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On the analysis of semiconductor materials suitable for the development of a radiation-stimulated power supply based on the nickel-63 radio isotope

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Abstract. At present, the urgent problem is the development of long-term service life of batteries. If one considers power supplies with a period of more than 10 years, and even up to 50 years of service life, then it is necessary to pay attention to the Nickel-63 radioisotope. The given isotope is safe from the point of view of radiation, but it can generate energy up to 50 years. The article shows that it is necessary to analyze semiconductor materials suitable for its development in the manufacture of a power source based on Nickel-63. Such an analysis is also important for the estimation economic requirements taking into account the increasing miniaturization of electronic equipment. A current level analysis was performed for each semiconductor material.

1. Introduction

In the Krasnoyarsk scientific school, activities are underway to develop long-term service life of power sources. One of the promising fields is the development of a radiation-stimulated power source based on the Nickel-63 radioisotope [1-4]. The article analyzes semiconductor materials suitable for the development of the radiation-stimulated power source based on the Nickel-63 radioisotope. Such materials as silicon, silicon carbide, gallium arsenide, gallium nitride, and diamond are considered. The results of this semiconductor materials analysis for their economic efficiency and possible level of the current strength are also presented.

2. Results of semiconductor materials analysis

The article discusses the main semiconductor materials, namely silicon, silicon carbide, gallium arsenide, gallium nitride and diamond, which can be used as a converter of ionizing radiation. It was necessary to take into account that wide-gap materials have a low level of short circuit current in the analysis process. This is due to the presence of a large number of defects and, consequently, a low lifetime in the quasi-neutral area. The economic requirements are taken into account due to the miniaturization of modern electronic equipment. That is why, the applied semiconductor materials must have high structural perfection and uniformity of the structure in volumes of about a micrometer or less [5-8].

2.1. Silicon

Silicon (Si) is one of the most applied materials in the earth's crust. Currently monocrystal line silicon has a leading place among other semiconductor materials as it has several advantages. The band gap is 1.12 eV. It provides a maximum operating temperature of devices based on it up to 200^0C, and silicon equipment has mall reverse currents, allow higher specific loads, and can also work in the breakdown region of the p-n junction. The elementary silicon in single crystal form is an indirect gap semiconductor and has a diamond type lattice.

The electro physical properties of crystalline silicon are greatly affected by the impurities contained in it. Atoms of elements of the III group, such as boron, aluminum, gallium, and indium are input into silicon to obtain silicon crystals with a hole conduction. Atoms of elements of the V*th* group, such as phosphorus, arsenic, antimony are put into silicon to obtain silicon crystals with electronic conductivity.

The modern level of technology allows the production of silicon wafers with high structural excellence and high carrier lifetimes of the order of ms, as well as creating a developed surface on the silicon surface. The developed technological processes allow reaching the depth of p-n junctions of the order of 0.1-0.3 microns and the space charge region of 5-10 microns. It should ensure high efficiency of energy conversion.

An important advantage of silicon is the SiO_2 layer, which easily forms on the surface of the plates, playing the role of a dielectric. SiO_2 layer is easily developed in a single technological cycle.

2.2. Silicon carbide

Silicon carbide (SiC) is a solid consisting of silicon and carbon atoms in equal proportions a crystalline structure such as sphalerite. The band structure of silicon carbide is similar to the band structure of diamond. This material has both ceramic and semiconductor properties. Silicon carbide is a solid, chemically inert, resistant to high temperature (over 1000 °C), oxidation and environmental exposure. It has a high thermal conductivity close to metal.

The growth of SiC from the gas phase by the method of sublimation is the most developed technological process. Silicon carbide is mainly used as a semiconductor material in electronics. Semiconductor devices based on it have stable time characteristics, are used in high-current electronics, microwave and optoelectronics. Based on silicon carbide, rectifiers, powerful diodes, photodiodes and transistors are created. Indeed, electronic devices made on the basis of silicon carbide are able to operate at higher temperatures, power, and frequency and in more aggressive environments than those made on the basis of other semiconductor materials (silicon, germanium).

The widespread use of electronic devices based on silicon carbide in transport should make a significant contribution to the preservation of the environment, since the main advantage of silicon carbide electronics over silicon is the reduction of energy losses in electronic devices while switching.эВ. The band gap of 4H-SiC is 3.2 eV. It should provide low leakage currents and high conversion efficiency.

