NANOSYSTEMS:
PHYSICS, CHEMISTRY, MATHEMATICS

Shalayev R.V., Varyukhin V.N. *Nanosystems: Phys. Chem. Math.*, 2025, **16** (2), 216–224.
http://nanojournal.ifmo.ru
DOI 10.17586/2220-8054-2025-16-2-216-224

Original article

Application of carbon nanomaterials in semiconductor electronics

Rostyslav V. Shalayev, Victor N. Varyukhin

Galkin Donetsk Institute for Physics and Engineering, Donetsk, Russia

Corresponding author: Rostyslav V. Shalayev, sharos@donfti.ru

PACS 61.46.+w, 81.05.ue, 81.05.ug

ABSTRACT This review examines the development of modern semiconductor technologies using various carbon nanomaterials, as an element base, to replace classical semiconductors (silicon, germanium, etc.). Examples of specific electronic devices demonstrate the gradual displacement of classical semiconductors by carbon compounds, which are much more promising, with the potential to create all-carbon electronics.

KEYWORDS carbon electronics, semiconductor technology, carbon nanostructures, fullerenes, nanotubes, graphene

FOR CITATION Shalayev R.V., Varyukhin V.N. Application of carbon nanomaterials in semiconductor electronics. *Nanosystems: Phys. Chem. Math.*, 2025, **16** (2), 216–224.

1. Introduction

For a significant part of the 20th century, classical semiconductors (silicon and germanium) dominated in semiconductor technologies. But gradually, alternative materials for using in electronics were sought, and by the beginning of the 21st century, there was noticeable progress in this area, especially after the “nanostructure boom” that broke out at the turn of the century. Indeed, nanometer-scale objects, according to many experts, have been called the most in-demand over the past decades in various fields of science and technology, including electronics.

Nanoelectronics includes technologies that use electronic devices with structural working areas of nanometer sizes [1, 2]. These include emission devices, various types of nanoantennas, semiconductor lasers, field and bipolar transistors with characteristic element sizes of approximately 100 nm, nanoscale electromechanical systems, etc. When reducing the size of electronic devices, it is necessary to take into account qualitatively new effects associated with the discreteness of the electric charge and the quantum-wave nature of electrons. Therefore, single-electron devices with discrete tunneling, as well as quantum dots, are also an important component of nanoelectronics.

For decades, progress in electronics has been accompanied by a reduction in the size of individual elements and an increase in their number on a chip. In turn, this has increased energy consumption and the amount of heat generated (the problem of heat removal still remains one of the most difficult in electronics). Therefore, increasingly complex technological problems emerged with the transition to more miniature technological processes. The growing problems led to the emergence of questions: are there limits to such miniaturization, will the Moore effect of increasing the number of elements in microelectronic circuits be observed in the future? Despite the fact that commercial production of chips using the 2 nm process technology is expected in 2025, there is an assumption that developments in the field of electronics will no longer obey this law in the future and silicon, as a material will approach the physically insurmountable limit of miniaturization of about 10 Å.

It is known that carbon is one of the most amazing chemical elements, forming a wide variety of structures and allotropic forms and possessing a variety of properties (often radically opposite) [3, 4]. In addition to the well-known graphite and diamond, the researchers are focused on the recently discovered fullerenes, carbon nanotubes (CNT), and graphene, the discovery of which gave a new impetus to the creation of specialized electronics. In fact, carbon nanostructures, due to their size, are a kind of transition bridge between individual molecules and crystalline formations and, accordingly, a very promising material for the elemental base of modern nanoelectronics, allowing a significant increase in the density of transistors in integrated circuits.

Therefore, there is currently an active discussion in the scientific community about the possibility of practical application of various carbon nanostructures in microelectronics as working elements of field-effect transistors, memory cells, integrated circuits, as well as in the creation of quantum computers and, in general, in the design of various promising composite materials. It is nanoelectronics that is one of the most attractive areas of use of carbon nanostructures (graphene, graphane, nanotubes and other similar structures) [5, 6] due to their small size, the most diverse (often unique) electrical and optical properties, superior mechanical strength and chemical stability. Each of these nanostructures has its own individual properties and prospects for application in nanoelectronics.

As mentioned above, today the obvious exhaustibility of silicon as a base for a semiconductor platform is already a practically indisputable fact, and more exotic gallium arsenide and diamond, despite the great hopes that were placed on them, have not become widely used materials in industrial electronics [7]. The nanostructured carbon materials (possessing many forms and modifications) are the potential alternative to classical semiconductors, namely as a fundamentally new component base for electronics, judging by the results of the latest research.

Some time ago researchers are already talking about completely "carbon" electronics [8, 9] in the near future, which, due to the combination of its unique properties, can become a replacement for "silicon" electronics. However, in our opinion, even at that time such a conclusion was somewhat premature.

Of course, today the contribution of carbon materials to the development of micro- and nanoelectronics is significant, especially, the contribution of carbon nanotubes, since they were obtained quite a long time ago, have been better studied [10] and many of their applications in electronics are already known. Developments related to fullerenes, and especially graphene, are still much fewer, but in general, graphene is a more promising material than CNTs. This is explained by the relative simplicity of the planar integrated circuits production, using planar graphene layers. No specific equipment is required for this, and it is enough to use already well-established nanolithography techniques for the mass production of new electronic devices.

