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A new spintronics device with noninteger coding for information storage and processing

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ABSTRACT

A new spintronics device with noninteger coding for information storage and processing is proposed. The device is constructed of paired trinucleotide sequences wound around the carbon nanotubes. The noninteger coding, working with a base of natural logarithm *e*, assumes operation with *e*-bits and *e*-bytes. These bits and bytes arise automatically in paired nucleotide sequences with strong spin-orbit and hyperfine coupling. The electron motion along the curved chains of trinucleotides (Spin Hall Effect upon a laser excitation), *e*-bits, change their spin polarization. Signals are read out as phase shifts between the changed and unchanged spin orientations. The device is highly speedy and principally may operate at 100 GHz or higher.

INTRODUCTION

Through thousand and thousand years of evolution the genetics has developed the unique code[1,2] that is still shrouded in mystery until now. According to many views,[2] this code is perfect and might serve the basis for constructing a new generation of computers[3].

Any computer initially suggests its numeral basis or a minimal digit system it operates with[4]. Today we know two integer digital systems that generate many others (a decimal e.g.) – a two-digital system (a binary code) and a thee-digital system (a ternary code).

A two-digital system dominates now on the computer market. Every notebook or smartphone operates with two digits – "1" and "0". A wide-spread use of the two-digital system is obvious as the current electronic materials[5] easier employ "1" and "0" signals to construct of them bytes.

However, there was a three-digit computer (ternary computers) that operated with trits ("0", "1" and "2" or "-1", "0", "1") and trytes (analogue to bytes in the two-digital system). Electronically based ternary series of computers under the name *Setun* (after the name of the river that flows into the Moscow river nearby the place where the Moscow University is located) was originally manufactured in the laboratory of N. Brusnetsov in Moscow State University (1958).[6-8] In the U.S. the ternary computer *Ternac* was developed in 1973. The ternary computer has an advantage over the binary computer in a number of factors: (this is not surprising because the binary constructed manifold is a subspace of the ternary manifold[8]), among which are higher computer performance, higher image resolution, extensive logic, and the code information density/ storage (*d*) that obeys a simple relation (1)

$$d = \ln \varepsilon/\varepsilon \quad (1)$$

Here ε is the base of a numeral system. From (1), *d* reaches its maximum at ε = *e* (the base of natural logarithm).

The binary and ternary information coding is integer. We know however that the most efficient system

pertaining to signal acquisition, storage and representation assumes the number *e* that is noninteger. The noninteger digital system operating with the number *e* is only starts paving its way. The way however is highly promising making computations much speedier.

Like each computer, the noninteger computer operates with its specific bytes (in the binary system this is byte, in the ternary computer this is tryte, in the noninteger computer this is e-byte, or Berry's byte).

***e*-bit is $e = 2.71828$**

***e*-byte (Berry's total byte) is $e^{\pi} = 23.10$**

Where does π come from? This is Berry's phase arising when the signal makes a total turn around a closed curved loop,[9] primarily on the Poincare sphere.

The noninteger algebra is not properly developed. For instance, this is difficult to understand what factorial *e* is while it is commonly known what is *n*! (*n* is an integer number). In the noninteger mathematics however it is accepted that the factorial operation is the raise to power of the numeral base, in our case this is the number e[10].

AIM OF THE PAPER

The paper aims to develop a new computer device that operates on a noninteger base. The base is the number *e*. The device offers a higher speed, compact information storage, and better image clarity than commonly used computers. The device is operating on the Spin Hall Effect that is applicable to a paired trinucleotide sequence wound around the carbon nanotube.

The paper is a revolutionary breakthrough into creation of noninteger chips of biological origin, possessing reproducible and stable signals. The device is based on reading out spin phases arising upon the electron motion along a curved trinucleotide (*e*-bit) sequences. The phase is detected through a rotating spin laser beam.

The phase energy accumulation results from large spin-orbit and hyperfine coupling[11]. The latter occurs thanks to repeatedly embedded spin-active ^{31}P (phosphorus) atoms in the polynucleotide backbones. The phase is non-dissipative, as it is in quantum computers, and changes its value upon the transfer from one ^{31}P to another. The total turn over the closed loop on the Riemann manifold (this is just a paired polynucleotide chain) returns the phase π (Berry's phase).

