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Development of thermal sensors by implantation ions P^+ and B^+ in different sides of Si(111)

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In the method of high-phase ion implantation of P^+ and B^+ to different sides of monocrystal silicon we obtained p-i-n- structure, which has a high thermal sensitivity of 2.3 mV/K in a broad band temperature of (20 ÷ 550) K. We studied the distribution profile P and B atoms implanted in the Si gradually decreasing energy. The effect of the subsequent thermal and annealing IR profile on the distribution of the atoms and the characteristics of the temperature sensor was studied.

Keywords: method of high-phase ion implantation, temperature-sensitive elements, sensor, annealing.

Introduction

The particular sensitivity of the properties of semiconductor materials to the presence of minor impurities, temperature, pressure, exposure to electromagnetic radiation, etc. widely used to create various types of sensors [1-3]. Thermosensitive elements based on silicon were obtained in a number of works [3-6]. In particular, studies of the electrophysical properties of silicon diffusion-doped with manganese have shown [6] the possibility of obtaining a material with high thermal sensitivity. However, both in [6] and in other works on temperature sensors based on silicon, known to us, structures were obtained that can measure the temperature of objects only up to (350-380) K. This is due to the fact that, at these temperatures, impurity atoms are ionized and more At high temperatures, the intrinsic conductivity of silicon occurs. Another disadvantage of Si-based thermoelements is the non-linearity of their temperature response.

Materials and methods

In order to create on the basis of silicon temperature sensor capable of measuring higher temperatures, we choose p-i-n - structure.

The following technological methods are commonly used to create p-i-n structures: epitaxial-diffusion, two-sided-epitaxial and two-sided-diffusion methods [7].

In the manufacture of semiconductor devices, depending on the type of dopant and technology used, various defects are formed in the structures, which deteriorate the quality of the diodes and their breakdown characteristics. In addition, when using high-temperature technologies, such as epitaxial and diffusion technologies for creating pin-structures, it is possible to activate impurities of the source material, such as Na atoms, which can create fast states, various traps [8], macroscopic fluctuations leading to the appearance of density tails [9], or large inhomogeneities, at least at high concentrations of about 10^{13} cm^{-2} [10, 11]. If the wave functions of such states overlap, tunneling becomes possible between them. At high temperatures, thermal excitation up to the mobility edge is also possible.

Therefore, to obtain the p-i-n structure, we have chosen the method of ion implantation, which does not subject the sample to high-temperature heating. Our task was to create a thermal sensor that meets the following requirements:

1) small size;

2) high temperature sensitivity;

3) a wide range of measured temperatures;

4) linearity of the temperature characteristics of the output signal of the sensor.

The last requirement was associated with the need to use the sensor as a primary device in the system for automatic control of the temperature of technological processes. Fulfillment of this requirement provided the sensor versatility for use in various technological processes.

To obtain a sensor that meets the above requirements, it was necessary to ensure the maximum degree of doping of the p- and n-layers and the creation of sharp boundaries of the p-i and i-n-transitions. To obtain such abrupt transitions, we carried out the implantation of P^+ ions and B^+ ions in different directions of purified Si(111) single crystals. The experiments were carried out with samples of Si(111) p - type with a specific resistance of ρ=3000 and 6000 Ωcm, with a thickness of 0.1 to 1 mm. The most good characteristics were obtained using Si samples with a thickness of 0.1 mm.

Before carrying out ion implantation, the initial Si(111) samples were thoroughly cleaned by thermal heating in two stages: long at 1200 K and briefly at T=1500 K. The implantation of P^+ and B^+ ions was carried out on a standard ion-like installation at a vacuum of 10^{-5} Pa. To create p and n layers in silicon, implantation of P^+ ions and B^+ ions was carried out and subsequent annealing. Figure 1 shows the distribution profiles of boron atoms implanted in Si(111) with the energy E_0 =1 keV and subjected to subsequent thermal and laser annealing.

