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Prospects for the Application of Nanotechnologies to the Computer System Architecture

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Computer system architecture essentially influences the comfort of our everyday living. Developmental transition from electromechanical relays to vacuum tubes, from transistors to integrated circuits has significantly changed technological standards for the architecture of computer systems. Contemporary information technologies offer huge potential concerning miniaturization of electronic circuits. Presently, a modern integrated circuit includes over a billion of transistors, each of them smaller than 100 nm . Stepping beyond the symbolic 100 nm limit means that with the onset of the 21 century we have entered a new scientific area that is an era of nanotechnologies. Along with the reduction of transistor dimensions their operation speed and efficiency grow. However, the hitherto observed developmental path of classical electronics with its focus on the miniaturization of transistors and memory cells seems arriving at the limits of technological possibilities because of technical problems as well as physical limitations related to the appearance of new nano-scale phenomena as e.g. quantum effects.

Keywords: Computer, Miniaturization, Nanotechnology, Graphene.

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1. INTRODUCTION

The time when a transistor was invented marks the beginning of a rapid development of integrated circuit technology (so called: small, medium and large scale integration). The first simple microchip composed of only 4 transistors was developed by Jack Kilby of the Texas Instruments company in 1958. In 1961, the first commercially available integrated circuits came from the Fairchild Semiconductor Corporation and ten years later the Intel Company presented its first microprocessor composed of 2250 transistors of the 10-micrometer process technology (such was the nominal distance between the source and drain in a unipolar transistor at that time). Another ten years passed and the Intel company produced its famous i8088 microprocessor (29 000 transistors of the 3-micrometer process technology) and the IBM company - the first personal computer (PC). Equally rapid technological development characterized the following decades as well. In 2004, the Pentium 4 of Intel included 125,000,000 transistors of the 90-nm process technology, which meets the definition of nanotechnology.

2. A REVIEW OF PROSPECTIVE TRENDS IN THE MODERN COMPUTER ARCHITECTURE TECHNOLOGIES

Is it possible for the further technological development in microelectronics to be realized solely by simple reduction of the dimensions of insulated-gate silicon transistors (MOSFET) and ferromagnetic memory cells. It is a popular opinion that the present technology and its development, according to the Moore's Law, cannot last longer than 5 – 10 years. It is related to numerous technical problems, often not too spectacular. For instance, to increase operation rate of a processor is less difficult than to solve the problem of lags related to the signal transmission via the terminals [1]. There are also barriers of a more fundamental character like diffraction-limited resolution in lithography, increasing probability of error, graininess of the matter and electric charge, quantum phenomena as electron tunneling in insulators or of magnetization tunneling between two states of ferromagnetic memory or finally - the problem of minimal energy required to perform a single operation and its emission in the form of heat. Up till now, industrial laboratories have been successful in overcoming the barriers. For instance, investigations into the development of a technology to produce polymers of a very low dielectric constant and apply copper terminals to them are currently in progress. It would make possible to reduce the product of capacity and electrical resistance and thereby to limit lags related to the signal transmission via the terminals [1]. Another idea is to replace silicon oxide in MOSFET's by oxides of zirconium and hafnium that are characterized by almost ten times higher permittivity. Its realization makes possible to increase the thickness of an insulator so that at a given gate voltage, density of an induced charge in the transistor channel remains unchanged, while tunneling current (leakage conductance) gets exponentially reduced. At the same time, new kinds of materials for magnetic memory are tested. Their magnetization vector is perpendicular to the disk surface, which makes possible further reduction of memory cells by a few times. The trend of continual miniaturization and the demand for materials of ever greater strength have made the engineers work on developing smaller and smaller machines without decreasing their efficiency. The technology has passed through the mili- and micro phases to arrive at the nano stage. Technologies for developing devices of the single-atom level seem to be the most promising science area. Scientists perceive it as a potential source of so called disruptive technologies – that is of inventions that can revolution-