In this article, we will consider only some areas of carbon nanostructured materials using in electronic engineering today, assess the prospects for the development of carbon electronics and applications in the widest areas of modern science and technology.

2. Electronics of fullerenes

Fullerenes, discovered in 1985, are an amazing class of carbon molecules with unique structural and electronic properties, are self-organizing structures, and are the third allotropic modification of carbon, in addition to the already known diamond and graphite structures. These are closed spherical carbon molecules consisting of pentagons and hexagons. Fullerenes containing from 28 to 100 carbon atoms have been discovered, but the most stable molecules are C_{60} and C_{70}. The best-known fullerene is C_{60}. It consists of 60 carbon atoms arranged in the form of a ball, similar to a football. Each carbon atom is connected to three neighboring carbon atoms, forming hexagons and pentagons.

Fullerenes have a wide range of properties which makes them the subject of considerable scientific interest and practical application. For example, studies have shown that fullerene is an organic semiconductor with a band gap of $\sim 1.5 - 2$ eV and exhibits strong acceptor properties with respect to most organic compounds. Fullerene can be used in artificial photosynthesis systems and organic solar cells based on high-molecular bulk heterojunctions, as a part of donor-acceptor complexes [11]. Field-effect transistors with a fairly high carrier mobility have already been created based on single-layer fullerene films. Due to the mobile π-electron system, the fullerene molecule is easily polarized and has nonlinear optical properties. Fullerenes also have interesting photochemical properties, including the ability to absorb and emit light. This makes them interesting for such areas of application as photovoltaic cells and optoelectronic devices. A solar cell is a device that converts solar radiation into electrical current, and fullerene plays an important role in increasing the overall efficiency of such a cell. Fullerenes short photoresponse time is the advantage of fullerene solar cells over traditional silicon. In addition, fullerenes are already used as components of molecular electromechanical transistors, single-electron transistors, Kondo effect elements, and much more.

In most organic materials, especially those used to create electronic devices, hole conductivity predominates over electron conductivity. One of the promising devices for organic electronics is an organic field-effect transistor (OFET) with a transport layer no more than ten nanometers thick, in which the flow of charge carriers is controlled by changing the charge density in an electric field.

Multilayer transistors have been created in which the semiconductor (fullerene C_{60}) and the light-controlled compound (spiropyran SpO_x) form separate layers (see Fig. 1) [12, 13]. A study of the current-voltage characteristics of the obtained transistors showed that the currents in the phototransistors are less than 1 nA in the absence of irradiation. The current between the source and drain increases by three orders of magnitude when irradiated with ultraviolet light (350 nm) in the transistor gap area, i.e. the ratio of the on-off currents is about 1000.

Also physical principles have been developed for creating a transistor analogue on a single fullerene molecule, which can work as a current amplifier in the nanoampere range [14]. Two gold point contacts on a silicon oxide substrate are the source and drain, respectively, between which a C_{60} molecule is located. The third electrode, which is a small piezoelectric crystal, is brought to the van der Waals distance opposite the C_{60} molecule (like a gate opposite the channel in a MOSFET transistor). The input signal is fed to the tip of the piezoelectric element, which deforms the C_{60} molecule located between the electrodes and modulates the conductivity of the intramolecular junction. The transparency of the molecular current flow channel depends on the degree of blurring of the metal wave functions in the region of the fullerene molecule. A simple model of this transistor effect is a tunnel barrier, the height of which is modulated independently of its width, i.e. the C_{60} molecule is used as a natural tunnel barrier. The supposed advantages of such an element are its small size and very short electron transit time in the tunnel mode, and, consequently, higher response speed of the active element.

The use of a fullerene molecule as a ready-made nano-sized object for creating nanoelectronic devices and devices based on new physical principles is very promising. For example, fullerene molecules can be used to create memory devices. It is proposed to place them on the surface of a substrate in a specially specified way using a scanning tunnel or

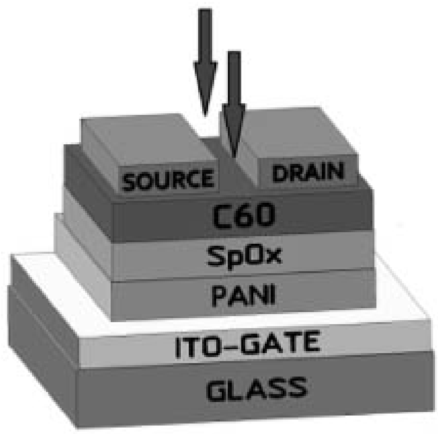

FIG. 1. Photocontrolled organic field-effect transistor [12]

atomic force microscope, and use this as a way to record information. To read information, the surface is scanned by the same probe. In this case, one bit of information is the presence or absence of a molecule with a diameter of 0.7 nm, which allows achieving record values of information recording density. Such experiments were conducted by Bell company.

Researchers from Cornell University have proposed a concept for non-volatile solid-state computer memory based on silicon dioxide and fullerene C_{60}. The memory cell in the proposed version is one C_{60} molecule (buckyball). The energy levels of such a molecule allow for charge tunneling, which enables data recording and deletion. The advantage of the new development is that buckyballs are relatively easily and evenly distributed in silicon, as they are not prone to aggregation and cluster formation.

The use of C_{60} molecules, according to the developers, makes it possible to increase the ratio of recording retention time to recording/erasing time by an order of magnitude compared to memory based on metal nanocrystals.

