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INVESTIGATION OF THE MAGNETIC PROPERTIES OF SILICON DOPED WITH RARE-EARTH ELEMENTS

Khodjakbar S. Daliev [a#], **Zavkiddin E. Bahronkulov** [b*], **Jonibek J. Hamdamov** [b#]
[a] *Branch of the Federal State Budgetary Educational Institution of Higher Education "National Research University MPEI", 1 Yogdu st., Tashkent, Uzbekistan*
[b] *Institute of Semiconductor Physics and Microelectronics at the National University of Uzbekistan, 20 Yangi Almazar st., Tashkent, 100057, Uzbekistan*
**Corresponding Author e-mail: zbakhronkulov@inbox.ru*
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This article discusses the electrical properties of silicon doped with rare earth elements (REE). Atoms of rare earth elements (REE) diffused onto the surface of the silicon substrate. To measure the electrical parameters, samples of n-Si, n-Si<Lu>, n-Si<Er> and n-Si<Gd> were prepared and their electrical properties were determined using the Hall effect, four-probe and thermal probe methods. The studies were carried out in the temperature range 77÷300 K. The samples were ohmically contacted using a mixture of 1% Sb + 99% Au for measurement on the HMS500 instrument. The specific resistance of the samples in layers, the concentration of charge carriers, and the mobility of the samples were also studied by the magnetoresistance method. The electrical parameters of the samples were measured on an Ecopia Hall effect measuring system (HMS5000).
Key words: *Silicon; Lutetium; Rare earth elements; Magnetoresistive; Diffusion; Magnetic field; Temperature*
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INTRODUCTION

At present, special attention is paid to the study of the nature of defects formed by the introduction of atoms of rare earth elements (REE) into semiconductor single crystals by the diffusion method. A lot of scientific work is being done on the formation of a deep energy level in silicon, which is the main material of semiconductor devices, its doping with additives that allow changing its properties, and the study of their resistance to heat and radiation [8-9].

Modern microelectronics main material silicon that it was due to, silicon in single crystal defects appear to be such as technological processes to study is very important. The physical and optical parameters of silicon doped with hafnium and lanthanum have been studied [1,5,6].

As is known, the first single crystals used for the manufacture of semiconductor devices are not without defects. Point and volume distortions of the crystal lattice occur in a single crystal even during its growth. In subsequent device manufacturing processes, these defects are filled with other defects in various parts of the semiconductor structure. In recent years, there has been a sharp increase in interest in semiconductor materials with special properties. Doping with rare earth elements is more widely used to obtain such materials. This is due to the use of silicon doped with these compounds in special semiconductor devices, for example, various types of photoreceptors, solar cells, high-radiation and thermally stable devices. In addition, most of the experiments were carried out using the Hall effect, and the sensitivity of measuring electrical conductivity, magnetic susceptibility, and other measurement methods is relatively low.

MATERIALS AND METHODS

Investigate for the Czochralski method grown n - type (ρ=40 Ω×cm) dimensions 7× 6 ×1cm^{-3}, to the (111) surface suitable silicon from a single crystal was used. Source diffusion was created by sputtering metallic lutetium (purity ~ 99.99).

Propagation from making the first silicon into monocrystals mechanic and chemical processing considering VUP-4 device using single crystal silicon on the surface of lutetium atoms high vacuum (10^{-6} mmHg.) under sprayed Use of quartz glass high vacuum ampoule received. The diffusion method has been used in many studies to study the properties of silicon with rare earth elements, transition elements, and refractory elements [1-7].

Distribution at high temperature 1523 K oven SUOL-0.4 30 hours of use time between was spent. From spreading after the samples have cooled rapidly. After diffusion annealing samples repeatedly washed in hydrofluoric acid, aqua regia, and also in a boiling mixture H_2O_2: HCl. Such washing usually allows almost completely remove the source of diffusion remaining on the surface of the sample [2-5].

After this edge of the sample cleaned to a depth of ~ 10 μm, significantly greater than the diffusion depth. The profile was determined by etching thin layers (in 1HF:50HNO_3 solution) and measuring surface resistance of a four-probe sample method, as well as the method Hall effect using Van der Pauw probes. Samples on the device HMS 500 measure for a mixture of 1% Sb + 99% Au received through an ohmic contact. The 175 Lu isotope was deposited onto the surface of a silicon sample. After diffusion and subsequent washes, as well as in the process of removing the layers, X-ray

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diffraction of samples was carried out to control the uniformity of alloying. The electrical parameters of the samples were determined using the Hall effect. Input concentration for the experiment: n-Si<Er> (N_{Er} = 2.3×10^{17} cm^{-3}), n-Si<Lu> (N_{Lu} = 2.43×10^{14} cm^{-3}) and n-Si<Gd> (N_{Gd} = 1×10^{16} cm^{-3}). samples are prepared.