The device is not a quantum computer as it is, but exploits the elements of quantum computing, including electron and nuclear spin.

Below we give brief information about the effects used in the device construction.

THE BACKGROUND OF THE SPIN-ORBIT AND HYPERFINE COUPLING

Spin-orbit coupling (SOC)

Unlike the Zeeman effect, which suggests the external magnetic field, the SOC is an external property of any atom, molecule, nanoscale cluster, or semiconductor, including quantum wires and dots[12]. The SOC is a relativistic effect. It results from interaction of the electron magnetic moments with the magnetic field generated by their own orbital motion. The SOC splits energies of the molecular cluster that initially possesses equal energies (the Femi energy level, ε_F, or the highest occupied energy level). The most important thing of the SOC is that it could change the spin phase. Depending on the structure, the SOC energy varies in a region 0.02 – 20 cm^{-1} that is detectable by modern optical techniques.

Hyperfine coupling (HFC)

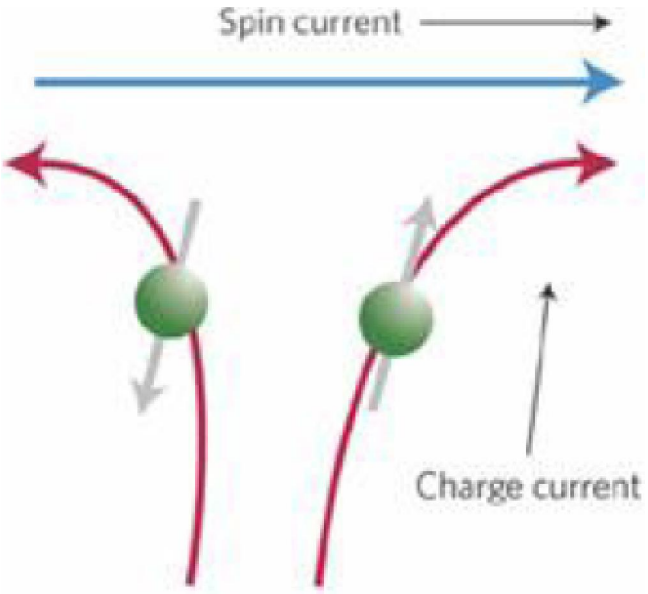

Figure 1 : The SHE on a semiconductor surface in the vicinity of the Fermi energy level. Green balls are hypothetical electrons

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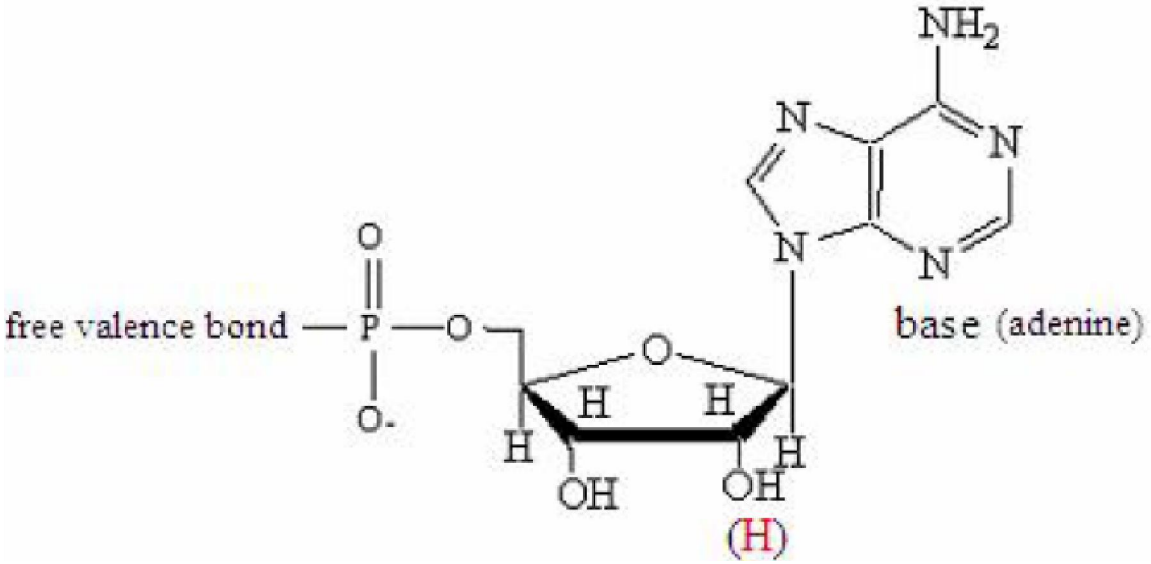