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ize the world in a similar way as a printing machine or a steam engine did that. Up to the present time, inventions of the **nanotechnology** area are not too spectacular but they are very interesting like laser television or self-cleaning materials. Additionally, nanotechnology has its decisive share in the continuous development of such popular devices as cell phones or personal computers. The present-day processors are produced with the 25-nm process technology (which denotes the distance between transistors) and reach clocking of the 4 GHz order. In order to produce a determined nanostructure one of the two accepted methods can be applied i.e. either “top-down” or “bottom-up”. The “top-down” method consists in processing of one uniform piece of material to obtain required nanostructures. Among many techniques that can be applied for that purpose are lithographic techniques. Their shared characteristic is th use of etching selectivity of various substances to obtain reproducible patterns on a given surface. For that purpose masks are made to shield a selected surface fragment during its irradiation with beams that change properties of the plate material. The next step is to subdue the plate to etching that removes the material fragment and exposes a pattern that is a reproduction of the mask applied at the irradiation. There are two basic disadvantages of the “top-down” method that is based on photo-lithographic techniques. The first one is the high cost of its application and the other one is that available accuracy has its barrier that appears at getting below the limit of 100 nm. For example, at producing paths for connections inside a microprocessor, breakdown or short circuit can occur between closely located paths. The “bottom-up” method presents a reverse procedure as compared to the above discussed one. It consists in setting up of a required nanostructure like it was built of blocks, which in that case are chemical particles and mostly self-organizing organic molecules. Richard Feynman was one of the first physicists to suggest the idea of building nanostructures up. The “bottom-up” method has been inspired by phenomena that occur in living organisms as, for example, the self-organization phenomenon that is a spontaneous formation of complex structures out of smaller elements. The mechanism that makes that possible is tending by the whole system to the minimum energy (in fact to the minimum of free energy or other thermodynamic potential) Thus, (if to ignore all activities that are indispensable for the initial setting of a system) no external stimulus is needed as the driving force of the whole process is a physical law. The technology of self-assembled monolayers (SAM) makes a good example of the “bottom-up” method. The monolayers form by a spontaneous self-arrangement of molecules into a single layer on a predefined surface. The SAM molecules are oblong with an atom at one end that binds the whole with the substrate. In order to form such a monolayer it needs to prepare a solution that includes SAM molecules, immerse a plate with an adequate substrate in it and wait an adequately long time. After a lapse of some dozen of seconds since the plate has been immersed the SAM molecules get adsorbed, although the self-organization process lasts much longer – usually about 24 hours. It follows from the above that an ideal arrangement of molecules requires finding of the system free energy minimum and the optimization of all the complex interactions between the adsorbed molecules. Hence, the disadvantage of the “bottom-up” method is the long time needed for the nanostructure formation.

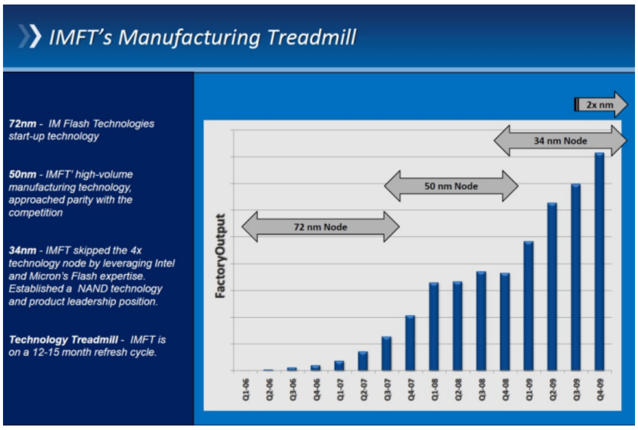

Fig. 1 – Illustration of the tempo of the information system architecture miniaturization that has been observed over recent years [13]

