Nanometer range: A new theoretical challenge for microelectronics and optoelectronics

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Abstract

The equation is identified, from a couple of odd percussions, which yields the pilot wave forming the aura of a particle in the space conjugate to the four-dimensional space of direct experience. This leads to a substitute of the Copenhagen Interpretation providing the frame for demonstrating Heisenberg’s uncertainty principle through a theorem of Fourier analysis. Revisiting the method of space-time domain paves the way to a new era of developments, by considering that a trapped particle located in a bounded bi-dimensional space, having less than 1 eV of kinetic energy, should have an associated wavelength representing a fraction of a wave cycle. In order to face the challenge, a new optoelectronics concept is proposed to contend with the broadening of the frequency bandwidth for a particle-wave trapped in a single-electron box: quasi-virtual electrons, trapped in nanometric single-electron thin boxes, interact by absorption–emission processes with coherent electromagnetic radiations. The migration is proposed for nanoelectronic transistor fabrication from semiconductor to semi-refractor materials.

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1. Reminder of Moore’s law

Over the last 20 years, the limits of optics in microlithography have been pushed back by the actors of the microelectronics industry, contrary to official augurs. Recently, designers of microprocessors have started developing components sized below the 60 nm range, where they meet some concerns about size limitations due to the quantum aspect of electron particles trapped in small cells. Recent spectacular demonstrations of silicon MOSFET with gate-lengths below 20 nm illustrate a rapid acceleration in aggressive scaling of these devices. Feature sizes now reach the dimension of one half of the wavelength used to define the patterns.

Moore’s law dates from the sixties and is rather a self-fulfilling prophecy by a founder of Intel, who announced that memory capacity would double every 18 months. It has translated into an industrial competition for shrinking lithography, at a rate halving critical dimensions at the same pace. Meanwhile integrated circuit layers had to be kept thinner than lithographic dimensions, turning the particle trapping cells into thin boxes.

Electronic components elaborated in atomic mono-layers are making the pursuit of Moore’s law critical by reason of the local space to consider as drastically limited for carrier displacement: their mean free path along one of the three dimensions of electronic components have no thermo-dynamical meaning, and the dynamical properties of electron–hole carriers are becoming anisotropic; their mean statistical lifetimes therefore are difficult to evaluate and measure.

Simultaneously Moore’s law lately appears to slow-down and the capacity doubling period has grown to three years and tends towards five, thus postponing to 2015 the passing of the lithographic threshold of 100 Å or 10 nm.

Reviews of recent technological research of advanced field-effect transistors and theoretical single-electron transistors and devices have been published by Sverdlov et al. and Walls et al. Accordingly, the prospect of a pursuit of the Si-MOSFET-based Moore’s law beyond the 10 nm scale limit is most uncertain.

Numerous suggestions are made to replace silicon with another channel material. Theoretically, for nanoscale ‘wave devices’, they consider using temporal quantum coherence of electrons for information processing. The nanoscale structures of ‘wave’ electron devices with high impedance (R > R0) are dominated by single-electron charging effects, as seen in by Likharev, 2003.

The ‘single-electron box’ device consists in one small conductor ‘island’ separated from an external electrode...
by a tunnel barrier with high resistance. Another key device is a ‘single-electron trap’. The main new feature of this system is its bi- or multi-stability. The last key single-electron device is the ‘parametron’, which consists essentially in a short segment of 1D array of islands. In this microelectronic device, both theory and experiment show that single-electron tunneling effects become visible at $E_a = 3k_BT$ (where $E_a$ is the energy necessary to put an additional electron on a transistor island, and $k_B$ is the Boltzmann constant) i.e. at $T \approx 100$ mK! The single-electron additional energy should however be as large as $\sim 3$ eV for reliable operation. Such advanced devices are scalable down to $\sim 5$ nm, while retaining relatively high performance.

The issue at stake is the potential coexistence of binary devices operating on bits together with quantum devices operating on qubits. In the 1980s and early 1990s, much attention was focused on such ‘quantum electronic devices’.

