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Original article

Electrical properties of "metal-carbon film" contact

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ABSTRACT Magnetron sputtering was used to obtain carbon films on of metal substrates of two types: titanium and tool chromium steel. The temperature dependence of the resistance of the films, which has a semiconductor character, has been studied. The current-voltage characteristics of the metal-carbon film contact were determined, which indicate the presence of the Schottky barrier junction.

KEYWORDS carbon film, magnetron sputtering, metal-semiconductor contact, Schottky barrier.

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1. Introduction

The metal–semiconductor contact (the Schottky barrier) has attracted the attention of researchers for a long time. This is due not only to its wide and various applications, but also to the abundance of requirements for it, due to the specific conditions of use and the expanding range of semiconductor materials involved in practice. It is customary to associate the beginning of research in the field of semiconductor electronics at the end of the 19th century with the metal-semiconductor contact, and since the beginning of the 60s of the twentieth century — with a new (modern) stage in the development of microwave electronics. The foundations of the physics of contacts were laid approximately in the late 1930s and early 1940s, and by the early 1980s, thanks to the work of a number of researchers, quite complete physical ideas about the properties of contacts were formed, which were reflected in a number of monographs (see, e.g. [1–4]).

As for the involvement of new semiconductor materials in practice, carbon materials seem to be quite promising in this respect today [5–9]. It should be noted that carbon-based materials have recently been increasingly used in micro- and nanoelectronics. The traditional silicon platform does not meet many modern requirements, and more and more often researchers name carbon as its potential replacement (at least in certain niches). Due to the huge variety of allotropic forms, this material has considerable potential in many areas, but for electronics it is of particular interest.

It has long been known that its electrical properties can vary over a very wide range. Separately, it should be said about graphene, the creation of which opened up additional possibilities. This material is characterized by high carrier mobility (under normal conditions, 10 times higher than in silicon) [10,11], ambipolar field effect, ballistic transport under normal conditions, and many other interesting properties. Prototypes of integrated circuits based on graphene have already been created, which operate at frequencies up to 10 GHz at room temperature and have an area of less than 1 mm^2. In addition, we should not forget that, in addition to graphene, carbon can also form ideal one-dimensional structures. Many researchers suggest that, in combination, all of the above will make it possible in the future to realize the idea of all-carbon high-speed nanoelectronics [12].

Keeping in mind all of the above, the creation and study of the "metal-carbon film" contact seems to be a rather urgent task. In this paper, we considered some electrical properties of such a contact.

2. Experimental technique

Samples for the research were obtained by magnetron sputtering of graphite (purity 99.9% C) in an argon atmosphere. Carbon films were deposited on dielectric and metal substrates (titanium and tool chromium steel). The plasma was created using a planar DC magnetron with a flat cathode and an annular anode. The conditions for deposition of samples on all types of substrates were the same: the gas pressure in the chamber was 150 mTorr, the film growth time was 40 min, the substrate temperature was 350 °C, and the magnetron current was 40 mA.

The electrical properties of the obtained samples were studied in a heat chamber in the range from 20 °C to 150 °C. According to [6], the conductivity perpendicular to the film growth direction is called transverse, and along the growth direction, longitudinal. The transverse conductivity was measured by the two-probe method in films on a glass substrate (to eliminate the influence of a well-conductive metal substrate) in the voltage range from -10 V to $+10$ V. Phosphor bronze contacts, contact area 0.3 mm^2, distance between contacts $\sim$1 mm. The longitudinal conductivity was measured in films deposited on metal substrates. The measurements were carried out in the following structure "substrate–carbon film–measuring contact". A pin brass contact with an R rounding of 0.2 mm^2 was used. The temperature dependences of the resistance of carbon films and the current-voltage characteristics of the metal-carbon contact were obtained. The band gap of the obtained samples was estimated graphically from the temperature dependences.

3. Main results and discussion

The films grown show predominantly graphite-like properties: the color varies from dark gray to almost black, and the adhesion is relatively weak. The temperature dependence of the film resistance R (measurements were made perpendicular to the film growth direction) has a classical semiconductor character: a decrease in resistance with increasing temperature — ($\frac{dR}{dT} < 0$). Thus, carbon films with semiconductor properties were obtained in the work as we can see.