However, everything has its limits. The famous **Moore’s Law**, according to which the number of transistors in processors should double every 18 months, has been revised many times. It is possible that soon it will lose it validity at all. It follows from the silicon technology limitations concerning distribution density of transistors. It is expected that the maximum performance of silicon processors will be reached in 2020 and then some silicon replacement will have to be found. Miniaturization of transistor and IC dimensions by conventional methods will also arrive at its limit soon. It will be difficult and expensive to adapt the presently used “top-down” technology to produce structures of the nano scale [3]. This year at the beginning of May the Intel Company has announced that at the end of 2011 it will start mass production of 22-nm Ivy Bridge processors. The processors will incorporate 3D transistors called “Tri-Gate”. That transistor type has been designed in 2002 by scientists and engineers of the Intel Company. It took almost 9 years of research work to bring the technology to the stage of its mass production implementation. The new 3D Tri-Gate transistors will make possible for processors to operate at lower feeding voltage and reduced power losses, which will result in their increased performance (by up to 37 %) and lower energy consumption as compared to the previous 32 nm transistor generation. In comparison to a 32 nm transistor, a 3D Tri-Gate transistor at the same performance level consumes by over 50 % less of energy. In a Tri-Gate *transistor the traditional "flat" two-dimensional planar gate is replaced with a thin three-dimensional silicon fin that rises up vertically from the silicon substrate. [2]. Control of the flowing energy is now accomplished by implementing a gate on each of the 3 sides of the “fin” – two on each side and one across the top – rather than just one on top as is the case of the 2-D planar transistor.* A surface as tiny as the end of a human hair cancontain over 6 millions of 3D Tri-Gate

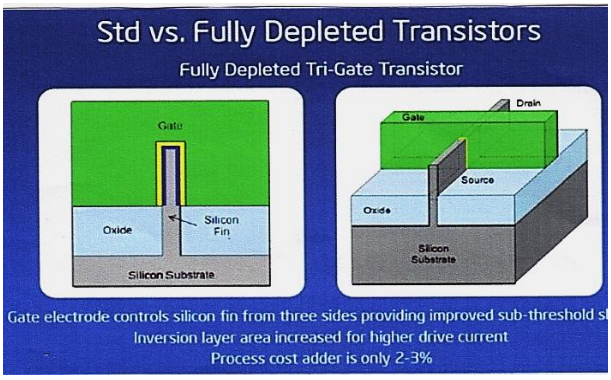

Fig. 2 – The essence of the "Tri-Gate" transistor operation [4]

transistors [2]. A new technology that enters the market this year is the 20-32 nm architecture, which will impact processors, flash memory and the DDR 4 memory. It is assumed that the weakest DDR 4 memory circuits will have 2133 MHz clock, which is nothing when compared to the fastest memory circuits that are meant to operate at the frequency value reaching 4266 MHz. Another advantage of the new technology is essentially reduced feeding voltage. DDR 4 circuits will operate at 1.2 or 1.1 V and JEDEC considers even the value of **1.05 V**, while standard feeding voltage value for the DDR-3 memory is 1.5 V and for the DDR 2 circuits – 1.8 V. The operating voltage reduction goes along with the reduction of memory chip process technology dimension. The 45 nm of the process technology applied to manufacture DDR3 chips is a value that is too high to meet conditions of the reduced power feed. There are rumors that DDR4's will be manufactured with the 25 nm or 32 nm process applied. **The first** DDR 4 modules will be made with the use of the 32 nm or 36 nm process technology which is a slightly higher dimension than it is in the case of the latest DDR3 chips (32 nm). What is important for the users is that the DDR4 high-capacity modules will probably be less expensive that DDR 3's. It will be imposed by changing principles of communication between the memory controller and the modules as in the DDR4 case there will be one channel per one module.