In silicon carbide equipment, the effect of temperature is significantly reduced. In the range of 25 - 150 °C, the change in resistance is only 20%, this is a very small change compared to the same indicator of 200% and even 300% for silicon equipment.

However, it is necessary to have a high degree of structural perfection of the obtained crystals to achieve the required electronic properties and high lifetime in SiC.

An analysis of the developed silicon carbide-based battery showed that the SiC substrate had too many defects after thinning, and the epitaxial film was grown on the surface of the substrate. An n-type film with a concentration of 4.6 1014 $cm^{-2}$was designed thick enough (19 μm) to collect most of the incident electrons. The sample was irradiated with a Ni^{63} plate with an activity of 1.5 mCi/cm^2.The authors claim high performance (23.6%) of a SiC-based beta-voltaic battery when irradiated with ^{63}Ni

isotope. The conversion efficiency of the thinned sample was 11.2%, due to the formed defects with a decrease in the thickness of the material by the chemical method.

In [5], the planar structure of the silicon carbide diode shown in figure 1 was investigated. The depth of the sharp, shallow n^+-p junction with the values of 0.25 and 0.5 μm was studied. Heavily doped n^+ layer provides good ohmic contact. The structures were obtained by vapor deposition (CVD). The thickness of the active film of silicon carbide was chosen to correspond to the average value of the penetration of β-electrons Ni-63 (3 μm), for optimal collection of charge carriers. The samples were irradiated with electrons with the energy of 17 keV and a current of 0.72 nA in a scanning electron microscope. The experiment showed that samples with a depth of 0.5 μm have a higher open-circuit voltage (0.95 V) and samples with a depth of 0.25 μm (0.72 V), but the short-circuit current of samples with a lower depth has a greater value (40 pA) than for samples with a greater depth (22 pA).

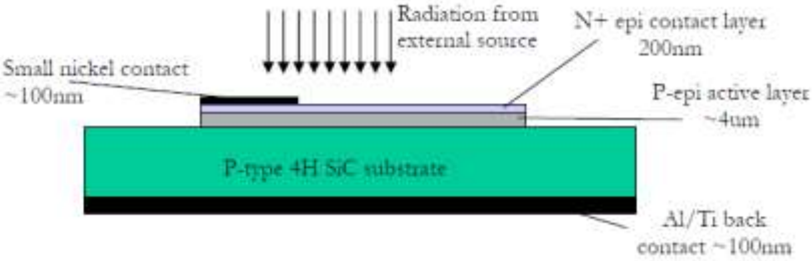

Figure 1. Structure of the silicon carbide silicon diode based on SiC.

2.3. Gallium arsenide

Currently the compounds of elements of groups III and V of the periodic table are widely used; the interest caused by them is associated with large values of the band gap and mobility. Recently, epitaxial layers of gallium arsenide that have a crystalline structure like sphalerite are widely used in the manufacture of semiconductor equipment. Epitaxial layers are obtained by liquid epitaxial growth. They based on crystallization of arsenic gallium melts. Some electronic properties of GaAs are superior to those of silicon. Gallium arsenide has higher electron mobility; it allows equipment to operate at frequencies up to 250 GHz. This material has found application in microwave equipment, centimeter and millimeter range detectors, and parametric diodes.

Semiconductor devices based on gallium arsenide have a higher radiation resistance than silicon; it determines their use in radiation conditions (for example, in solar panels operating in space).Great success was achieved in the development of solar panels, so work was done to develop gallium arsenide based on it. So, in [2-4], GaAsp-i-n structures were fabricated and experiments were performed under ^{63}Ni irradiation. The structures are shown in figure 2.

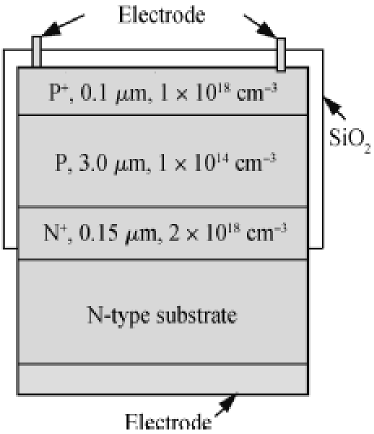

Figure 2. Structure of a GaAs-based beta voltaic battery.