In their modeling of component behavior in nanoscale electronic devices, the authors of recent works take into account the famous particle-wave duality with a quantum mechanical interpretation that electrons behave either as discrete particles or as continuous de Broglie waves. Their original approach however leaves unresolved the theoretical restrictions to the use of infinite lattices of Bloch functions for a single-electron box in a semi-conductor lattice, which is finite. Another challenge is the so-called renormalization: this procedure works for quantum electrodynamics in vacuum, but is based on Lorentz invariance that is obviously lacking in an integrated circuit.

2. Modeling of electromagnetic wave propagation

Consider a physical system in two spaces, the coordinates of which are given in multidimensional notation as: $r^\mu = (ct, x, y, z)$ for the gravitational space directly perceived said $D$, medium where any velocity is lower than or equal to the velocity of light $c \geq v = \alpha \beta / \sqrt{\omega}$ in free space, which is linked to dielectric constants of permittivity ($\varepsilon_0$) and permeability ($\mu_0$) by $c^2 = 1 / \varepsilon_0 \mu_0$, that is to say to the electrostatic and magnetic forces respectively; and $k^\mu = (s, k_x, k_y, k_z)$ with $s = i/c$ so that $s = i/c$ with $v = i/\sqrt{\omega}$ and the wave numbers $k_n = in$ (with $n$ the refractive index) for the harmonic or conjugate space $C$, which is the ether of vibration of the aura (i.e. physical zone of particle), the perception of which is subtle and where any velocity $u = \partial r^\mu / \partial t = \lambda v$ thus is higher than or equal to the velocity of light in free space since $1/c \geq 1/u$ where $u \geq c$, which thus refers to the speed which all dimensions have in common and can communicate at.

The need for dimensions beyond the four ones addressed by Albert Einstein, in the theory of generalized relativity, dates from Theodor Kaluza [10], but we consider here only the medium which propagates the microparticles of light, initially explored by Karl von Reichenbach, abandoned by Michael Faraday then Erwin Schrödinger, revived by William Tiller [11], and recently demonstrated by Gerhard Grössing [12]. This puts an end to the Copenhagen interpretation, while positing that locality is merely a property internal to each space.

3. Criterion of reality

In accordance with [13], these coordinates $r^\mu$ and $k^\mu$ are stated as linked by the Fourier transform associating a function $F(r^\mu)$ in $D$ space with $F\hat{\mu}(k^\mu)$ in $C$ by:

$$\int F(r^\mu) e^{-i2\pi r^\mu \cdot k^\mu} dr^\mu = F\hat{\mu}(k^\mu)$$

(1)

and conversely

$$\int F\hat{\mu}(k^\mu) e^{+i2\pi r^\mu \cdot k^\mu} dk^\mu = F(r^\mu)$$

(2)

so that they define with their derivatives the state vector of a single entity in a complex system.

The Gaussian representation thus is chosen for a particle, as a Dirac percussion in the limit $\lambda, \epsilon$, because it is identical in the two conjugate spaces since:

$$\int e^{-\pi r^\mu 2} \int e^{-i2\pi r^\mu \cdot k^\mu} dr^\mu = e^{-\pi k^\mu 2}$$

(3)

and conversely

$$\int e^{-\pi k^\mu 2} \int e^{+i2\pi r^\mu \cdot k^\mu} dk^\mu = e^{-\pi r^\mu 2}$$

(4)

 Appropriately the Fourier transform is the essential criterion of physical reality [14], much like mass is a criterion for localization of matter, and above all for its capability to follow a vibration.