According to the assumptions, the DDR 4 memory should offer lower energy consumption and higher throughput rate – if the peak clocking value for the DDR3, according to the JEDEC standard, is 2,133 MHz, then in the case of the new DDR4 modules that operating parameter can reach the value of even 4,266MHz. Taking into account a period of transition between those two standards, at the beginning modules of the 1,600 MHz speed will be available. Operating voltage will be reduced from the present 1.65 V and 1.3 V (for DDR3 and DDR3L, respectively) down to 1.2 V or even 1,05 V for the DDR4 [3]. However, it is still quite a long way to go to arrive at a real change for the DDR4 memory and the time to wait will probably be longer that it was in the case of DDR3's. The reason for that considerable delay is that manufacturers of mainboards and microchips will have to introduce to the manufacturing process much greater changes than it was in the case of transition from the DDR2 standard to the DDR3 one. Recently, the Intel Company has released SSD disks of the 320 series and 25 nm technology meant for the market of the mid-range workstations. Older SSD modules of the 510 series and the 34nm technology are meant for the market of powerful workstations and solutions of the Enterprise class. One of the reasons why the new 25nm disk is addressed to non-corporate users is the problem of reliability. The application of the latest 25nm process means NAND cells of smaller dimensions and consequently of lower cell charge, which can bring about a larger charge leak. It can be particularly troublesome in the case of the multi-level cell (MLC) memory, where a single cell stores more than one information bit at multiple charge levels. To a cell that stores two bits (four possible states) four various cell-charge levels that are ascribed to those two bits are applied. Charge leak in the MLC memory can cause the occurrence of errors that can destroy the record of one or both bits of the stored information. In the SLC memory case the process requires much higher voltage drop, which makes that memory type much more resistant and reliable than the MLC memory. Much more challenging objective for the spin electronics is to design a free-access magnetic memory MRAM [8]. Such a device would combine advantages of magnetic memory and DRAM. It needs to elaborate such methods for magnetization and reading of the magnetization direction that would be totally independent of mechanical systems. It is an example of a field, where a development requires coupling of material science, nanotechnologies, mesoscopic physics and spin-orbital interactions. It would be an important step forward on that development path to acquire isothermal control of magnetization with the use of light or electrical field, similar way as it is done for the semiconductor memory DRAM, where information recording is controlled by voltage application to the gate of an adequate MOSFET-type transistor. In the presently used equipment, magnetization control (information record) requires considerable amounts of energy as magnetic field used for that purpose is induced by electric current (Oersted law) or by heating up to the Curie temperature by a laser beam, which makes possible to turn the irradiated domain by a comparatively weak magnetic field [5].

3. NANOTRANSISTOR – A TRANSISTOR OF THE FUTURE

Two independent research teams have announced that they have been successful in designing nanotransistors based on single molecules of a chemical compound. At the beginning of November, 2010, a physicist HendrikSchon and his research team of the Bell Laboratories have announced in the "Science" magazine that they have designed a transistor with a channel of the single-molecule length and the first logical nanogate. The publication along with an enthusiastic welcome has also raised reservations of a few scientific groups in the world. Nobody has been successful in repeating the experiment of the Bell Labs team and the published nanotransistor characteristics have been like the ones of classical designs (all the graphs included identical noise pattern at the background). Schon has been accused of a scientific fraud and the hopes for electronic elements of the single-molecule size have been dashed. However, two scientific teams, independent of each other, have reported that they have succeeded in designing such transistors. As the basis for their designs, both teams have used golden electrodes of the 200 nm diameter set on a silicon substrate. Electric current passing through the electrodes induces vibration of the gold atoms, which results in the formation of a one-nanometer gap. To "patch" the gap the scientists have used adequate chemical molecules bonded to the electrode ends. A team of the Cornell University has chosen a large molecule of a complex organic compound with cobalt as one of its components and have used sulfur as the binder. A Harvard team, on the other hand, has applied a molecule composed of two vanadium atoms bonded with a chain of carbon and nitrogen atoms. Transistors made of single molecules of a chemical compound present a large potential for the future electronics. Theoretically, they can be manufactured with the application of conventional lithographic techniques [12]. Even if they will not be used as the building material for future processors certainly some other interesting applications (sensors, memory chips) will be found for them.

