PROSPECTS OF GRAPHENE NANOELECTRONICS

Zhuravleva, Lyubov M., *Moscow State University of Railway Engineering (MIIT), Moscow, Russia.*
Nikulina, Yulia A., *Moscow State University of Railway Engineering (MIIT), Moscow, Russia.*
Lebedeva, Anna C., *Moscow State University of Railway Engineering (MIIT), Moscow, Russia.*

ABSTRACT

The article with regard to transport developments deals with topical issues of improving electronics engineering and of transition to new technological structures associated with nanotechnology. It is noted that the main direction of evolution of nanoelectronics is linked to new electronics components based on new materials like graphene. Possibility and prospect of replacing traditional and most used silicon materials with graphene are reviewed. Brief information about methods of manufacturing, benefits and advantages of the use of graphene is followed by the arguments in favor of development of technique capable to open the band gap, allowing transition of graphene into semiconductor. Methods of mass commercial manufacturing of graphene semiconductor are discussed.

Keywords: transport, science, functional material, graphene, graphite, electronics, nanoelectronics, nanotechnology.

Background. *Development and implementation of a long-term program of railway network development is inextricably linked to the issues of improving the quality indicators of basic elements of optical fiber information transmission systems (OFITS). Improving optoelectronic characteristics of semiconductor lasers, photodetectors, optical modulators directly affect the quality of transmission of service information through operational and technological communication, process control efficiency and traffic safety. Currently, the main focus of raising the technical level of the element base of optoelectronics is to improve the quality of the functional material (increasing the speed of the charge carriers, reducing the inertia of the environment). One of the most promising materials of optoelectronics is graphene.*

Objective. *The objective of the authors is to review advantages and to consider prospects of graphene use in transport-related nanoelectronics.*

Methods. *The authors use general scientific and engineering methods, comparative analysis.*

Results. *Graphene is a two-dimensional allotropic modification of carbon, formed by a single atom thick layer of carbon atoms in the state of sp^3-hybridization and connected within a two-dimensional hexagonal crystal lattice. It can be represented as a single graphite plane, separated from the bulk crystal [1].*

Graphene combines unique properties: high mechanical strength, electrical and thermal conductivity, gas impermeability, transparency to light, etc., making it an attractive material for many applications, including transport equipment and machinery.

Thus, the mobility of electrons in graphene at room temperature is comparable to the speed of light [2], Young's modulus is equal to 1 TPa, internal resistance to deformation – 130 GPa, thermal conductivity is above 3000 W, the ability to maintain an extremely high density of current (a million times higher than copper). However, some of these characteristics are fixed only in samples of highest quality obtained under mechanical delamination of graphene flakes (Pic. 1) using a flexible tape and through their subsequent application to special substrate of hexagonal boron nitride.

Properties of graphene and its use (Pic. 2) are very dependent on the quality of material, substrate, type of defects, etc. which are derivatives for the most part of the method and conditions of production.

Extent and timing of implementation of graphene as a functional material in the final product, especially electronics, are connected to the problems of industrial production in large quantities of graphene sheets with dimensions of a few centimeters. Thus methods for obtaining graphene can be divided into three classes:

– Graphene or flake-shaped recovered graphene oxide for composite materials, conductive inks, etc .;

– Flat graphene for low-performance and inactive devices;

– Flat graphene for high-performance electronic devices.

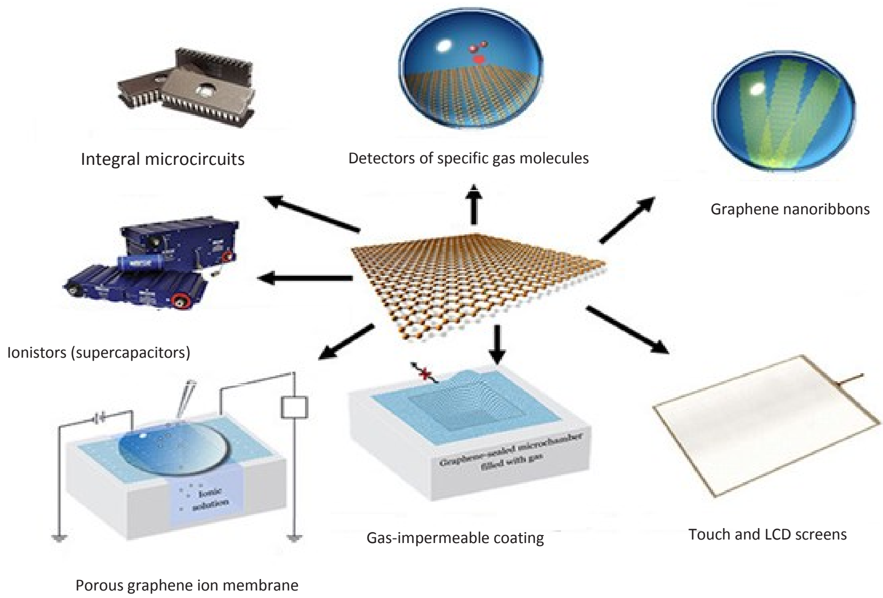
Industrial methods for graphene production are presented in the table 1.