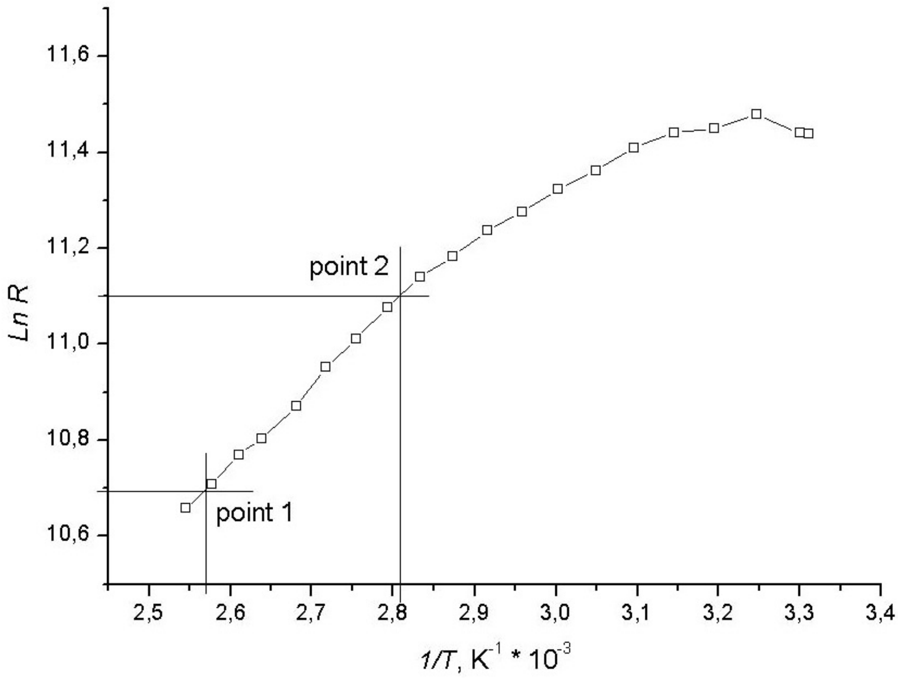

FIG. 1. Dependence $\ln R(1/T)$ for the film on a dielectric substrate. R is measured in Ohm

Now consider this dependence in the form $\ln R$ vs $(1/T)$ curve shown in Fig. 1. It makes it possible to estimate the band gap (activation energy) of the resulting carbon film from the slope of the dependence graph. We chose the high-temperature section of the graph, where the conductivity of a classical semiconductor is predominantly determined by its own conductivity. Calculations carried out according to the formula:

$$\Delta E = 2k \frac{\ln R_2 - \ln R_1}{\frac{1}{T_2} - \frac{1}{T_1}},$$

where k is the Boltzmann constant and values from the abscissa/ordinate axis at point 1 and point 2 on the graph, showed that the activation energy ΔE of the film is approximately 0.29 eV (assuming that we have an undoped or lightly doped semiconductor).

Thus, when such films are deposited on metal substrates, we obtain a "metal-semiconductor" contact, which is the subject of study in this work. Let's consider some features of these contacts.

The current-voltage characteristics of the obtained contacts, shown in Fig. 2, are nonlinear and asymmetric, therefore, we can talk about obtaining some kind of rectifying "metal-semiconductor" contact junction (with a potential Schottky barrier). If we compare the current-voltage characteristics of contacts based on titanium (Fig. 2a) and based on steel (Fig. 2b), it can be noted that the former is characterized by a transition to the open state at lower applied voltages than the latter. Presumably, this may be due to different work functions of the metal substrate.

We have mentioned above that, at present, there are a considerable number of diodes based on the Schottky barrier, and the requirements for them vary greatly and depend on the application. The semiconductor materials most commonly used in modern diodes are silicon, silicon carbide, and gallium arsenide. Each of them has its own advantages and disadvantages. If we talk about the material used in this work, then the current-voltage characteristic demonstrates at least one of its obvious advantages compared to most other materials – a contact based on it goes into an open state at very low voltage values (tens of microvolts). This property may be of interest in many applied areas, which allows us to speak about the prospects for further research in this direction.