4. ALTERNATIVE SOLUTIONS TO THE SILICON TECHNOLOGY

This year, an international research team has presented the first microprocessor made of a synthetic material. It is possible that the material can replace silicon in the future. The discussed microprocessor is an 8-bit unit of a 6 Hz clock. A team of scientists of the Nanotechnology Center in Leuven (Belgium), research organization TNO and Dutch company Polymer Vision have designed a microprocessor composed of 4,000 organic transistors. In their opinion the product is less expensive and more user-friendly than traditional silicon-based microprocessors. The polymer microprocessor operates with a clock of 6Hz that is at a million times slower clocking rate than microprocessors of the presently used PC's do. It is an 8-bit unit, while the presently used microprocessors are 128-bit units. It performs a simple program composed of 16 instructions. Its design includes a substrate of a plastic foil of the 25-nm thickness [10]. One of the researchers has said that is like the food wrap only that a little thinner. On top, there is a 25-nm-thick gold layer patterned to make the circuit. Above that sits an organic dielectric, followed by a second patterned gold layer, and finally the semiconductor composed of 4,000 organic transistors.Voltage application to the system causes its heating up and the pentacene formation on that layer. Pentacene is an organic chemical compound – polycyclic aromatic hydrocarbon consisting of five linearly fused benzene rings - that is considered to be one of the best organic semiconductors. The other layers include lithographically-etched paths for semiconductors. [10]. Scientists say that in the next few years a mass-scale replacement of silicon-based microprocessors in PCs and servers with the plastic ones will not be possible yet, but their manufacturing for the popular use purposes can start soon. Organic materials are much less expensive than traditional silicon ones, which makes polymer microprocessors 10-times cheaper than silicon ones. Even with their lower performance parameters the cheap polymer microprocessors could be applied as elements for the control of sensors or systems of protection against leaks in gas or oil pipelines. Obviously, implementation of organic microprocessors will take time and needs continued research before the technology reaches the level of the silicon technology, but the presented research results seem to be very promising.

5. GRAPHENE THE MATERIAL OF THE FUTURE

Popular understanding of the term carbon associates it with the fuel and the image of a coal mine, while in the nature it also occurs in other forms like graphite or as 'the girl's best friend' that is diamonds. There also are other allotropic carbon forms like fullerenes of a shape resembling a football ball or nanotubes classified among materials of the highest strength. Recently, graphene has joined the group of carbon allotropes. It is an amazing material of great potential. It is transparent, conducts electric current and its structure resembles honeycomb. Its strength by dozens of times exceeds the strength of steel. For many years such structure has been acknowledged only hypothetically as theoretical models with no idea how to obtain it in practice. Only in 2004, researchers of the Manchester University together with Russian scientists of the Institute for Microelectronics Technology in Chernogolovka isolated individual graphene planes with the use of adhesive tape. In 2010 the Nobel Prize in Physics was awarded to Andre Geim and Konstantin Novoselov "for groundbreaking experiments regarding the two-dimensional material graphene". Graphene seems to be a miracle material. It is characterized by amazing strength and little weight. It conducts current and transmits light. In 2008, graphene produced by exfoliation was one of the most expensive materials on Earth, with a sample that can be placed at the cross section of a human hair costing more than $1,000. Only a year after the method for graphene isolation was invented it has been found that electrons contained in that material move faster than in any other hitherto recognized material. Up till now, gallium arsenide has been applied in order to obtain higher frequency of the equipment operation rate. Graphene exceeds the advantageous characteristics of that compound by 25 times and it is because electrons there move at the velocity of 1/300 light speed. Additionally, owing to its low electric resistance the material makes an excellent current conductor and that is why electronic equipment manufacturers are interested in it. In October, 2007, IBM has designed the first field transistor