In the field of nanoelectronics, quantum dots are of the greatest interest in terms of possible applications. Such dots have a number of unique optical properties that allow them to be used, for example, to control fiber optic communications, or as processor elements in the optical supercomputer currently being designed. Fullerenes are ideal quantum dots in many respects, and, accordingly, have a chance to become the smallest microcircuit in a computer nanoprocessor.

3. Electronics of CNTs

The discovery of carbon nanotubes in 1991 [15] practically led to the emergence of a new field of solid-state physics, since CNTs (which combine the properties of both individual molecules and a solid) generally represent a unique intermediate state of matter.

It is known that carbon nanotubes can serve as excellent conductors in electronic integrated circuits, since they have good contact with metals widely used in modern microelectronics – platinum, gold, titanium, and are capable of conducting currents without noticeable heating, three to four orders of magnitude higher than conventional metal conductors. Carbon nanotubes can switch currents with a density of up to 10^8 – 10^9 A/cm^2 (up to 10^{10} A/cm^2 for multi-walled CNTs) due to the low defect concentration. At the same time, a copper conductor is destroyed due to heat release already at current densities of $\sim 10^6$ A/cm^2.

The current demand for carbon nanotubes is driven by the growing desire to miniaturize semiconductor components [16]. Nanotubes, with their superior mechanical strength and chemical stability, small size and conductivity controlled by synthesis, are considered a desirable material for the production of working elements in microelectronics. Materials containing CNTs are already being used by companies producing semiconductor components due to their exceptional electrical characteristics, combining both metallic and semiconductor properties. Let us consider some realistic examples of the use of carbon nanotubes in electronics.

3.1. CNT transistors

The first field-effect transistors on carbon nanotubes were obtained at the end of the 20th century, and the technology of their production continues to improve [17–20]. It is possible to achieve a higher response speed of the transistor junction when using carbon nanotubes with semiconductor properties in transistors, and, accordingly, operation at higher frequencies, due to the higher electron mobility than in classical semiconductors. In addition, for CNT transistors there is no miniaturization limit of tens nanometers, typical for silicon semiconductor devices, i.e. today they already have dimensions an order of magnitude smaller than silicon ones.

The approximate structure of a CNT-based field-effect transistor is shown in Fig. 2. Carbon nanotubes with semiconductor properties (channel) are placed between two metal electrodes (source and drain) deposited on a silicon wafer, which is the gate of the device. If there is no voltage on the gate, the transistor channel (nanotube) is closed, since there is a barrier in the forbidden zone of the semiconductor nanotube. If voltage is applied to the gate, the electric field causes the channel band diagram to rearrange and conductivity to appear in it. Consequently, it is possible to control conductivity (open or close the transistor junction) by changing the voltage applied to the gate.

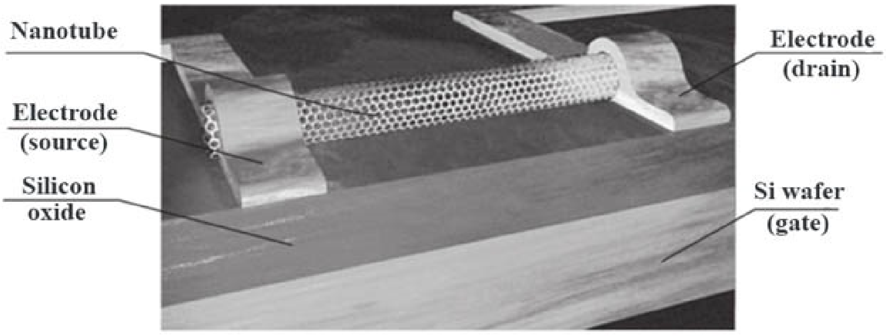

FIG. 2. Structure of a CNT field-effect transistor

There are also Y-shaped CNT transistors, first proposed by researchers at the University of California, San Diego and Clemson University (USA). Their construction is fundamentally different from the construction of the field-effect transistor discussed above, but it has electronic properties similar to those of traditional metal-oxide MOSFETs used to produce computer microprocessors, RAM, and other integrated circuits.

These transistors were obtained using a special technique of branching conventional carbon nanotubes during growth, with the addition of an iron-titanium catalyst, the particles of which stimulated the branching of the growing nanotube. The result was Y-shaped nanotubes with metal particles at the junction of the trunk and branches (see Fig. 3(a)). When such a structure is connected to a source of electric current, it becomes possible to control the electrons entering one of the branches by switching them through a metal nanoparticle at the junction (as in a conventional MOSFET transistor, see Fig. 3(b)). The metal particle of the catalyst either passes or does not pass current from one branch to another (drain – source), depending on the potential applied to the main trunk of the nanotube (gate).

FIG. 3. SEM image (a) and schematic diagram (b) of a transistor built on a Y-shaped carbon nanotube

3.2. CNT memory devices

The use of CNTs makes it possible to develop various versions of computer flash memory, with the possibility of a noticeable increase in capacity per unit area due to the small size of the nanotubes [21, 22]. Fig. 4 shows a memory cell on a CNT transistor with a cantilever. The cell is assembled on a field-effect transistor located on a silicon plate (*1*) with a source (*2*), drain (*3*), channel-tube (*7*) and a "floating" gate (*4*). An electric charge is supplied to the gate through an electrode (*6*) and a metal cantilever (*5*), which, by default, has no contact with the gate. But if a potential is supplied to the control electrode (*8*) during the recording process, electrostatic forces bend the cantilever, and it contacts the gate. As a result, an electric charge flows to it, which is equivalent to recording a logical unit. Even if the potential on the control electrode disappears, the charge on the insulated gate is retained for a long time, i.e. such memory is non-volatile. The power consumption of this type of memory during operation can be significantly lower than that of classic flash memory, since the cantilever switches under the influence of electrostatics with minimal heat dissipation.