Figure 2 : Adenosine monophosphate (ribonucleotide; RNA molecules). Deoxyribonucleotide (DNA) differs from the shown structure by replacing the right OH group by the H atom (shown in red). The sequence appears through adding nucleotides (the nature offers only four nucleotides differing by their bases: adenine, guanine, thymine (uracil in RNA), cytosine) to a free valence bond (left) of the P atom. The sequence is normally twisted. The P atom creates the hyperfine interaction, see the text

The HFC is the interaction of a nuclear spin with the electron spin[13]. The effect is much weaker than the SOC – two-five times in energy. Not every atom possesses the nuclear spin. Biology however offers this atom, ^{31}P (phosphorus), that shows a 100% abundance of nuclear spin. ^{31}P atoms are the integrable part of any polynucleotide backbone[1,2].

The spin hall effect (SHE)

The HFC is a transport phenomenon predicted by M. Dyakonov and V. Perel in 1971[12,14]. It consists of the appearance of spin accumulation on the lateral surfaces of an electric-carrying sample; the sign of the spin directions being opposite on the opposing boundaries. In a cylindrical wire, the current-induced surface spins wind around the wire. When the opposite current occurs, spins gain reversal. The SHE needs no external magnetic field. The spin accumulation induces circular polarization of the emitted light as well as the Faraday (or Kerr) polarization rotation of the transmitted (or reflected) light, which allows researchers to monitor the SHE by optical means. Figure 1 shows the SHE for two arbitrary electrons treated as classical rotating balls. It is necessary to emphasize that the electrical current might be replaced by any laser impact or heat.

The berry phase

The HFC is the geometric phase that arises in a curved space (the Poincare sphere, e.g.)[9]. In electrodynamics, the Berry phase φ_B is a 1-form of the vector potential A

$$A_i = i \langle \psi | \frac{\partial}{\partial \lambda_i} | \psi \rangle, \quad (1)$$

$$\varphi_B = \oint_C A = \int_{S_C} F, \quad F = dA, \quad (2)$$

λ_i is a number of parameters (normally these are coordinate displacements from point to point on the manifold); C is a closed loop, and F is a differential of A; normally $\varphi_B = \pi(1-\cos\theta_i/2)$[9]. The full turn over the loop returns $\varphi_B = \pi$ that corresponds to a spin reversal.

The Berry phase allows us to create a number of states differing in the angle of polarization. This comes from the ability of the vector potential undergoes a gauge transformation when A is identical to $A+\nabla\gamma$.

$$\mathbf{A} \rightarrow \mathbf{A} + \nabla\gamma \quad (3)$$

$\nabla\gamma$ is a gauge; in traditional electrodynamics γ is electrostatic potential that differs from point to point.

In agreement with electrodynamics, the vector A is associated with the appearance of magnetic field $B = \nabla \times A$. This B affects the strength of SOC and HFC.