The main area of application of graphene is nanoelectronics (high-frequency transistors, photodetectors, optical modulators, lasers with mode synchronization, optical polarizers, etc.) [3].

Of particular note is the importance of creating graphene-based photodetectors. In contrast to semiconductor photodetectors having a limited width of the light absorption graphene can absorb light of any color (full spectrum). Thus, graphene has high capacity, which makes it an indispensable material for high speed data transmission systems built with optical fiber components.

However, graphene could replace silicon only in the case of opening in a band gap (conversion of

Pic. 1. Graphene.



Pic. 2. Areas of application of graphene.

Table 1

Industrial methods for obtaining graphene

Method	Crystallite size (microns)	Sample size (mm)	Mobility of charge carriers (room temp.) ($cm^2 V^{-1} s^{-1}$)	Area of application
Mechanical flaking-off	>1000	>1	$>2 \cdot 10^5$ and 10^6(at low temperature)	Research
Chemical flaking-off	≤0,1	–	100 (for a layer of flakes, overlapping each other)	Coatings, paints / inks, composite materials, transparent conductive layers, capacitors, bioapplications
Chemical flaking-off through graphene oxide	~100	–	1 (for a layer of flakes, overlapping each other)	Coatings, paints / inks, composite materials, transparent conductive layers, capacitors, bioapplications
CVD	1000	~1000	10000	Photonics, nanoelectronics, transparent conductive layers, sensors, bioapplications
SiC	50	100	10000	High-frequency transistors and other electronic devices

grapheme-semimetal into graphene-semiconductor). It is necessary not only to open a band gap, but also to make it commensurate with the width of the band gap of silicon. There are several ways to create a semiconductor graphene:

1) coating strips of graphene with chemical elements affecting electrical conductivity of graphene;

2) mechanical uniaxial stress on the strip of graphene.

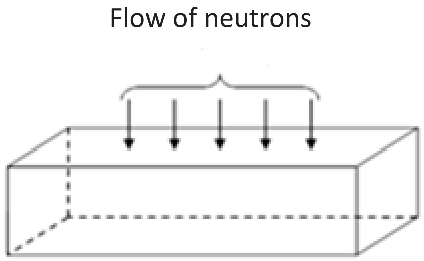
The main disadvantage of those methods is complexity of implementation in industrial environment.

Isotopic method (changing number of neutrons in the nucleus while number of protons is constant) seems to be most appropriate method for mass production of semiconductor material from graphene. With addition of one neutron in the carbon nucleus, a renormalization of the electron energy and the increase (or opening) in a band gap occurs. Thus, the replacement of the light isotope ^{12}C with a heavier ^{13}C increases the energy of interband transitions, which leads to changes in the frequency of the optical phonon mode.

It is known that uniaxial mechanical tension of 1% of the corresponding peak for atomic bonds leads to formation of a band gap with a size of 300 meV. This is indicated by the red optical phonon frequency shift in the Raman spectrum, equal to 14,2 cm^{-1} [4]. Similar changes occur in isotopic substitution in graphene of ^{12}C isotope by the isotope ^{13}C. The magnitude of the shift depends on the percentage of the heavier isotope. It can be concluded that in case of isotopic substitution in graphene by a heavier isotope opening of the band gap will occur [4]. Such replacement must be done using the method of neutron irradiation. Thermal neutrons with energy from 0,025 to 1 eV are most suitable for irradiation (Pic. 3).

Thus, the average value of neutron absorption depth by graphite preform L is given by:

$$L=1/K_{0\sigma i}, \quad (1)$$



Pic. 3. Scheme of irradiation of graphite preform.

where K_0 is number of graphite atoms in 1 cm^3, equal to $3{,}402 \cdot 10^{23} at/cm^3$;

σi = 0,0033 barn – absorption cross-section of isotope ^{12}C.

After substituting values K_0 and σi in the formula (1) we obtain the neutron absorption depth which will be L = 8,91 m. This figure indicates that at a depth of several centimeters, for example, every second isotope ^{12}C will be transferred with a high probability into isotope ^{13}C. The value of the band gap in graphene will reach more than six hundred meV.

The time required to increase concentration of the isotope ^{13}C in the graphite preform can be calculated according to the formula (2). In particular, the integrated flow ϕt for 50% transfer of ^{12}C into the isotope ^{13}C is equal to:

$$\phi t = 0{,}5/\sigma i, \quad (2)$$

where ϕ is intensity of neutron flow;

t is time of exposure.

When the intensity of neutron flow is 10^{19} n/s cm^2 time t is 175,365 days. If intensity is increased by an order (by 10 times), then irradiation will require 17,54 days. These figures confirm the reality of obtaining semiconductor graphene using thermal neutrons. The magnitude of the band gap can be deduced from the following proportion:

$$x = [32\,(cm^{-1}) \cdot 300\,(meV)]/14.2\,(cm^{-1}) = 676\,(meV),$$

where 32 cm^{-1} is frequency shift of the optical phonon at 50 percent substitution of isotopes.