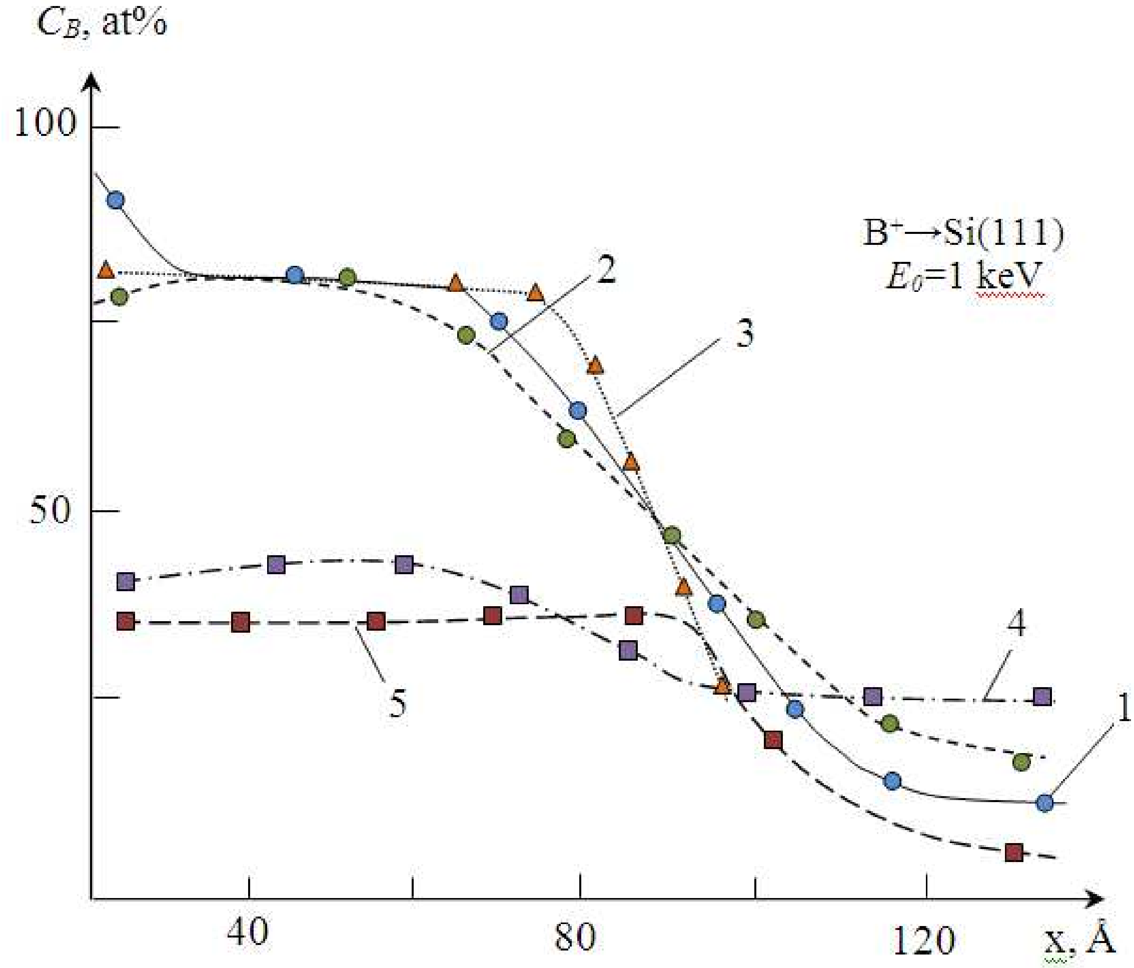

Figure 1. Concentration distribution profiles of boron atoms implanted into Si(111) with the energy E_0 =1 keV over depth x, obtained after thermal annealing at (1) 300, (2) 900, and (4) 1200 K and laser annealing at an energy density W of (3) 1.0 and (5) 3 J cm $^{-2}$.

Results and discussion

Thermal annealing at T=900 K of Si(111) samples implanted with B^+ ions with E_0 =1 keV allows one to anneal defects and obtain a single crystal boron silicide SiB_3 film in the surface region of the sample $\approx$ 40 Å thick (Figure 1). Pulsed laser annealing of Si(111) implanted with B^+ ions at W=1.0 J $\cdot$ cm $^{-2}$, as well as in the case of P^+, allows one to obtain a heterostructural transition SiB_3-Si with a sharper interface. For the decomposition of the chemical compound SiB_3 and the complete electrical activation of the remaining B^+ atoms, thermal heating is required at T=1200 K or laser annealing with W=3 J $\cdot$ cm $^{-2}$. We note that after laser annealing of ion-implanted samples, an n^{--}–p transition is formed in the case of P and p^{++}-p - in the case of B. In addition, we also investigated the distribution profiles of the P and B atoms implanted in Si(111) with a higher energy of 10, 20 and 80 keV. In this case, annealing of ion-implanted samples was carried out by thermal heating and pulsed infrared (IR) radiation with a wavelength $\lambda = 1$ μm and a pulse duration of $\approx$ units of microseconds.