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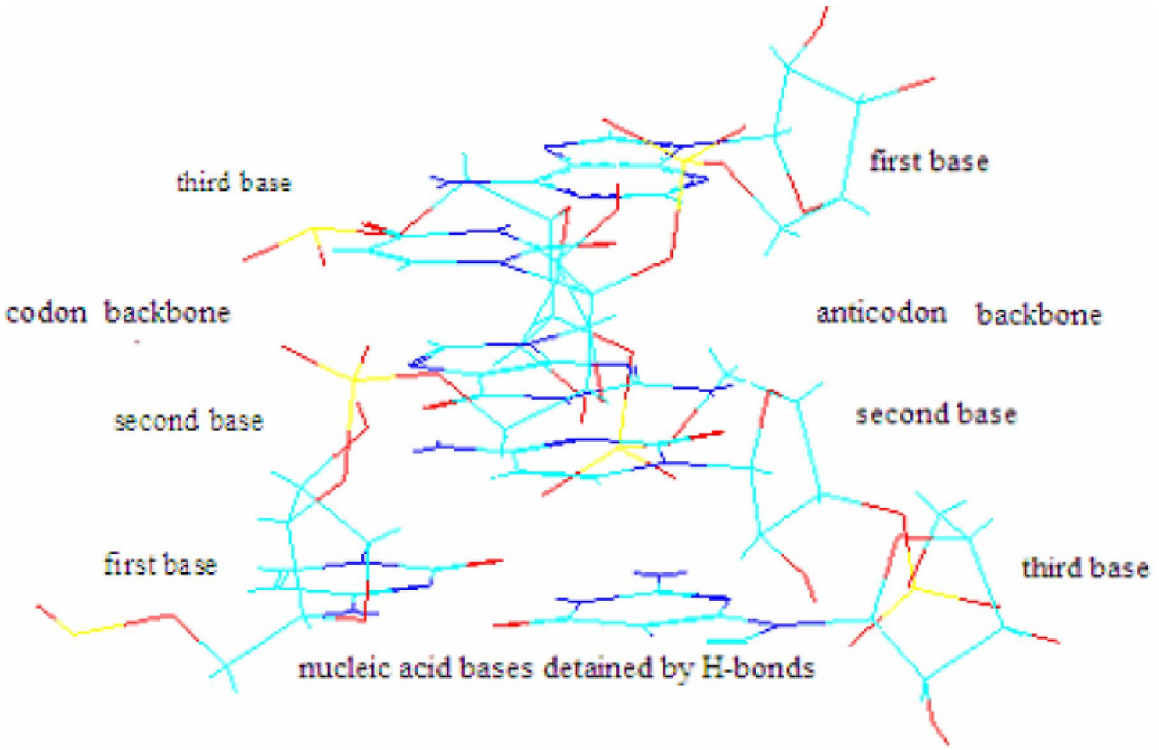

Figure 3 : A realistic codon (rC-rG-rA)-anticodon (rG-rC-rU) sequence comprising three nucleotides from both sides (traditionally the numbering of bases on both backbones is opposite). Hydrogen bonds, H-bonds, (see the text) detain both sequences together; they are not displayed and could extracted from manual on biology or on the Internet. Yellow are ^{31}P (with spin abundance of 100%) atoms; blue are carbon atoms, dark blue are nitrogen atoms; Hydrogen bonds between bases are not displayed. A sequence of three bases (they are paired with those of the codon; form the noninteger computer base

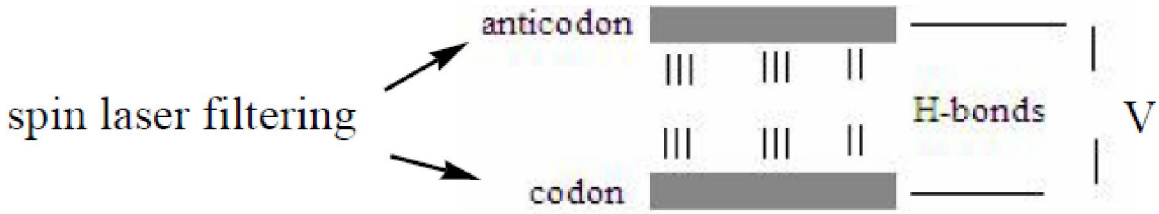

Figure 4 : A simplified picture of that shown in Figure 2. Gray thick lines indicate the backbones of the codon and anticodon (the twist is not shown). Thin vertical lines stand for hydrogen bonds (H-bonds) – three lines for rC-G and rG-rC and two lines for rA-rU (the Watson-Crick pair rules). The V is the electrostatic potential that keeps the layers together