Modification variants of such memory cells by selection of dielectric materials for gate insulation (silicon oxide, hafnium oxide, etc.) allow one to reduce the time of information reading/writing cycle to hundreds of nanoseconds, which in principle is not the final value for the productivity and speed of this memory type. And the high memory speed can contribute to the use of such cells not only as non-volatile flash memory, but also as high-speed RAM.

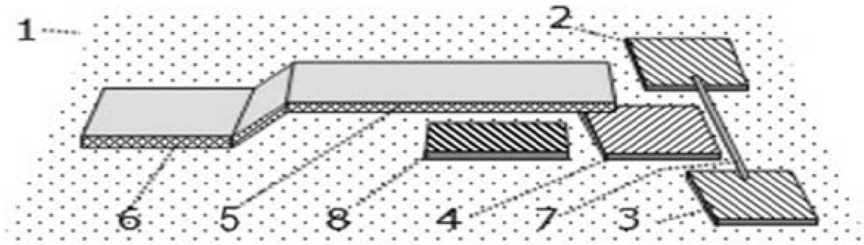

FIG. 4. Design of an elementary cell of flash memory on CNTs [1]: *1* – silicon wafer, *2* – source, *3* – drain, *4* – "floating" gate, *5* – metal cantilever, *6* – electrode, *7* – channel- tube, *8* – control electrode

3.3. CNT displays

Carbon nanotubes are used to produce various types of displays now: as a field emitter in field emission display (FED), a transparent electrode in organic light-emitting devices (OLED), a polarizer in liquid crystal displays (LCD). The use of CNTs in displays is primarily associated with FED technology, developed and introduced by LETI company in 1991. FED displays were supposed to use a matrix of "cold" cathodes. But the first FED displays turned out to be uncompetitive due to the high percentage of defects and the reduction in cost of competing display production technologies.

But this technology came back to life in the early 21st century, when FED displays were developed that proposed using CNT arrays as cathodes [23], which significantly reduced the cost of FED display production. Large-area field emission displays were manufactured using single-layer carbon nanotube emitters. Triode-type field emission display structures were also studied to achieve ultra-high brightness. In this form, carbon nanotube FED displays can compete equally with large-diagonal panels, and they will also compete with plasma panels in the future, which currently dominate the field of ultra-large screen diagonals.

Single-walled carbon nanotubes can also be used as electrodes in OLED displays based on organic light-emitting diodes and light-emitting transistors [17, 24] operating at low voltage, with low power dissipation and high luminosity in three primary colors. Such OLED displays can be extremely flexible and transparent due to the high strength of the nanotubes and the ultra-thin thickness of the electrode matrix, which will allow the creation of sheets of very thin electronic paper. In general, the main trend of the world market in recent years has been the growth in demand for touch screens. Therefore, the development of flexible electronics is one of the main technologies that will only gain momentum in the coming years [25]. It is necessary that the material used to create a flexible display have the ability to deform when pressure is applied. CNTs are such a promising material, suitable for the production of flexible electronics.

The development of a low-temperature method for producing carbon nanotubes, which would allow them to be applied to substrates made of various materials (for example, not to damage the glass substrate used in the final device) was one of the important tasks facing researchers working in this area. This problem has now been solved, particularly, in the works of employees of the Donetsk Institute for Physics and Engineering (DonIPE) [26, 27], which made it possible to obtain arrays of carbon and carbon-nitrogen nanotubes on glass substrates.

3.4. CNT integrated circuits

After the creation of the field-effect transistor on nanotubes, periodic reports appear on the development of electronic devices consisting of a relatively large number of transistors and other elements of circuitry implemented using CNTs. As an example, we can point to elements that perform logical functions, high-frequency pulse generators, electromagnetic wave detectors, and even microprocessors [28–30].

It is necessary to form hundreds and thousands of transistors in a crystal to achieve more complex functionality of integrated circuits. Back in 2013, Stanford University scientists created a simple processor of only 178 transistors (modern silicon processors contain billions of transistors) on carbon nanotubes [28]. Its performance was low, it operated at a frequency of 1 kHz and had extremely limited capabilities. But microelectronics on a silicon platform also went through this path, so this important result can be considered as the first milestone in the development of all-carbon electronics. Already in 2019, a fully functional 16-bit microprocessor with more than 14,000 CNT transistors on the RISC-V architecture was presented [29], which could execute the 32-bit set of commands.

To sum up, despite significant efforts in the field of applied research on carbon nanotubes, they have not yet led to any radical breakthrough in the development of modern nanoelectronics over the past few decades. The unique properties of CNTs as working elements of nanoelectronic devices have not yet been fully implemented, and their combination with existing silicon technologies raises many questions.