3.1. Equation of the aura

Louis Victor de Broglie has identified around each particle its pilot wave, but their relationship remained to be specified. Since, the elementary wave equation is:

$$\nabla^2 \psi = 0$$

(5)

which can be turned into an eigenvalue equation:

$$\nabla^2 \psi = 1/c^2 \frac{\partial^2 \psi}{\partial t^2}$$

(6)

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1 Notations. The threshold of energy exchange $\varepsilon = \hbar \nu \omega$ corresponds to a photon, luminous particle of force, of which is the vibration frequency with $s = \nu c$, where $s$ is the action quantum, Planck’s constant, lays the foundation of quantified energy. Let $\lambda$ the spatial wavelength such that $\lambda = 1/k$ and the phase constant or spatial period $\beta$ is linked with the wave number $k = \omega \beta$ by $\beta = 2\pi k/c = 2\pi \omega \beta \hbar / p h$, where $\hbar = h/2\pi$ is the normalized constant, so that phase velocity is $u = c = \omega \beta \hbar / p h$ in space $C$. The temporal period of wave vibration is $\tau = 1/\omega$ (while the angular frequency is $\omega = 2\pi / t$ so that $\omega = E / c$).
accepting as solutions functions with the form:
\[ r^\mu = f(r_n \pm ct) \]  

This eigenvalue equation confirms the essential character of the Fourier Transform, because, to every variable perceptible in classical mechanics, there corresponds a linear Hermitian operator in Wave or Quantum Mechanics, with orthogonal eigenfunctions, which precisely forms a Fourier series, as a development over an orthonormal set.

For modeling the propagation of a wave group modulated over a single 'half-period' like the aura of a particle, the Compton effect must be represented. It proceeds from the percussion by a photon with some initial frequency, ejecting an electron from its atomic orbit, and followed by a percussion opposite in phase, emitting a photon when the electron settles on another orbit.

This couple of odd peraccumulations with interval \( \delta \) is noted \( I \) (k). This effect is expressed by ‘finite differentiation’ in spectral analysis [14], equivalent to a convolution [13], where \( I \) (k) triggers the emission of a photon at the resulting frequency, together with the propagation of its aura wave by modulation of the incompressible fluid of Aurions, these massic particles filling space \( C \).

Tiller has conjectured the bi-dimensional reality of each direct dimensions recognized by physicists. Depeyrot [15] has shown that the propagation of piston waves of photons were the outcome of finite differentiation due to a couple of odd peraccumulations, with the result that the properties attributed to the photons appeared as those of Aurion waves in the conjugate space.

However, Gerhard Grössing [12] has demonstrated that no discontinuity between classical mechanics and quantum physics does exist. According to the Copenhagen interpretation, the probability of particle attendance (governed by the modulus of wave function) can serve to determine their behavior in a space-time domain.

This virtual reality permits to investigate the quantum dimensions with determinism even before expecting, on the one hand the replacement of semi-conductors by semi-transparent materials, and on the other hand the replacement of transistors operating with electrons by conjugate operators on Aurions.

Indeed with the thin boxes of microelectronics, the thermodynamical theory of carriers and the volume of photon-particle interactions henceforth are about reduced to a limited space with two dimensions. In this new size arrangement, the cross-section, which governs the flux of particle energy exchange, should be reformulated to take into account these new space-time conditions.

4. Complex space versus probability space

The Fourier uncertainty relation, concerning the dual representations of a single entity or signal in spectral analysis, has the consequence that coordinates are non-commutative since the sequencing of their identification reveals a difference between \( [r^\mu, k^\mu] = i \hbar \delta(r^\mu, k^\mu) \) with the uncertainty scalar:
\[ \Delta r_n \cdot \Delta k_n \geq \frac{\hbar}{2} \]  

which is a strict equality only in the case of the Gaussian structure.

Consequently the weighing of \( k^\mu \) by the kinetic action quantum \( \hbar = 2\pi \) such that the moment which generalizes \( p = \hbar k \) is that \( \hbar^2 = \hbar \) which the operator \( k^\mu \hbar = p^\mu = -i \nabla_\mu \) where \((\nabla_\mu \psi) n = \partial \psi / \partial r_n\), results in:
\[ \Delta r_n \cdot \Delta k_n \geq \frac{\hbar e}{2} \]  