RESULTS AND DISCUSSION

In this work, we studied the magnetic field dependences of the magnetoresistive effect and the Hall effect in silicon doped with Er, Gd, and Ho. Doping with rare earth elements (REE) was carried out in the process of growing from a melt according to the Czochralski method. The magnetic field dependences of the magnetoresistance (MR) and the Hall effect were studied in a constant magnetic field up to 1.4 T in the temperature range 20–300 K. The study of the temperature dependence of the Hall mobility μH(T) showed that in samples doped with REE, its value was ~10–20% lower than in the control material, which indicates that additional scattering of charge carriers occurs in Si<REE> due to the inclusion mi lanthanides.

The magnetic field dependences of the magnetoresistive of the control undoped single crystals over the entire temperature range have a close to quadratic (Δρ/ρo) ~ br (μHB) γ, where γ=1.8-1.9, dependence on the magnetic field. At T = 300 K, REE doping did not change the general form of the dependence of magnetoresistive on the magnetic field, although the magnitude of the magnetoresistive effect decreased significantly. At liquid nitrogen temperature in Si<REE> in a weak magnetic field (B < 0.5 T), the magnetoresistive effect is negative and reaches its maximum value in a field B ≈ 0.25 T. Negative magnetoresistive in fields B > 0.3 T begins to decrease and passes into the region of positive magnetoresistance. A further decrease in temperature to 20 K leads to the disappearance of the negative MR and the appearance of a positive magnetoresistive, despite the fact that the charge transfer mechanism has not changed. Immediately after growth, lanthanides in silicon show no electrical activity. However, later studies did not confirm this assumption. Samples magnet resistance magnet in the field $\frac{\Delta\rho}{\rho_0} \sim b_r\ (\mu_H B)^\gamma$ expression via connected [10-16]. Here ρ - comparison resistance b_r- magnetic resistance μ_H- magnetic field constant, B - magnetic field induction.

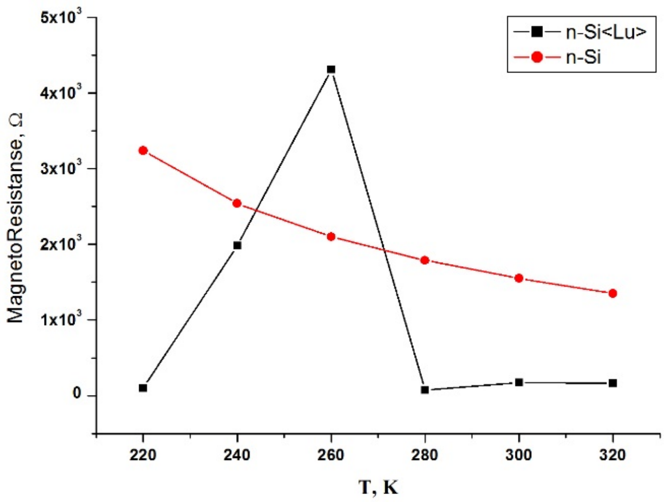

Figure 1. T =220÷320 K magnetic resistance to temperature depending on: n-Si (control) (1); n-Si <Lu> (2).

In Figure 1, the red line is lutetium doped with silicon, the black line is the control sample. As can be seen from the figure, the magnetic resistance of a single crystal of silicon (control sample) in the temperature range 220÷320 K practically did not change.

The magnetic resistance of a silicon sample doped with lutetium (n- Si<Lu>) increased from 101 Ω to 4308 Ω in the temperature range 220÷260 K, decreased from 4308 Ω to 87 Ω in the temperature range 260÷280 K, increased from 87 Ω to 175 Ω in the temperature range 280÷300 K and after 300 K the value has not changed. It was noticed that the magnetic resistance of the control sample decreased exponentially from 3249 Ω to 1349 Ω in the temperature range 220-260 K. As can be seen from Fig. 1, lutetium atoms have influenced the magnetic resistance of single-crystal silicon. The resistivity of our lutetium-doped silicon sample increased dramatically below 220 K. Since the lutetium-silicon alloy is being studied for the first time, the magnetoresistance compared with samples of silicon with rare earth elements.