4. Electronics of graphene

The discovery of graphene and initial studies of its unique properties give hope that an alternative material that can become the basis for the creation of future universal electronic nanotechnologies has been found, and carbon nanotubes are only the first step in the development of carbon nanoelectronics. Over the past few years, graphene-based electronics have been the subject of hot discussions. It is assumed that graphene sheets of a sufficiently large area will allow the formation of electronic elements using long-known methods of modern microelectronics, such as thin-film technology, various types of nanolithography and carbon particle printing, which will make it possible to implement the density of electronic elements required today and in the future.

Graphene was discovered in 2004 by Russian-born scientists Konstantin Novoselov and Andre Geim [31]. Graphene is a layer of carbon atoms in a hexagonal two-dimensional lattice, and, in fact, it is a one atom thick carbon film with a strictly ordered crystalline structure. Its disadvantages include the absence of a forbidden zone in unmodified graphene, as well as the difficulty of obtaining large homogeneous sheets of such material. A great advantage of graphene is that it can work as a single base material for both nanoelectronics and nanooptics [32], and can be combined in different combinations with elements of optoelectronic circuits, which is very convenient.

It turned out that graphene has many interesting properties, including high stability, high thermal and electrical conductivity (including at room temperature). The mobility of electrons in graphene is 10 – 20 times higher than in classical silicon semiconductors, and, therefore, such a material is promising for creating electronic circuits suitable for operation at terahertz frequencies [33] (as well as the CNT devices discussed above). Conventional planar technologies tested in microelectronics for many decades are applicable to graphene and this is the advantage of graphene over carbon nanotubes. In addition, the control current of the electronic devices used graphene can be proportionally increased by changing the width of the conductive channel, due to the two-dimensional structure of the material. Let us consider practical examples of using graphene in modern electronics.

4.1. Graphene transistors

Today, the main applied electronic application of graphene is in the field of analog electronics, since the problem of forming its energy gap has not yet been finally solved. The main advantage of electronic devices designed on graphene basis is their high performance, due to the record value of charge carrier mobility in graphene. Therefore, graphene attracted much attention immediately after its discovery as a material for creating field-effect transistors [34, 35] and research in this direction continues [36]. The first experimental field-effect transistor on graphene was obtained in the same 2004, on a doped silicon substrate (gate), covered with a layer of silicon oxide (gate dielectric) hundreds of nanometers thick. The simplicity of the design had its drawbacks in the form of parasitic capacitance formed by the conductive silicon substrate, so the applicability of such a transistor in radio-frequency circuits is very problematic. But a start had been made and the prospects of the newly discovered material have been demonstrated in practice.

It is necessary to reduce both the thickness of the gate dielectric and the width of the graphene channel as much as possible to improve the electrical and frequency characteristics of field-effect transistors. The high permittivity group dielectrics is desirable to use instead of the silicon oxide used in the first trial transistor model. The design of a graphene field-effect transistor with a gate dielectric made of Al_2O_3 (the layer thickness is a few nanometers, which is a few orders of magnitude lower than the thickness of the previously used SiO_2) is shown in Fig. 5.

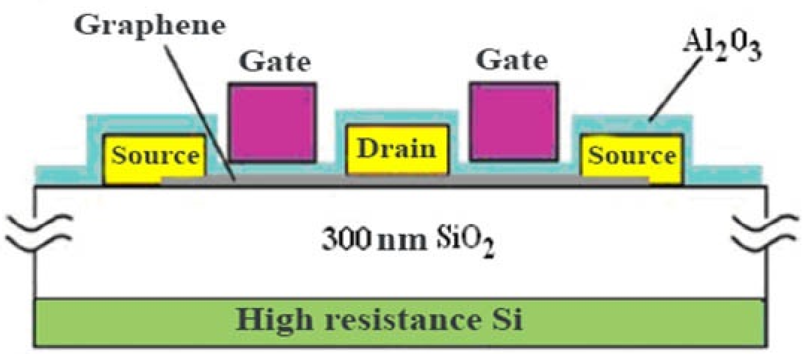

FIG. 5. Structure of a field-effect transistor on graphene [1]

As mentioned above, the lack of a closed state in graphene transistors is an obstacle to the use of such devices in digital circuits due to the inaccessibility of the forbidden zone in graphene. Under normal conditions, a graphene field-effect transistor does not close completely, therefore, devices using such circuitry are not energy efficient enough. However, there are modifications of graphene transistor designs where the current exponentially depends on the gate voltage [35]. Such a device is distinguished by a low closed-state current, typical for conventional semiconductor field-effect transistors, and a high open-state current, typical for graphene. Analog electronics do not require a forbidden zone, so many analog radio-frequency devices are already built on graphene transistors. From year to year, the size of such devices is decreasing, and their operating frequency is increasing. Graphene transistors with a length of 600 nm and an operating frequency of up to 34 GHz, then 150 nm and a frequency of 26 GHz, 240 nm and 100 GHz, and so on, up to 400 GHz, have been consistently reported. Therefore, even experimental field-effect transistors on graphene are already comparable in frequency to the best semiconductor electronics of III-V group compounds, and have significantly outpaced their silicon counterparts.

4.2. Graphene memory devices

Similarly to CNT, graphene, with its unusual properties, is promising for building various types of memory [37–39], including high-performance non-volatile memory. Graphene is able to capture a significantly larger charge and, thus, is promising as a material for the field-effect transistor electrode in the cell for building memory.