This simply expresses the Principle said of Heisenberg’s Uncertainty and deprives it of probabilistic significance. As in a gravitational space \( D \) of field vector \( \gamma \) a displacement is a variation of potential energy \( \Delta V = \Delta r^\mu \gamma \), by multiplying by the velocity \( e \) in the harmonic space \( C \), it follows that energy \( E = pe \) is generalized by \( \hbar c e = \Delta K_e \), hence:
\[ \Delta V \cdot \Delta k \geq \frac{\hbar e}{2} \]  

It must be noted that \( \Delta V \) and \( \Delta K_e \) (see above) are the two components of Schrödinger’s equation. Erroneous physical interpretations stem from hasty associations of variables as conjugate. The potential energy in such a relation of uncertainty appears associated with the position in \( D \) space, temporal term of the state vector or wave equation, and its conjugate as the kinetic energy associated with the moment in \( C \) space, spatial term of the wave equation.

That is the reason why Heisenberg’s uncertainty principle must be assessed in the case of limited sizes for thin cells, where the particle momentum of the classical inequality may be not strictly defined: even if the uncertainty law is written in transit time, such as \( \Delta E \Delta t \geq \hbar \), it remains that the transit time along the thickness of the considered bi-dimensional space becomes ultra-short: \( < 1.688 \) femtosecond for \( 1 \) nm of propagation length at \( 1 \) eV. Therefore, a kinetic energy band of a medium, lower than \( 1 \) eV, has no physical meaning. However, considering the other two dimensions, the physical laws remain ever valid and applicable.

While the present formalism provides a simple explanation for superposition in Young’s double-slit experiment, several likely conjectures remain in competition for explaining aspect’s entangled particle experiment and Bell states of qubit pairs. Their exploration shall exploit, on the one hand the symmetry of the momentum operators \( q \) and \( p \) in \( [q, p] = qp - pq = i \) when replacing \( i \) by \(-i\) which emphasizes the reciprocity of the diagonal operators of \( D \) and \( C \) spaces as \( p = -id/dq \) and \( q = +id/dp \), and on the other hand, the fact that asymmetrical functions have a complex transform.

Such as in mono-dimensional space: \( \hbar \) with \( \hbar k = p = \hbar k/e \) where for \( k = 1 \), it becomes \( p = \hbar /c \), representing the quantum of movement which corresponds to the Planck length: \( l \equiv (1/\hbar)/(G/p) \), where \( G \) is the Newton gravitation constant, and \( p = E/c \).
5. An approach applying the method of space-time domain

The kinetic energy of the particle, in the present circumstances an electron, trapped between two discontinuities of potential, namely with infinite barrier heights, is analytically expressed following two different formalisms: either in space-time directly measurable in reference time, or in a conjugate space associated with the spectral transformation.

On the one hand, the analytical expression of the kinetic energy \( W_k \) in the conjugate domain shows the quadratic dependence in frequency as follows:

\[
W_k = \frac{k^2 \hbar^2}{2m_e} \tag{11}
\]

where \( m_e \) is the effective mass of electron and \( k = 2p \), but the space-time parameter is not brought-out. This expression permits to evaluate that 1 eV of kinetic energy corresponds to 1 nm, i.e. 10 Å, of electron wavelength, where \( m_e = m_0 \) is the mass of the electron at rest. If we consider this mass within a silicon crystal lattice\(^3\), its corresponding wavelength becomes 2 nm.

On the other hand, the analytical expression in the space-time domain is as follows:

\[
W_k = \frac{K^2 \hbar^2}{2m_e l^2} \tag{12}
\]

where \( K \) is the integer number of wavelength and \( l \) is the wavelength associated with the particle.

Currently, the wave function of energetic electrons and atoms trapped between high discontinuities of potential are ruled by the limit conditions, which determine the quantification of their stationary wave momentum and kinetic energies. The corresponding orthonormal wave functions become:

\[
\psi = \sqrt{\frac{2}{l}} \sin \frac{K \pi x}{l} \tag{13}
\]

which are the eigenfunctions of the Schrödinger equation, where \( l \) is the length of the single-electron box and \( x \) the coordinate on the X-axis.