THE DEVICE DESCRIPTION

The device is composed of two hydrogen (H-) bond paired nucleotide sequences - codons and anticodons (each of three nucleotides, Figure 2-4), totally 23 (this is *e*-byte), – wound around a arbon nanotube of 2nm thickness (this is close to that in a living cell)[3]. The carbon nanotube (CN) is an excellent support for nucleotide sequences thanks to stacking interactions between the nucleotide bases and carbon rings (CNs have very small E_{SOC} and E_{HFC} compared to those in polynucleotides 5 cm^{-1} (E_{SOC}) and 0.05 cm^{-1} (E_{HFC})). Figure 5 shows a polynucleotide chain wound around the CN (physically, this is a topological insulator;[15] 2,2 nm long). H-bonding arises automatically between two correctly aligned (base-to-base correspondence) polynucleotide chains. Polynucleotide chains of desired sequence are now routinely synthesized in chemical laboratories through the world. CN supports and polynucleotide winding around them is now created in many chemical laboratories, like ours, using standard protocols and tunneling microscope technique.

A distinctive feature of the device is the energy equality of two highly occupied electrons, which fill the Femi level (see above). The equality is reached by varying a

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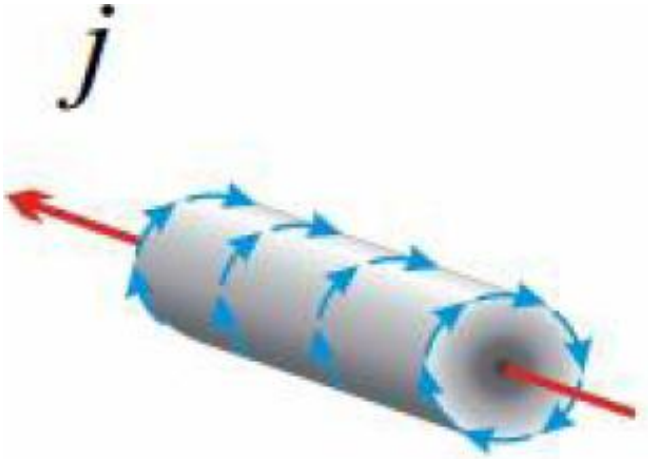

Figure 5 : A polynucleotide chain winded around the carbon nanotube. *j* means the direction of the laser beam or charge current

distance (tunneling microscope) between the codon and anticodon triplets, Figure 4. Compared with the classical Watson-Crick pairs, our distances are longer by 0.17 Å (DFT:B3LYP, 6-31G** basis set, quantum chemistry computations[16]).

Initially, the electron spins on the E_c and E_{ac} levels have the opposite directions. Upon laser excitation two electrons become distributed over three states – two excited states, indicated with red arrows, and the conductivity level, Figure6; the amount of each nucleotide contribution is of no significance because three nucleotides are required together. The SOC splits the energy of each electron (left or right, Figure 6) into the oppositely directed combination (not shown).

The HFC in turn splits the energy of the SOC sublevels. The HFC split could leave a spin unchanged or reverse it. Everything depends on the strength of the interaction between the active ^{31}P nuclei and the electron. If the strength is not enough, the spin remains unchanged, if yes – the spin alters its orientation. In our case ($E^1_{HFC} > E^3_{HFC}$), we have the energy diagram shown in Figure6 where the excited state is singlet (two dashed red arrows)[13]. The excited state on the right is practically equal to the energy of the conductivity zone (red dashed line).

Any computer operates with bytes. To make *e*-byte from *e*-bits it is not enough to raise the *e*-bit to π power, see introduction. We have to learn the device to read out spin phases from *e*-bits, which constitute the *e*-byte. This is carried out with a spin laser using two beams, passing through two ferromagnet nanometer filters, Figure4(left), aligning the electrons in opposite directions (this leads to appearance of the red arrows, Figure 6). The presence of the conductivity zone allows the electron on the right to move along the *e*-byte (the paired polynucleotide chain). This electron motion changes the electron polarization (eq.(3)) on passing each *e*-bit through the HFC.