Conclusion. *The irradiated preform of graphite should be split mechanically into separate atomic strips of graphene that are poorly linked. Once in contact with a chemically clean and smooth surface of the substrate of silicon oxide, a graphene layer remains on the surface, which is able to reach an area of 1 cm^2. Neutron irradiation can be performed on research reactors RF. With the launch of industrial facilities for production of semiconductor graphene an era of graphene nanoelectronics will come.*

This is an option for solving the problem. And it is at the same time our forecast.

REFERENCES

1. Graphene. [Electronic source]: https://ru.wikipedia.org/wiki/%D0%93%D1%80%D0%B0%D1%84%D0%B5%D0%BD. Last accessed 27.11.2015.

2. Poverennaya, M. Graphene boom. Results [*Grafenovyj bum: itogi*]. *Nanotehnologicheskoe soobshhestvo,* Iss. October 26,2012. [Electronic source]: http://www.nanometer.ru/2012/10/26/13512365078102_298275.html. Last accessed 27.11.2015.

3. Nobel Prize in physics was awarded for creation of graphene [*Za sozdanie grafena prisuzhdena Nobelevskaja premija v oblasti fizike*]. [Electronic source]: http://venture-biz.ru/tekhnologii-innovatsii/93-grafen-nobelevskaya-premiya. Last accessed 27.11.2015.

4. Zhuravleva, L. M., Plekhanov, V. G. Isotopic creation of semiconductor graphene [*Izotopicheskoe sozdanie poluprovodnikovogo grafena*]. *Nanotehnika*, 2012, Iss. 3, pp. 34–39.

5. Graphene. Physics [*Grafen.* Fizika]. [Electronic source]: http://4108.ru/u/grafen_-_fizika. Last accessed 27.11.2015.

6. Yudintsev, V. Graphene. Nanoelectronics is rapidly gaining strength [*Grafen. Nanoelektronika stremitel'no nabiraet sily*]. *Elektronika, nauka, tehnologija, biznes*, 2009, Iss. 6. [Electronic source]: http://www.electronics.ru/journal/article/269. Last accessed 27.11.2015.

7. Samardak, Alexander. Graphene, new methods of synthesis and the latest advances [*Grafen: novye metody poluchenija i poslednie dostizhenija*]. *Elementy*. Iss. 30.09.2008. [Electronic source]: http://elementy.ru/novosti_nauki/430857/Grafen_novye_metody_polucheniya_i_poslednie_dostizheniya. Last accessed 27.11.2015.

8. 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, V.* 306, 22 October 2004, pp. 666–669.

9. Bekyarova, E., Itkis, M. E., Cabrera, N., Zhao, B., Yu, A., Gao, J., Haddon R. C. Electronic Properties of Single-walled Carbon Nanotube Networks. *Journal of American Chemical Society*, 2005, Vol. 127, No. 16, pp. 5990–5995.

10. Palnitkar, U. A., Kashid, R. V., More, M. A., Joag, D. S., Panchakarla, L. S., Rao, C.N.R. Remarkably Low Turn-on Field Emission in Undoped, Nitrogen-doped, and Boron-doped Graphene. *Applied Physics Letters*, 2010, Vol. 97, No. 6, pp. 063102–063102.

11. Chernozatonsky, L. A., Sorokin, P. B., Belova, E. E., Bruening, J., Fedorov, A. S. Superlattices consisting of «lines» of adsorbed hydrogen atom pairs on graphene [*Sverhreshetki, sostojashhie iz «linij» adsorbirovannyh par atomov vodoroda na grafene*]. *Pis'ma v ZhETF,* 2007, Vol. 85, Iss. 1, pp. 84–89.

12. Novoselov, K. S. Graphene: Materials of Flatland [*Grafen: Materialy Flatlandii*]. *UFN*, 2011, Vol. 181, pp. 1299–1311.

13. McCann E., Koshino M. The Electronic Properties of Bilayer Graphene // *Reports on Progress in Physics*, 2013, Vol. 76, No. 5, pp. 056503(28).

14. Chernozatonsky, L. A., Sorokin, P.B., Belova, E.E., Bruening, J., Fedorov, A. S. Superlattices metal – semiconductor (semimetal) on a graphite sheet with vacancies [*Sverhreshetki metall – poluprovodnik (polumetall) na grafitovom liste s vakansijami*]. *Pis'ma v ZhETF*, 2006, Vol. 84, Iss. 3, pp. 141–145. ●

Information about the authors:

Zhuravleva, Lyubov M. – Ph.D. (Eng.), associate professor of Moscow State University of Railway Engineering (MIIT), Moscow, Russia, zhlubov@mail.ru.

Nikulina, Yulia A. – 4th year student of Moscow State University of Railway Engineering (MIIT), Moscow, Russia, yulcka1995@mail.ru.

Lebedeva, Anna C. – 4th year student of Moscow State University of Railway Engineering (MIIT), Moscow, Russia, anka238105@yandex.ru.

Article received 02.06.2015, revised 27.11.2015, accepted 28.11.2015.