The structures were obtained by molecular beam epitaxial growth with a high resistance region from 1 to 3 μm. The battery area was 5x5 mm^2 to which a nickel-63 plate with an activity of 10 mCi / cm^2 was pressed, the short-circuit current was 7.43 nA with an open-circuit voltage of 0.3 V.

By physical characteristics, GaAs is a more fragile and less heat-conducting material than silicon. Gallium arsenide substrates are much more difficult to manufacture and about five times more expensive than silicon. It restricts the use of this material. In addition, many dislocations and point defects will form in gallium arsenide during growth, on which recombination of the generated electron-hole pairs will occur.

2.4. Gallium nitride

Gallium nitride (GaN) is a binary inorganic chemical compound of gallium and nitrogen. Under ordinary conditions, it is a solid with a crystalline structure of wurtzite. Direct band semiconductor with a wide band gap. It began to be widely used in LEDs since 1990, as well as powerful and high-frequency semiconductor equipment. The high band gap makes gallium nitride suitable for energy conversion of high-energy particles. GaN has the increased resistance to ionizing radiation. It will allow the development of beta voltaic batteries based on high-energy radioisotopes. The material becomes attractive for creating devices used in harsh conditions due to the fact that gallium nitride equipment can remain operational at higher temperatures and voltages than silicon equipment. On the basis of this material, the industry has practiced LEDs with a wide gamut of colors, photo detectors operating in a significant range of wavelengths and microwave transistors that operate at frequencies of 50 GHz.

The technological level of gallium nitride production is far from perfect. One of the most important parameters for GaN-based beta-voltaic batteries is the doping of the GaN layer. A high-resistance GaN layer will be obtained at a low doping level; it will increase the depletion region. Nowadays, the main method for growing GaN structures is the metal-organic chemical vapor deposition (MOCVD). However, it does not allow growing a high-quality and sufficiently thick high-resistance GaN layer, which leads to depletion of the pn junction region. The development of contacts to thin GaN layers is also a sophisticated task, since during the annealing of metallization, the upper layers are melted.

In [9, 10], gallium nitride was used as the material for the beta voltaic battery. The beta voltaic battery demonstrated in [9] is based on a p-i-n diode. The GaN structure (figure 3) was grown on sapphire substrates by the MOCVD method.

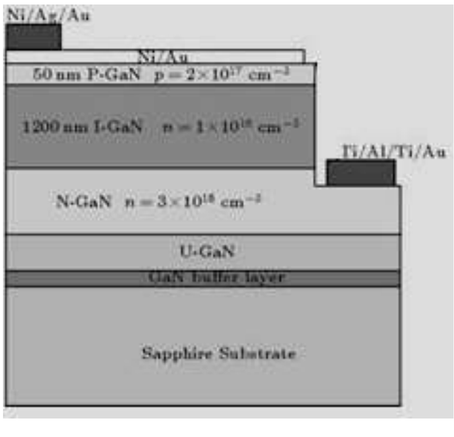

Figure 3. Structure of a GaN pin beta voltaic micro battery.

As a radioactive isotope, a thin Ni^{63} plate with an area of 4 x 4 mm^2 with an activity of 2 mCi was used. During the investigation, it was found that the open circuit voltage reaches a value of more than 1.62 V, and the short circuit current density is 16 nA cm^{-2} with a conversion efficiency of 1.13%.

The structure in [10] represents a cylinder with a diameter of 1 cm, the thickness of the I layer was 1 and 1, μm, respectively. The source of β particles was the promethium-147 isotope. The structure is shown in figure 4.