with graphene set on silicon. A year later, other groundbreaking discoveries took place. It has been found that the newly discovered carbon allotrope is the hardest and at the same time the most ductile of all known materials. Professors Jeffrey Kysar and James Hone, of the Columbia University placed graphene pieces into holes drilled in a silicon wafer. Then, they used a diamond probe to break bonds between atoms. That way, they have found that the tested material is 100 times stronger than steel. If the thickness of a graphene sheet approached food wrap parameters then it would need over 30-ton stress to pierce it with a needle. At the end of 2008, Professor James Tour together with Yubao Li and Alexander Sinitskii of Rice University have observed that it could make an excellent material for the computer memory manufacture. Its life could reach 10 millions of cycles and it could be successfully applied within the temperature range from – 77 °C up to 200 °C, which means higher performance without the need for any intensive cooling. This year, considerable acceleration of the research can be observed. In February, IBM again has entered the scene with their design of a transistor operating at the breath-taking speed of 100 GHz. According to the IBM scientists graphene-based circuits potentially can reach even the 1 THz speed, but for the time being there is no idea how to practically attain that. In the meantime, Professors Matthias Batzill and Ivan Oleynik of the South-Florida University have found a method for graphene cutting. A graphene sheet can be cut with the use of monocrystals and then nickel can be used to clean the edges. Two sheets produced that way are subsequently put together to form one sheet that includes some structure disorder. Such procedure yields graphene structures of the pentagon and octagon forms unlike the original hexagon from. They form a kind of a "path" where current can pass as in an ordinary conductor. Additionally, it has been found that the discussed carbon allotrope makes an excellent heat conductor – 10 times better than silver that has been hitherto considered to be the best in that respect. Graphene seems to be a prospectful replacement for silicon as the silicon technology seems to arrive at its limits. Graphene processors will be characterized by much higher performance parameters. It is possible that graphene applications can bring about a major technological leap forward. It is a high-strength very plastic material that it can be applied to manufacture touchscreens of high scratch resistance, so plastic that they could be easily and safely scrolled. It is also a perfect material for the sensor and biosensor manufacture. The William King's team of the Illinois University has observed a very interesting phenomenon, namely that a graphene transistor when touching metal connections exhibits a self-cooling effect, meaning that it is capable of reducing its temperature. It is possible that owing to that property the need for external cooling of electronic devices will be eliminated in the future. In 2011, Dr. WłodzimierzStrupiński's research team of the Institute of Electronic Materials Technology and Department of Physics, Warsaw University, announced a joint development of acquisition technology of large pieces of graphene with the best quality so far. In April of the same year, Polish scientists began the procedure for granting a patent to their discovery around the world. Graphene that is acquired by chemical methods, when mechanical and optical characteristics are more important than the electron transport, can be applied to produce composite materials, transparent electrodes for solar cells, supercapacitors and hydrogen cells. As Dr. Strupiński says, the mentioned technology is a modified version of the trend developed in the Georgia Institute of Technology (Atlanta, USA), where in 2004 the scientists have patented a method for graphene-production by the formation of a thin carbon layer on the silicon carbide surface. At high temperature, silicon gets evaporated out of the surface, where thin graphene film forms. That American patent includes specialized equipment that, according to Dr. Stupiński, is hard to make and be used in industrial conditions. Polish researchers have used standard devices for the production of epitaxial semiconductor structures. For the time being they are the first and the only ones to have done that and their method can make a starting point for a breakthrough as far as large-scale graphene applications are concerned. The Polish method is easier applicable and flexible, which makes it more attractive for possible industrial applications.