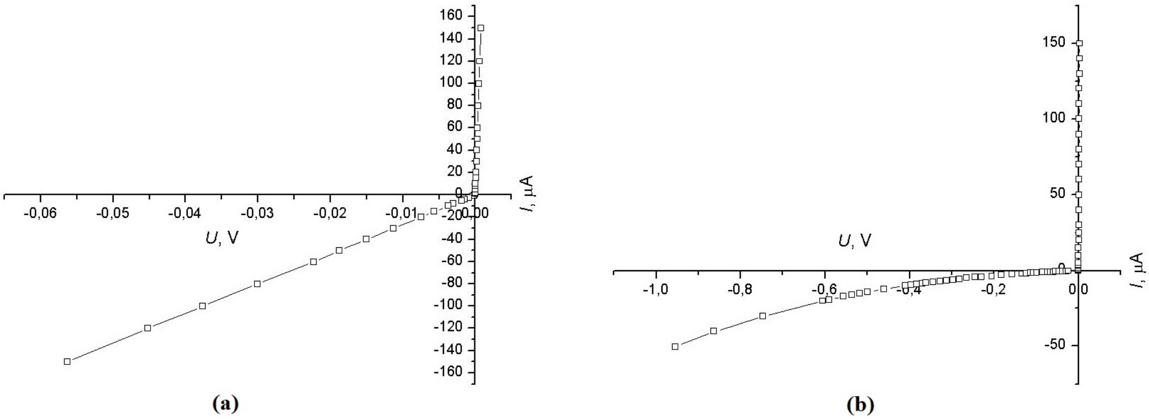

FIG. 2. Current-voltage characteristics: a) “titanium-graphite-like film” contact; b) “chromium steel-graphite-like film” contact

4. Conclusion

Preliminary studies of the obtained samples allow us to suggest that graphite-like carbon films can be successfully used in rectifying metal-semiconductor junctions with the Schottky barrier. According to the current-voltage characteristics, the “metal-carbon film” contact goes into an open state at very low voltage values, thus, we can say that the proposed semiconductor material in some areas will have certain advantages over the traditional materials.

References

[1] Henish H.K. *Semiconductor rectifying contacts*. Oxford, Oxford University Press, 1957, 372 p.
[2] Striha V.I. *Theoretical foundations of the operation of a metal–semiconductor contact*. Kiev, Naukova Dumka, 1974, 264 p.
[3] Roderic E.H. *Metal-semiconductor Contacts*. Moscow, Radio and Communications, 1982, 210 p.
[4] Pikus G.E. *Contact Phenomena. Semiconductors in Science and Technology*. Moscow, Leningrad, Publishing House of the USSR AS, 1956, v.1, 148 p.
[5] Vinogradov A.Ya., Grudinkin S.A., Besedina N.A. Koniakhin S.V., Rabchinskii M.K., Eidelman E.D., Golubev V.G. Structure and properties of thin graphite-like films produced by magnetron-assisted sputtering. *Semiconductors*, 2018, **52**(7), P. 914–920.
[6] Hvostov V.V., Streletskiy O.A., Yakunin V.V., et al. Properties of carbon films with high conductivity anisotropy. *Vestn. Mosk. Univ.* Ser. 3. Phys. Astron., 2012, **1**, P. 78–84.
[7] Kalinin Yu.E., Kashirin M.A., Makagonov V.A., et al. Properties of amorphous carbon thin films grown by ion beam sputtering. *Technical Physics*, 2017, **62**, P. 1724–1730.
[8] Berezin V.M., Shepovalov I.I., Lukashev V.S. Transparency factors and electrical resistance of graphite-like films on glass. *Chelyabinsk Physical and Mathematical Journal*, 2017, **2**(4), P. 483–488.
[9] Demidov A.A., Rybalka S.B. Modern and promising semiconductor materials for microelectronics in the next decade (2020-2030). *Prikladnaya matematica & Fizika*, 2021, **53**(1), P. 53–72.
[10] Schwierz F. Graphene transistors. *Nature Nanotechnology*, 2010, **5**, P. 487–496.
[11] Breusing M., Ropers C., Elsaesser T. Ultrafast Carrier Dynamics in Graphite. *Phys.Rev.Lett.*, 2009, **102**(8), P. 086809.
[12] Gubin S.P. All-carbon nanoelectronics. *Radioelectronics. Nanosystems. Information Technologies*, 2011, **3**(1), P. 47–54.

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