Throughout the studied range of magnetic fields, the criterion of a classically weak ($\mu_H B$ << 1) magnetic field was fulfilled, and the value of the magnetoresistance coefficient lay within the range b = 0.2...0.4, which is close to the theoretical value of b characteristic of scattering charge carriers by acoustic phonons background b_τ^{phon} = 0.27. The slightly overestimated value of b may be caused by the additional contribution of the geometric effect to the magnetoresistance due to the short-circuiting of the Hall emf by current contacts. The sample resistance in the absence of a magnetic field is due to both the scattering of charge carriers by acoustic phonons and their scattering by magnetic clusters with a random orientation of magnetic moments. According to the giant magnetoresistive model, an external magnetic field orients the magnetic moments of clusters in the direction of the field, which leads to a decrease in the scattering of charge carriers (resistance of the sample), i.e. to negative magnetoresistive. The smallness of the negative magnetoresistance in the studied Si<REE> samples is due to the fact that the conditions for observing a giant magnetoresistive are far from optimal, when the sizes of isolated magnetic clusters and the distance between them is of the order of the mean free path of the carriers.

On Fig. 2 shows a graph of the temperature dependence of conductivity. The red line is an n-Si sample (control), and the black line is a single crystal of silicon doped with lutetium (n-Si<Lu>). The mobility of the control sample in the range of 220÷320 K did not change. In a sample of single-crystal silicon (n-Si<Lu>) doped with lutetium, the electron mobility increased by 3×10^9 cm^2/Vs in the range 220÷240 K, decreased by 5.35×10^{19} cm^2/Vs at 240÷260 K, increased by 1.13×10^{19} cm^2/Vs in the temperature range 260÷280 K and after 280 K coincided with the control sample.

As a result of our studies in Fig. 3 it is established that single-crystal silicon doped with rare-earth elements does not change the general form of the dependence of magnetic resistance on the magnetic field at T = 300 K. At the same time, due to the uneven distribution of lutetium atoms in a single crystal of silicon, the magnetic resistance coefficient of the sample was higher than the theoretical value. As can be seen from Fig. 3, the magnetic resistance of silicon samples doped with rare earth elements in a weak magnetic field (B < 0.5 T) at liquid nitrogen temperature has a negative value and reaches a maximum value in the field B ≈ 0.25 T. B > 0.3 T changed to a positive value. This indicates that the Hall constant in rare earth doped silicon is almost positive.

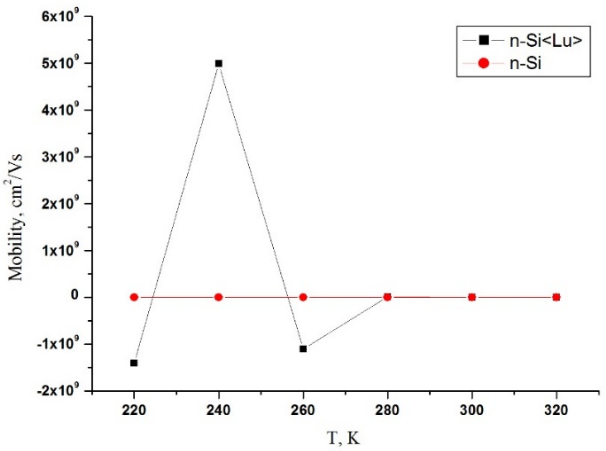

Figure 2. T =220÷320 K mobility to temperature depending on: n-Si (1); n-Si<Lu> (2)

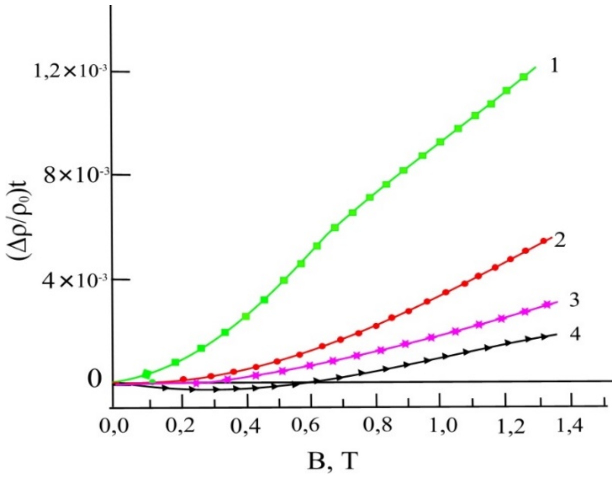

Figure 3. Room temperature control n - Si (1); n - Si<Gd> (2); n-Si<Er> (3;) and n-Si<Lu> (4), magnet resistance magnet samples in the field dependence

The magnetic resistance of silicon samples doped with rare earth elements at 77 K is evidenced by the nature of the dependence of the magnetic resistance on the magnetic field (Fig. 4). This resistance is the algebraic sum of the measured positive and negative component values:

$$\Delta\rho_\Sigma = \Delta\rho_- + \Delta\rho_+$$

The closest to optimal conditions for observing negative MR due to scattering by magnetic clusters are realized in samples doped with erbium at a concentration of 2.3×10^{17} cm^{-3}. A decrease in the REE concentration leads to a decrease in the size of lanthanide inclusions and, ultimately, to a decrease in the negative MR (see Fig. 4).