The prototype of the new memory, proposed at Rice University (USA) under the supervision of Prof. James Tour, consists of silicon modules with a dozen atomic layers of graphene, no more than 5 nm thick (see Fig. 6). Accordingly, this affects the size of the memory cell, which is at least an order of magnitude smaller than the cells of modern NAND memory. This will allow a multiple increase in the capacity of memory modules without deteriorating its performance and reliability – tests confirm a large number of memory cell rewriting cycles. Graphene-based memory also is capable of operating in a wide range of temperatures, which makes it possible to function with poor heat dissipation or even the absence of cooling and ventilation. Perhaps, the most interesting property of graphene memory is its low sensitivity to the destructive effects of penetrating radiation, which allows such memory to be used in extreme conditions.

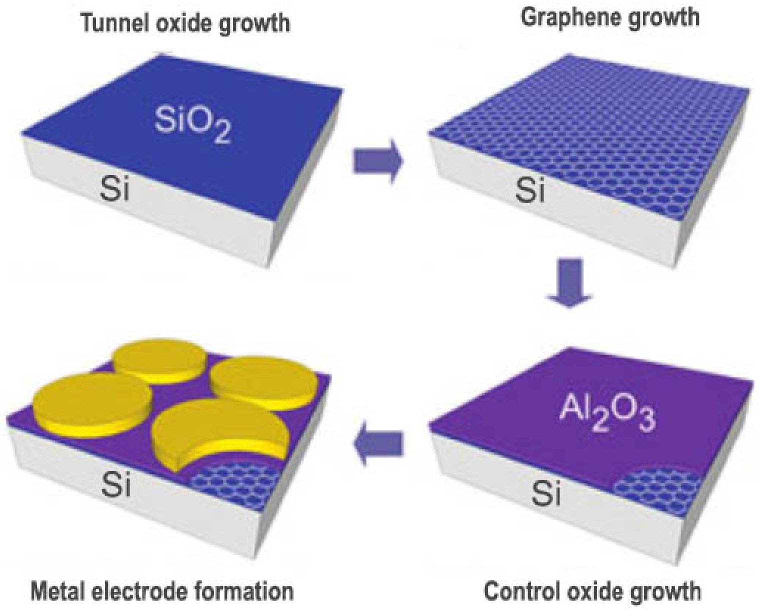

FIG. 6. Flash memory cell based on graphene layers [37]

One of the lacks of the proposed graphene memory is the access time, which is still several times longer than the characteristic response time of modern memory devices, but there is no doubt that further improvement of the proposed prototype will solve this problem. Moreover, Professor J. Tour's group continues to actively work towards improving industrial technologies for obtaining graphene memory [38].

4.3. Graphene integrated circuits

The first integrated circuit based on graphene was created back in 2011 by employees of the IBM Research division [40]. It was a prototype of a frequency mixer operating at frequencies up to 10 GHz and based on a graphene transistor. A broadband frequency mixer is one of the key components of high-frequency radio equipment, generating a signal at the output that is the sum or difference of the signals arriving at the inputs of the device.

The proposed circuit consisted of a graphene transistor with a characteristic size of 550 nm and two aluminum inductors several micrometers thick, located on a silicon carbide substrate (see Fig. 7). The problems of layout of the component elements were solved in the process of creating a single chip. They consisted in the fact that when placing metal components (inductor coil) on top of the graphene transistor, they damaged the graphene sheet and disrupted the functionality of the circuit. Changing the sequence of the RF circuit manufacturing process (first forming passive metal components, and then graphene transistors) made it possible to eliminate the previously observed damage to the graphene layers in order to obtain the expectedly high device characteristics. The circuit operated in the temperature range from room temperature to 125 °C at a frequency of 10 GHz with stable characteristics.

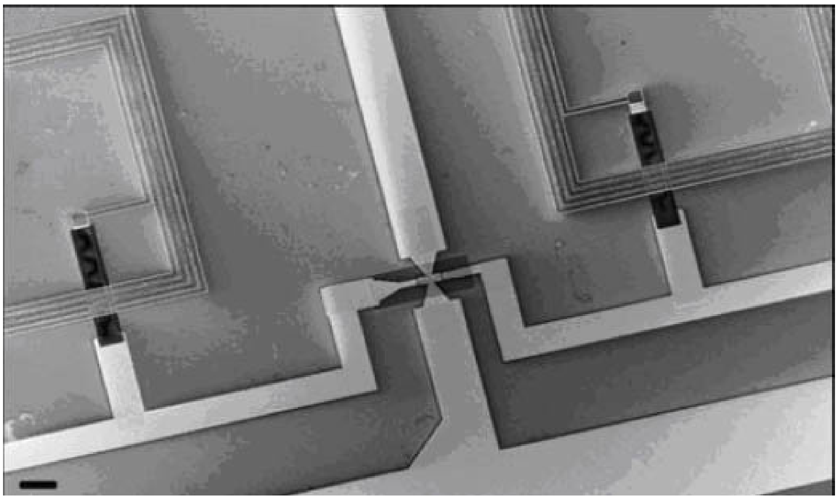

FIG. 7. SEM image of a graphene frequency mixer integrated circuit [1]

However, despite significant progress in the development of graphene field-effect transistors in recent years and the favorable prospects for their use [41], a number of unresolved problems that prevent the mass appearance of radio-frequency integrated circuits using graphene components still remain.