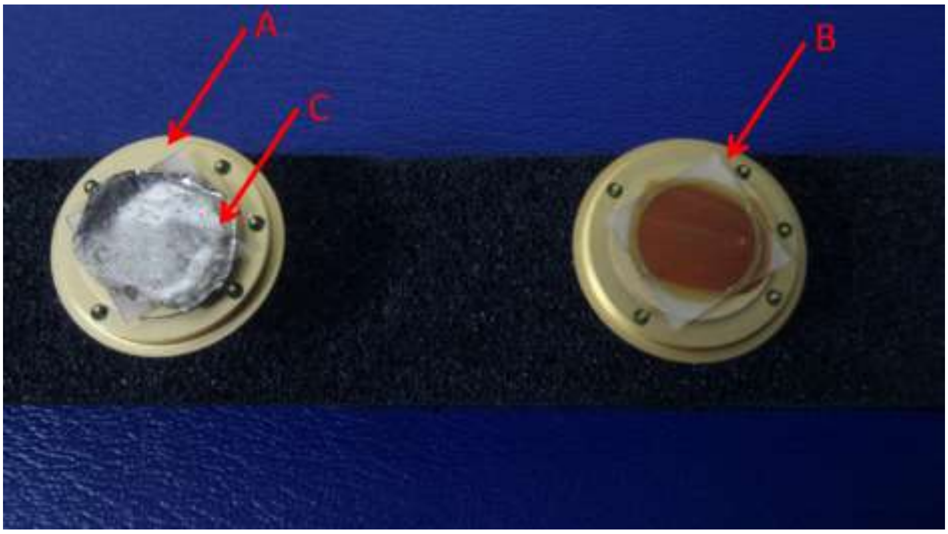

Figure 4. GaN structure, A - promethium 147, B - structure 1, C - structure 2.

The equipment showed the best results so far found in the literature among GaN structures. The short circuit current was 59 nA, and the open circuit voltage was 1.4 V, with a maximum output power of 49.4 nW.

2.5. Diamond

Diamond is a crystalline carbon modification of cubic syngony. It has the highest hardness of all known natural minerals and artificial alloys, the hardness of diamond on the Mohs scale is 10, the micro hardness is 10060 $kgf \cdot mm^{-2}$ according to Khrushchov-Berkovich, and the density of diamond varies from 3.01 to 3.51 $gc \cdot m^{-3}$.

The refractive index of diamond for waves with different lengths varies in the range of 2.42-2.71; diamond has a high dispersion of 0.063. A characteristic feature of most diamonds is their luminescence when irradiated with ultraviolet, x-ray, cathode and gamma rays. In different excited states, diamonds have different glow, both in intensity and spectral structure. Diamond has high thermal conductivity and usually low electrical conductivity; it is one of the hydrophobic minerals.

Diamond is widely used in industry as an abrasive material, diamond dies, for reinforcing cutting tools, in measuring instruments. Due to its semiconductor properties, it is used in electronic measuring instruments capable of operating at high temperatures in active chemical environments. The leading role of diamonds is in jewelry production; diamonds unsuitable for this purpose are used for technical purposes: micro crystals less than 1.2 mm, aggregates, and fragments with a large number of defects.

The application of diamond as a converter of ionizing radiation allows one to solve the problems of developing high-energy beta voltaic batteries.

Firstly, diamond differs from other semiconductor materials in its increased radiation resistance. It will make it possible to develop non-degrading beta voltaic batteries over time based on radioisotopes emitting high-energy electrons and use them under more severe conditions.

The threshold electron energy sufficient for defects to occur in diamond is of greatest interest. It is 165–220 keV [11]. The band gap of diamond is in 5 times greater than silicon. This means that diamond is more suitable for converting the energy of high-energy particles.

Diamond also has a high mobility of electrons and holes. It significantly reduces the probability of recombination and leads to the increase in the energy conversion efficiency. The presence of high thermal conductivity in diamond simplifies the problem of heat removal greatly.

It is the problem in creating n type conductivity. The n-type conductivity is only at high temperatures, since the activation energy of the impurity is very high. Therefore, beta voltaic batteries can be implemented only on Schottky barriers. It in turn has large leaks and a low contact potential difference.

In this case, the space charge region will be no more than 1 μm, and high-energy electrons will simply fly through this region without having time to generate electron-hole pairs, it remains only to rely on the contribution of the quasineutral region. As a result there is another disadvantage. It is the low lifetime of charge carriers, it is about some units of nano seconds.

3. Conclusion

The article considered the basic semiconductor materials that can be applied as a converter of ionizing radiation.

It is shown that wide-gap materials have a low level of short circuit current, this is due to the presence of a large number of defects and, as a result, a low lifetime in the quasi-neutral region.

Materials should have high structural perfection and uniformity of structure in volumes of the order of a micrometer or less based on economic requirements and the increasing miniaturization of electronic equipment. Nowadays, such requirements can only be satisfied on silicon.

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