The read-out process occurs on the x-y plane (Berry's plane). This is possible thanks to a famous formulae,[10] eq.(4)

$$e^{\pi} = \pi e^2 \qquad (4)$$

The right part of (4) is a mantissa of a spared circle. Finally, instead of the *e*-byte (an upward cylinder with unknown technical approach of how to read out spin

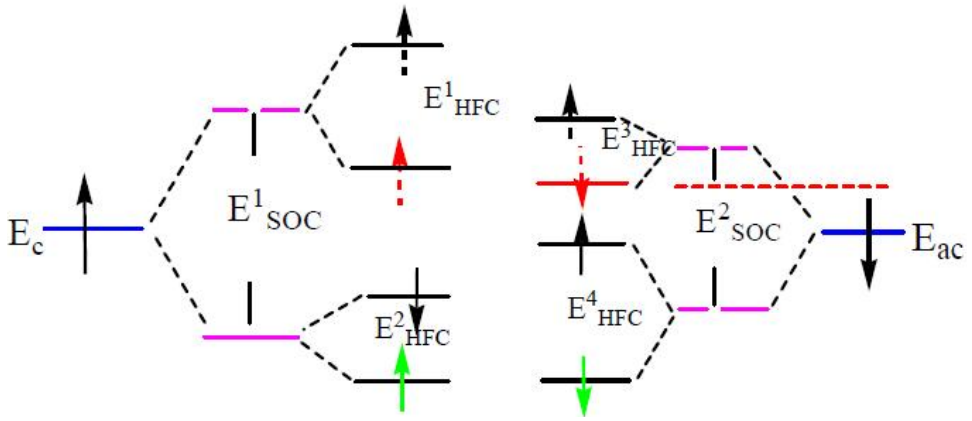

Figure 6 : The energy diagram of the two highly occupied electrons in the vicinity of the Fermi level. The energy of the codon is equal to the energy of the anticodon: $E_c = E_{ac} = \varepsilon_F$. E_{SOC} and E_{HFC} stand for the energy of SOC and HFC. Solid arrows (long initial, shorter are those on the split sublevels) indicate the spins in low-energy states; green arrows indicate the spins in the ground state. Dashed arrows indicate spins in excited states. Red dashed line indicates the conductivity zone on the polynucleotide spiral

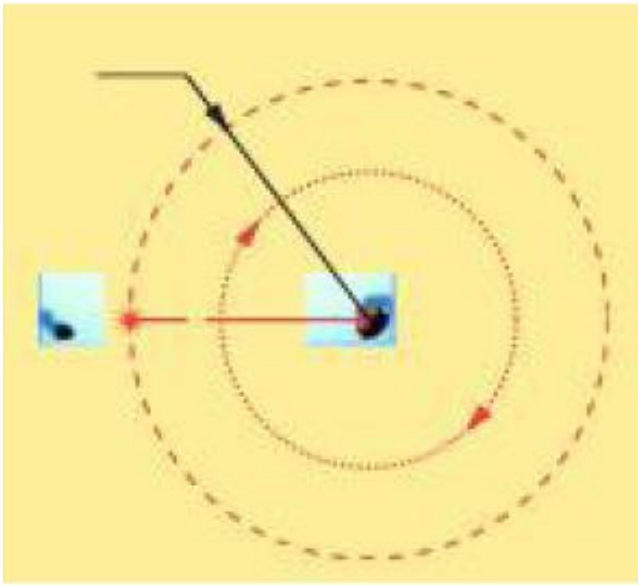

Figure 7 : Schematic picture of the signal read-out processing. The inner circle depicts the rotating read-out beam, the outer circle depicts "frozen" phases; for details see the text

polarizations) we deal with a simple rotation of the polarization angle along a two- nanometer circle, see above. Simplistically, this is shown in Figure 7. The circle is divided into 23 sectors corresponding to *e*-bits. The laser beam from the transmitter with the fixed orientation (Figure6, left energy level) rotates along the circle filled out with changing orientations of each sector. This is possible because the transmitter velocity is 23 times higher than that on the *e*-byte[10].

Signal reading out comes from comparing the phases. The phase change upon laser excitation occurs at 100 GHz and higher. This is great technical breakthrough in computer operation power.

What we have outlined before is the spin laser technique. Practically, the complex of the laser source (femtosecond laser at 265 nm) and two filters demand a very low energy and might be highly compact.

The number of *e*-bytes might be numerous. First, this is achieved through changing nucleotide positions in trinucleotide sequences and, second, through changing spin orientation angles on the filters. Both approaches are mostly identical.

The reliability of the device preventing decoherence is achieved through selection rules.

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