5. Conclusion

So, as we see, promising carbon compounds are partially replacing silicon and other classic semiconductors in the electronics industry. Most elements of modern micro- and nanoelectronics can already be implemented (at least as test devices) on the basis of graphene or carbon nanotubes. Such world industry leaders as IBM and Intel are the largest sponsors of research projects in the field of using nanostructured carbon in microelectronics.

IBM researchers have already achieved multiple increases in the speed of electronic circuits based on carbon nanotubes. Although this speed is still lower than that of modern silicon chips, there is confidence that new nanotechnological processes will eventually unlock the enormous potential of carbon-based electronics. But only if the problems associated with the influence of structural defects on the electronic properties of carbon nanomaterials will be solved in the future (since ideal graphene layers or ideal nanotubes still do not exist).

On the other hand, it is too early to abandon silicon absolutely. It is still unlikely that classical semiconductors will be completely replaced by carbon nanostructures in microchips within the next few decades. In the future, silicon still has many potential applications in nanoelectronics as nanowires, nanotubes, nanodots and other structures, which are the subject of research in many modern laboratories around the world. There are many prospects for the development of modern nanoelectronics and it is impossible to predict what will happen in this industry in 10 or 20 years.

References

[1] Smirnov V.I. *Nanoelectronics, nanophotonics and microsystems engineering: a tutorial*. UlSTU, Ulyanovsk, 2017, 280 p.

[2] Kelsall R., Hemley I., Geoghegan M. *Scientific foundations of nanotechnology and new devices*. Intellect, Moscow, 2008, 800 p.

[3] Georgakilas V., Perman J.A., Tuček J., Zbořil R. Broad family of carbon nanoallotropes: classification, chemistry, and applications of fullerenes, carbon dots, nanotubes, graphene, nanodiamonds, and combined superstructures. *Chemical reviews*, 2015, **115** (11), P. 4744–4822.

[4] Podgorny D.A. *Carbon in all its diversity: a tutorial*. SUrSU, Chelyabinsk, 2014, 31 p.

[5] Avouris P., Chen Z., Perebeinos V. Carbon-based electronics. *Nat. Nanotechnol.*, 2007, **2**, P. 605–615.

[6] Nicholas R., Mainwood A., Eaves L. Introduction. Carbon-based electronics: Fundamentals and device applications. *Philosophical transactions A.*, 2007, **366**, P. 189-193.

[7] Kang Y.H. *Semiconductor Technologies in the Era of Electronics*. Springer, Dordrecht, 2014, 149 p.

[8] Gubin S.P. All-carbon nanoelectronics (project). *Radioelectronics. Nanosystems. Information technology*, 2011, **3** (1), P. 47-55.

[9] Weiss P.S. A Conversation with Phaedon Avouris, nanoscience Leader of IBM. *ACS Nano*, 2010, **4** (12), P. 7041–7047.

[10] Dyachkov P.N. *Carbon nanotubes. Structure, properties, applications*. Binom, Moscow, 2006, 293 p.

[11] Kronholm D., Hummelen J.C. Fullerene-Based n-Type Semiconductors in Organic Electronics. *Material Matters.*, 2007, **2**, P. 16–19.

[12] Tuktarov A.R., Salikhov R.B., Khuzin A.A., Popod'ko N.R., Safargalin I.N., Mullagaliev I.N., Dzhemileva U.M. Photocontrolled organic field effect transistors based on the fullerene C_{60} and spiropyran hybrid molecule. *RSC Adv.*, 2019, **9**, P. 7505–7508.