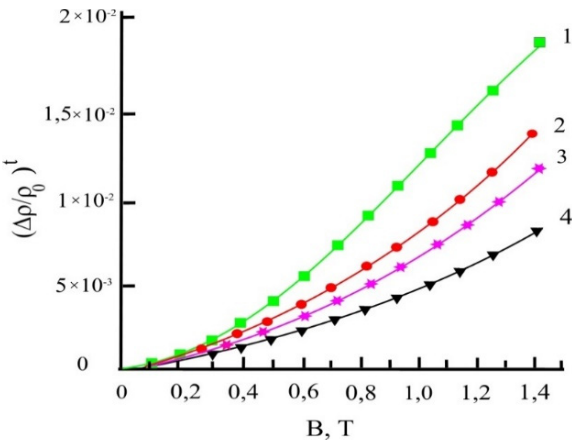

Figure 4. At a temperature of 77÷300 K, control n - Si (1); n - Si <Gd> (2); n - Si <Er> (3); and n - Si <Lu> (4) samples magnet resistance magnet in the field dependence.

An additional confirmation of this mechanism of the negative component of the MR at B < 0.6 T can be the independence of the Hall constant on the magnitude of the magnetic field, which is not typical for the band transfer mechanism and "traditional" mechanisms of scattering of charge carriers, for which the Hall factor decreases with increasing magnetic field in classical magnetic fields.

The results of studies carried out at temperatures of 300 and 77 K show that single crystals of silicon with rare earth elements do not change their general properties at both temperatures. According to the results obtained, it was found that the Si <Lu> sample is more resistant to magnetism than the Si <Er> and Si <Gd> samples.

CONCLUSIONS

A temperature graph of the magnetic resistance of samples doped with lutetium (n- Si <Lu>) has been obtained. Such a conclusion can be drawn from the analysis of the obtained results.

1. Magnetic aging of lutetium-doped silicon (n- Si <Lu>) and control (n- Si) samples at room and nitrogen temperatures was studied for the first time.

2. After alloying single-crystal silicon with lutetium atoms, it was found for the first time that the magnetic resistance does not change at room temperature and changes at nitrogen temperature.

3. Samples in a weak magnetic field (B<0.5 T) The magnetic resistance of silicon samples doped with Lu, Er and Gd elements at liquid nitrogen temperature has a negative value and reaches a maximum value in a field B ≈ 0.25 T.

This indicated that the Hall constant in silicon doped with Lu, Er and Gd elements is positive.

4. In the temperature range of 77-300K, it was established that the resistance of n-Si<Lu> samples to a magnetic field is higher than that of n-Si<Er> and n-Si<Gd> samples.

ORCID
Khodjakbar S. Daliev, https://orcid.org/0000-0002-2164-6797; **Zavkiddin E. Bahronkulov,** https://orcid.org/0009-0002-9843-8344
Jonibek J. Hamdamov, https://orcid.org/0000-0003-2728-3832

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ДОСЛІДЖЕННЯ МАГНІТНИХ ВЛАСТИВОСТЕЙ КРЕМНІЮ ЛЕГОВАНОГО РІДКОЗЕМЕЛЬНИМИ ЕЛЕМЕНТАМИ

Ходжакбар С. Далієв[a], Завкіддін Е. Бахронкулов[b], Джонібек Дж. Хамдамов[b]
[a] *Філія ФДБУ «Національний дослідницький університет МПЕІ»,*
Йогду, 1, Ташкент, Узбекистан
[b] *Інститут фізики напівпровідників та мікроелектроніки Національного університету Узбекистану,*
100057, Ташкент, Узбекистан, вул. Янги Алмазар, 20

У цій статті розглядаються електричні властивості кремнію, легованого рідкоземельними елементами (РЗЕ). Атоми рідкоземельних елементів (РЗЕ) дифундували на поверхню кремнієвої підкладки. Для вимірювання електричних параметрів були підготовлені зразки n-Si, n-Si<Lu>, n-Si<Er> і n-Si<Gd> та визначені їх електричні властивості за допомогою ефекту Холла, чотиризондового та термічного зондового методів. Дослідження проводили в інтервалі температур 77÷300 К. Омічний контакт зразків створювали сумішшю 1% Sb + 99% Au для вимірювання на приладі HMS500. Також питомий опір зразків у шарах, концентрацію носіїв заряду та рухливість зразків досліджували методом магнітоопору. Електричні параметри зразків вимірювали за допомогою системи вимірювання ефекту Холла Ecopia (HMS5000).

Ключові слова: *кремній; лютецій; рідкоземельні елементи; магніторезистивний; дифузія; магнітне поле; температура*