1126/science.1102896>
- [35] K. S. Novoselov, "Two-dimensional atomic crystals", *Proceedings of the National Academy of the United States of America*, vol. 102, no. 30, pp. 10451–10453, 2005. <https://doi.org/10.1073/pnas.0502848102>
- [36] K. S. Novoselov, "Two-dimensional gas of massless Dirac fermions in graphene", *Nature*, vol. 438, pp. 197–200, 2005. <https://doi.org/10.1038/nature04233>
- [37] N. M. Peres, "Graphene, New Physics in two dimensions", *Europhysics News*, vol. 40, no. 3, pp. 17–20, 2009. <https://doi.org/10.1051/epn/2009501>
- [38] P. R. Wallace, "The band theory of graphite", *Physical Review*, vol. 71, no. 9, 1947. <https://doi.org/10.1103/PhysRev.71.622>
- [39] S. Das Sarma, "Electronic transport in two-dimensional graphene", *Reviews of Modern Physics*, vol. 83, pp. 407–2011. <https://doi.org/10.1103/RevModPhys.83.407>
- [40] L. E. Foa, S. Roche, J. C. Charlier, "Introduction to Graphene-Based Nano-materials", Cambridge University Press, New York, 2014.
- [41] D. Fathi, "A Review of Electronic Band Structure of Graphene and Carbon Nanotubes Using Tight Binding", *Journal of Nanotechnology*, vol. 2011, 2011. <https://doi.org/10.1155/2011/471241>
- [42] C. Kittel, "Introduction to Solid State Physics", 8th ed. John Wiley & Sons, Inc., New York, 2004.
- [43] V. Ariel, A. Natan, "Electron effective mass in graphene", International Conference on Electromagnetics in Advanced Applications, 2013. <https://doi.org/10.1109/ICEAA.2013.6632334>
- [44] E. Tiras, "Effective mass of electron in monolayer graphene: Electron-phonon interaction", *Journal of Applied Physics*, vol. 113, no. 4, 2013. <https://doi.org/10.1063/1.4789385>
- [45] F. D. Haldane, "Model for a Quantum Hall Effect without Landau Levels: Condensed-Matter Realization of the Parity Anomaly", *Physical Review Letters*, vol. 61, no. 18, 1988. <https://doi.org/10.1103/PhysRevLett.61.2015>
- [46] J. Cayssol, "Introduction to Dirac materials and topological insulators", *Comptes Rendus Physique*, vol. 14, no. 9, pp. 760–778, 2013. <https://doi.org/10.1016/j.crhy.2013.09.012>

- [47] K. S. Park, K. S. Yi, "Supersymmetric Quantum Mechanics in Graphene", *Journal of the Korean Physical Society*, vol. 50, no. 6, 2007. <https://doi.org/10.3938/jkps.50.1678>
- [48] K. S. Park, "Topological Effects, Index Theorem and Supersymmetry in Graphene", in *Physics and applications of graphene theory*, ed. by Sergey Mikhailov, 2011. <https://doi.org/10.5772/15353>
- [49] J. K. Pachos, A. Hatzinikitas, M. Stone, "Zero modes of various graphene configurations from the index theorem", *The European Physical Journal Special Topics*, vol. 148, no. 1, p. 127-132, 2007. <https://doi.org/10.1140/epjst/e2007-00232-6>
- [50] K. S. Novoselov, "A roadmap for graphene", *Nature*, vol. 490, no. 7419, pp. 192-200, 2012. <https://doi.org/10.1038/nature11458>
- [51] P. Miró, M. Audiffred, T. Heine, "An atlas of two-dimensional materials", *Chemical Society Reviews*, vol. 43, pp. 6537-6554, 2014. <https://doi.org/10.1039/C4CS00102H>
- [52] Z. Lu, "2D Materials Based on Main Group Element Compounds: Phases, Synthesis, Characterization, and Applications", *Advanced Functional Materials*, vol. 30, no. 40, 2020. <https://doi.org/10.1002/adfm.202001127>
- [53] W. Han, "Graphene spintronics", *Nature nanotechnology*, vol. 9, no. 10, p. 794-807, 2014. <https://doi.org/10.1038/nnano.2014.214>