At the California University, Berkeley, a **graphene-based optical modulator** has been designed. As its designers claim, such a device can soon allow users to stream full-length, high-definition, 3D movies onto a smartphone in a few seconds. The device has been developed by a research team supervised by Professor Xiang Zhang. It is the tiniest optical modulator in the world and it is optical modulators that in data communications are the heart of speed control. Owing to the graphene technology it is possible to design amazingly small modulators that operate at the 10-times higher speed than the presently used equipment does. As Ming Liu, one of the team members claims, graphene modulators should be very cheap to make as graphite contained in one pencil can provide enough of graphene to produce 1 billion optical modulators.

The Zhang's team has adapted graphene to absorb light of the wavelength used by telecommunication services. The researchers have found that the electron energy, referred to as the Fermi level, can be easily altered depending upon the voltage applied to the material. Thus, using electric energy it is possible to decide whether graphene will absorb the light or not. At an adequate negative voltage, electrons leave graphene and it does not absorb photons as it is completely transparent for them. Graphene is also transparent at certain positive voltages because, in that situation, the electrons become packed so tightly that they cannot absorb the photons.

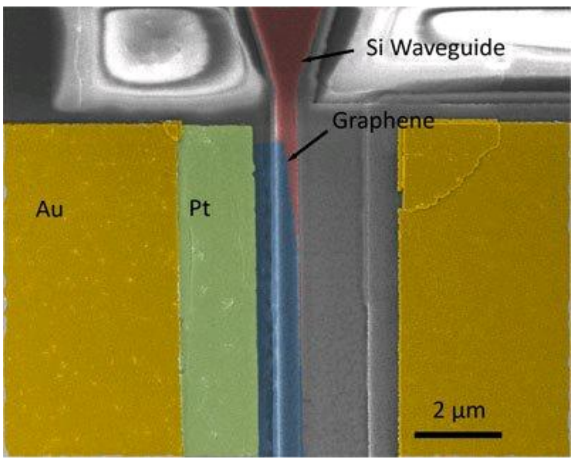

Fig. 3 – Scanning electron microscope (SEM) image magnifying the key structures of the graphene-based optical modulator © Ming Liu, UC Berkeley[10]

By their experiments, the researchers have found an optimal point where graphene can be switched. Their prototype modulator operated with the modulation rate of 1 GHz, but they claim that theoretically the speed can reach as high as 500 GHz.

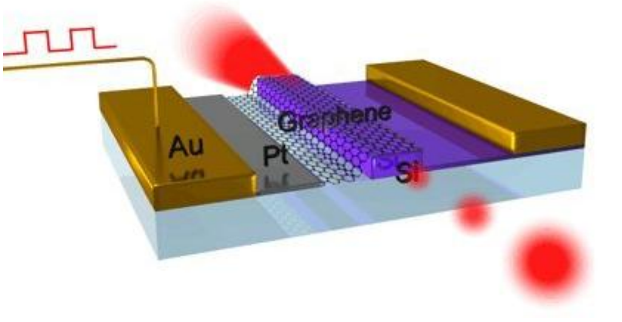

Fig. 4 – Graphene-based modulator on a silicon waveguide (blue) Electric signals used to control the modulator are sent via gold and platinum © Ming Liu, UC Berkeley [10]

Graphene-based modulators offer a chance for designing optical computers in the future. Light enables faster data processing than electrons. However, wavelength poses a problem there as it is much larger than the size of a single electron. Light waves are less agile in tight spaces than their electrical counterparts, so photon-based applications have been primarily addressed to large-scale devices, such as fiber optic lines. Graphene-based modulators can overcome the space barrier of optical devices. The prototype modulator of Berkeley has been successfully shrunk down to a relatively tiny 25 square microns, a size roughly 400 times smaller than a human hair [11]. The footprint of a typical presently used commercial modulator can be as large as a few square millimeters. Additionally, graphene can absorb a broad spectrum of light, ranging over thousands of nanometers from ultraviolet to infrared wavelengths. This allows graphene to carry more data than the current state-of-the-art modulators that operate at a bandwidth of up to 10 nanometers. Graphene-based modulators not only offer an increased data processing rate, but also make possible to packgreater amounts of data into each pulse. Instead of broadband, we will have 'extremeband'.Graphene-based modulators present a huge step forward not only within the area of commercial electronics, but also in any field that is now limited by data transmission speeds, including bioinformatics and weather forecasting. Hopefully, the first industrial applications of graphene modulators will enter the market within the next few years [11].

6. CONCLUSIONS

Although the number of integrated circuits in traditional silicon processors gets doubled every 18 months at the average, contemporary technologies soon will reach the limit of their potential. That is why the entire scientific world looks for new technological solutions. One of them is a so called quantum computer that uses single electrons as the basis for digital operations.

Owing to nanotechnologies it is possible to manipulate atoms and develop new materials, electronic devices and sensors. If to couple that with biotechnology, which investigates molecular structures of living organisms, in the future it will be possible to develop completely new structures and organisms. The basic difference between biological systems and the modern computers is that the computers adapt, evolve and think only in the environment and operation conditions that we develop for them by elaborating reaction mechanisms. However, along with the development of future technologies, that paradigm will be extended over the entire surrounding space. As the recent developments concerning quantum computers have been rather insignificant, many novel ideas concerning the information nanotechnology area have emerged. The discovery of graphene opens a new vista for the development of personal computers and nanotechnologies. Its excellent current-conducting characteristic and amazingly high mechanical strength make this material an object of vivid interest and open prospects of its application within the area of industrial nanotechnology.

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