This space-time formalism enables verifying that, if the thickness of one atomic layer is close to 1 nm, the calculation of the kinetic particle \( W_k \) (i.e. electron) trapped between these two discontinuities of potential represented by the walls of this layer, yields 1 eV. In this spatial configuration, it results that the transit time through the thickness of such a bi-dimensional space becomes ultra-short: \(< 1.688 \text{ femtosecond for 1 eV of electron kinetic energy.} \)

In consequence, a trapped particle located in such a type of bounded bi-dimensional space having less than 1 eV of kinetic energy should have an associated wavelength representing a fraction of a wave cycle. In the spectral domain, this fraction of wave cycle corresponds to a broadening of frequency bandwidth for the particle wave. It is tantamount to the case of a wave packet equivalent to an electromagnetic missile \[16\].

In order to imagine the physical consequences and meaning of such a bounded bi-dimensional space, it is necessary to conceive a direct real space-time, where the particles become virtual, as they benefit from the progress of microelectronics to virtually atomic dimensions. In this space, the deterministic perception and the direct location of the real particles are directly lost, but indirectly detectable and measurable. In such a borderline case, the particle seems solely governed by a probability of attendance in the space-time domain; it thus is necessary to consider a transient regime for the dynamic behavior of particles with lifetime lesser than the femtosecond range (i.e. attosecond range).

The Drift-diffusion theory of carriers becomes inapplicable. The Perturbation theory seems appropriate for estimating the probability of electron attendance, correlated with the amplitude, which determines their dynamic behaviors in a real space-time domain. Currently, the square modulus of the coefficient of wave function, which represents the probability to find the electronic (or atomic) system in an energetic state at the time \( t \), is expressed with a time-independent operator of the matrix element of a wave function. In case of an ultra-short time interaction, this first modulus becomes the first order of a time square function as \( t^2/2 \). The system response thus is governed by a non-linear function in time.

Moore’s law invites us to proceed from Fermi–Dirac to Bose–Einstein for its continuation of validity towards Semi-refractor transistors.

We propose to model quasi-virtual electrons trapped in nanometric single-electron thin boxes, which interact by absorption–emission processes with coherent electromagnetic radiations, as a laser micro-pulse. It amounts to taking into account the broadening of absorption–emission line-shapes of microelectronics medium as a monolayer diamond film. Indeed, the poly-crystal diamond monolayers are good candidates for semi-refractor elements with high resistivity \((10^4 \Omega/cm)\) and a wide bandgap (above 5 eV). As photoconductor switches, these diamond films afford a high mobility of carriers \((1800 \text{ cm}^2/\text{Vs})\), close to gallium–arsenide mobility, which determines the required optical power to rapidly generate a current \[17\] in the picosecond range. They provide the grid-control function of a new generation of transistors driven by a laser micro-chip acting as a photo-switch of a photoconducting monolayer.

6. Paving the way to practical physics

Heisenberg’s uncertainty principle is not a theoretical wall, as concrete as the Fourier uncertainty theorem, but is rather a frontier awaiting the revision of the traditional analytical approach, an overdue revision, to which the pace of Moore’s law does not leave much time for procrastination. In order to model new features of the nano-electronics medium, a quantum approach in terms of probability of wave-function amplitude is worth investigating in this new light.
In our modeling, we have to take into account quasi-virtual electrons trapped in nanometric space-cells, which interact by absorption–emission processes with coherent electromagnetic radiations. The excited energetic electrons and atoms should be radiating their energy owing to their interaction with high discontinuities of potential due to the borderline conditions of the semiconductor or semi-refractor media.

In order to take into account these technical challenges and theoretical difficulties, we have proposed the implementation of a new optoelectronic concept, which will provide the grid-control of a new generation of transistors by a laser micro-chip used as a photo-switch in a photoconducting monolayer deposited on the diamond substrate. In this nanoelectronic technology, we suggest the use of polycrystal diamond monolayers, which should be good candidates as semirefractors with a wide bandgap for a suitably fast micro-optoelectronic medium.

References