- [54] D. Akinwande, N. Petrone, J. Hone, "Two-dimensional flexible nanoelectronics", *Nature Communications*, vol. 5, 2014. <https://doi.org/10.1038/ncomms6678>
- [55] J. Park, "Flexible electronics based on one-dimensional and two-dimensional hybrid nanomaterials", *InfoMat*, vol. 2, no. 1, pp. 33-56, 2020. <https://doi.org/10.1002/inf2.12047>
- [56] B. Radisavljevic, M. B. Whitwick, A. Kis, "Integrated circuits and logic operations based on single-layer", *ACS Nano*, vol. 5, pp. 9934-9938, 2011. <https://doi.org/10.1021/nn203715c>
- [57] B. Sa, "Strain Engineering for Phosphorene: The Potential Application as a Photo-catalyst", *The Journal of Physical Chemistry C*, vol. 118, pp. 26560-26568, 2014. <https://doi.org/10.1021/jp508618t>
- [58] S. Zhang, "Atomically thin arsenene and antimonene: semimetal- semiconductor and indirect-direct band-gap transitions", *Angewandte Chemie International Edition*, vol. 54: pp. 3112-3115, 2015. <https://doi.org/10.1002/anie.201411246>
- [59] Z. Ni, "Tunable bandgap in Silicene and Germanene", *Nano Lett.*, vol. 12, pp. 113-118, 2012. <https://doi.org/10.1021/nl203065e>
- [60] Z. Zhang, "Tunable electronic and magnetic properties of two-dimensional materials and their one-dimensional derivatives", *WIREs Computational Molecular Science*, vol. 6, pp. 324-350, 2016. <https://doi.org/10.1002/wcms.1251>
- [61] Y. Cao, "Correlated insulator behaviour at half-filling in magic angle graphene superlattices", *Nature*, vol. 556, no. 7699, p. 80-84, 2018. <https://doi.org/10.1038/nature26154>
- [62] T. Vincent, "Opportunities in Electrically Tunable 2D Materials Beyond Graphene: Recent Progress and Future Outlook", *Condensed Matter, Mesoscale and Nanoscale Physics*, 2013.
- [63] R. Bistritzer, A. H. MacDonald, "Moiré bands in twisted double-layer graphene", *Proceedings of the National Academy of Sciences of the United States of America*, vol. 108, no. 30, pp. 12233-12237, 2011. <https://doi.org/10.1073/pnas.1108174108>
- [64] B. A. Bernevig, T. L. Hughes, "Topological insulators and topological superconductors", Princeton University Press, 2013. <https://doi.org/10.1515/9781400846733>
- [65] E. Vega, J. Pacheco, M. Baquero, "Threads and nanotechnology: monitoring of the vital pulse signal", *Visión electrónica*, vol. 2, no. 1, Special edition, 2019. <https://doi.org/10.14483/issn.2248-4728>
- [66] L. H. Camargo-Casallas; J. F. Pantoja-Benavides; D. J. Rodríguez-Patarroyo, "Kinetics of nanoparticles in sanguinean torrent by approximation, Womersley flow", *Visión electrónica*, vol. 13, no. 1, 2019, pp. 33-38. <https://doi.org/10.14483/22484728.14409>

- [67] S. Anand, V. Verma, A. Gupta Aggarwal, “2-Dimensional Multi-Release Software Reliability Modelling considering Fault Reduction Factor under imperfect debugging”, *Ing. Solidar*, vol. 14, no. 25, pp. 1-12, 2018. <https://doi.org/10.16925/v14i0.2229>
- [68] M. Gupta, V. Kumar Solanki, V. Kumar Singh, “A Novel Framework to Use Association Rule Mining for classification of traffic accident severity”, *ing. Solidar*, vol. 13, no. 21, pp. 37-44, 2017. <https://doi.org/10.16925/in.v13i21.1726>
- [69] K. Landines Jiménez, N. Nieves Pimiento, C. A. Toledo Bueno, “Simulation of forces applied to the human femur: Analysis of finite elements”, *Revista Vínculos*, vol. 16, no. 1, pp. 73–81, 2019. <https://doi.org/10.14483/2322939X.15575>