[13] Woebkenberg P.H., Bradley D.C., Kronholm D., Hummelen J.C., de Leeuw D.M., Coelle M., Anthopoulos T.D. High mobility n-channel organic field-effect transistors based on soluble C_{60} and C_{70} fullerene derivatives. *Synthetic Metals*, 2008, **158** (11), P. 468–472.
[14] Park H., Park J., Lim A.K.L., Anderson E.H., Alivisatos A.P., McEuen P.L. Nanomechanical oscillations in a single-C_{60} transistor. *Nature*, 2000, **407**, P. 57–60.
[15] Iijima S. Helical Microtubules of Graphitic Carbon. *Nature*, 1991, **354** (5), P. 56–58.
[16] Jagessar R.C. Carbon Nanotubes and its Application in Nanotechnology. *J. of Nanosciences Research & Reports*, 2021, **3** (4), P. 1–4.
[17] Wang C., Zhang J., Ryu K., Badmaev A., Arco L. G. D., Zhou C. Wafer-Scale Fabrication of Separated Carbon Nanotube Thin-Film Transistors for Display Applications. *Nano Lett.*, 2009, **9** (12), P. 4285–4291.
[18] Crippa P., Biagetti G., Turchetti C., Falaschetti L. et al. A high-gain CNTFET-based LNA developed using a compact design-oriented device model. *Electronics*, 2021, **10** (22), P. 2835–2914.
[19] Zhang Z., Passlack M., Pitner G., Natani Sh. et al. Complementary carbon nanotube metal–oxide–semiconductor field-effect transistors with localized solid-state extension doping. *Nat. Electron.*, 2023, **6**, P. 999–1008.
[20] Lee Y., Buchheim J., Hellenkamp B., Lynall D. et al. Carbon-nanotube field-effect transistors for resolving single-molecule aptamer–ligand binding kinetics. *Nat. Nanotechnol.*, 2024, **19**, P. 660–667.
[21] Gilmer D.C., Rueckes T., Cleveland L. NRAM: A disrupting carbon-nanotube resistance-change memory. *Nanotechnology*, 2018, **29**, 134003.
[22] Qu T.Yu., Sun Y., Chen M., Liu Z., Zhu Q.B. et al. A Flexible Carbon Nanotube Sen-Memory Device. *Advanced Materials*, 2020, **32** (9), 1907288.
[23] Lee N.-S., Chung D., Han I., Kang J.H. et al. Application of carbon nanotubes to field emission displays. *Diamond and Related Materials*, 2001, **10**, P. 265–270.
[24] McCarthy M.A., Liu B., Donoghue E.P., Kravchenko I., Kim D.Y., So F., Rinzler A.G. Low-Voltage, Low-Power, Organic Light-Emitting Transistors for Active Matrix Displays. *Science*, 2011, **332**, P. 570–573.
[25] Cai L., Wang C. Carbon Nanotube Flexible and Stretchable Electronics. *Nanoscale research letters,* 2015, **10** (1), P. 1013–1021.
[26] Shalaev R.V., Ulyanov A.N., Prudnikov A.M., Shin G.M., Yoo S.I., Varyukhin V.N. Noncatalytic synthesis of carbon-nitride nanocolumns by DC magnetron sputtering. *Phys.Status Solidi A.*, 2010, **207** (10), P. 2300-2302.
[27] Liechtenstein I.Ya., Schemchenko E.I., Varyukhin V.N. Mechanism of formation of the internal structure in multi-walled carbon nanotubes produced by a DC-magnetron. *PHPT*, 2021, **31** (4), P. 42–47.
[28] Shulaker M.M., Hills G., Patil N., Hai W., Chen H.Y., Wong H.S.P., Mitra S. Carbon nanotube computer. *Nature*, 2013, **501**, P. 526–530.
[29] Hills G., Lau C., Wright A., Fuller S., Bishop M.D. et al. Modern microprocessor built from complementary carbon nanotube transistors. *Nature*, 2019, **572**, P. 595–602.
[30] Si J., Zhang P., Zhao C., Lin D., Xu L., Xu H. et al. A carbon-nanotube-based tensor processing unit. *Nature Electronics*, 2024, **7**, P. 684–693.
[31] Novoselov K.S., Geim A.K., Morozov S.V., Jiang D., Zhang Y., Dubonos S.V., Grigorieva I.V., Firsov A.A. Electric field effect in atomically thin carbon films. *Science*, 2004, **306**, P. 666-669.
[32] Avouris P., Xia F. Graphene applications in electronics and photonics. *MRS Bulletin*, 2012, **37**, P. 1225–1234.
[33] Golovanov O.A., Makeeva G.S., Varenitsa V.V. Conductivity of graphene in the terahertz and infrared frequency ranges. *Reliability and Quality of Complex Systems*, 2014, **4** (8), P. 26–33.
[34] Meric I., Han M.Y., Young A.F. et al. Current saturation in zero-bandgap, top-gated graphene field-effect transistors. *Nature nanotechnology*, 2008, **3** (11), P. 654–659.
[35] Svintsov D.A., Vyurkov V.V., Lukichev V.F., Orlikovsky A.A., Burenkov A., Ochsner R. Tunnel field-effect transistors based on graphene. *Semiconductors*, 2013, **47** (2), P. 244–250.
[36] Hu B., Sun H., Tian J., Mo J., Xie W., Song Q.M., Zhang W., Dong H. Advances in flexible graphene field-effect transistors for biomolecule sensing. *Front. Bioeng. Biotechnol.*, 2023, **11**, 1218024.
[37] Hong A., Song E.B., Yu H.S., Allen M.J., Kim J., Fowler J.D. et al. Graphene flash memory. *ACS nano*, 2011, **5** (10), P. 7812-7817.
[38] Wang G., Lee J.-H., Yang Y., Ruan G., Kim N.D., Ji Y., Tour J.M. Three-Dimensional Networked Nanoporous Ta_2O_{5-x} Memory System for Ultrahigh Density Storage. *Nano Letters*, 2015, **15** (9), P. 6009–6014.
[39] Zongjie S., Chun Z., Yanfei Q., Mitrovic I.Z., Li Y., Jiacheng W. et al. Memristive Non-Volatile Memory Based on Graphene Materials. *Micromachines*, 2020, **11** (4), 341.
[40] Lin Yu-M., Valdes-Garcia A., Han S.-J., Farmer D. et al. Wafer-Scale Graphene Integrated Circuit. *Science*, 2011, **332**, P. 1294–1297.
[41] Fadil D., Passi V., Wei W., Ben Salk S., Zhou D. et al. A Broadband Active Microwave Monolithically Integrated Circuit Balun in Graphene Technology. *Appl. Sci.*, 2020, **10**, 2183:8.

Submitted 21 March 2025; revised 5 April 2025; accepted 6 April 2025

Information about the authors:

Rostyslav V. Shalayev – Galkin Donetsk Institute for Physics and Engineering, R. Luxembourg str. 72, 283048, Donetsk, Russia; ORCID 0000-0003-1258-2434; sharos@donfti.ru

Victor N. Varyukhin – Galkin Donetsk Institute for Physics and Engineering, R. Luxembourg str. 72, 283048, Donetsk, Russia; ORCID 0000-0001-7717-8745; director@donfti.ru

Conflict of interest: the authors declare no conflict of interest.