Figures 2 and 3 show how the distribution profiles of implanted P and B atoms with different energies are transformed as a result of thermal and IR annealing. As can be seen from the above figures, annealing by IR radiation, as well as laser annealing, allows one to obtain sharper profiles of implanted atoms than thermal annealing.

Obviously, at such ion energies, even at high doses of irradiation, the concentration of impurity atoms is much less than the concentration of Si atoms. However, this does not mean that chemical interaction between atoms is not possible. Based on the analysis of the distribution profiles of P and B atoms implanted with a high dose of $D \approx 10^{17}$ cm^{-2} with different energies before and after annealing with IR radiation, we determined the optimal energies, irradiation doses and conditions of the subsequent annealing to obtain the maximum possible concentration of electrically active impurities P and B with their uniform distribution over the depth of the sample. It was found that to obtain a uniform distribution of P atoms in Si(111), it is necessary to implant P+ ions first with an energy of $E_0 = 80$ keV and a dose of $D = 1.8 \cdot 10^{16}$ cm^{-2} (Figure 4), and then with $E_0 = 20$ keV and $D = 1.8 \cdot 10^{15}$ cm^{-2}. Annealing by infrared radiation should be carried out after each stage of ion implantation.

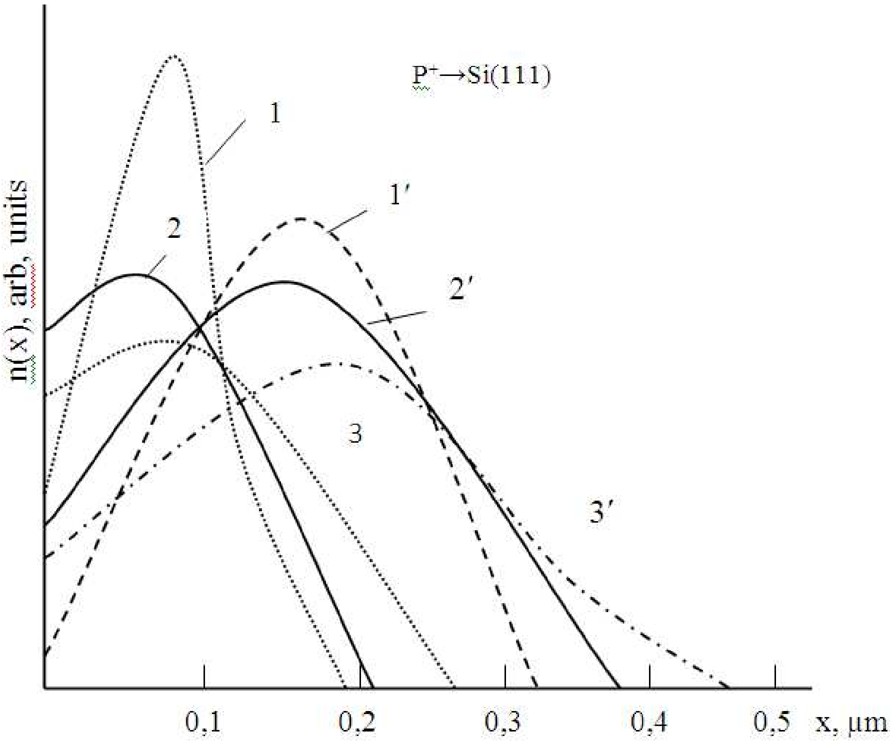

Figure 2. The distribution profiles of P atoms implanted in Si(111) with $E_0 = 20$ keV (1), after IR annealing (2), thermal annealing at T=1200 K (3) and with $E_0 = 80$ keV (1′), after IR annealing (2′) and thermal annealing at T=1200 K (3′).

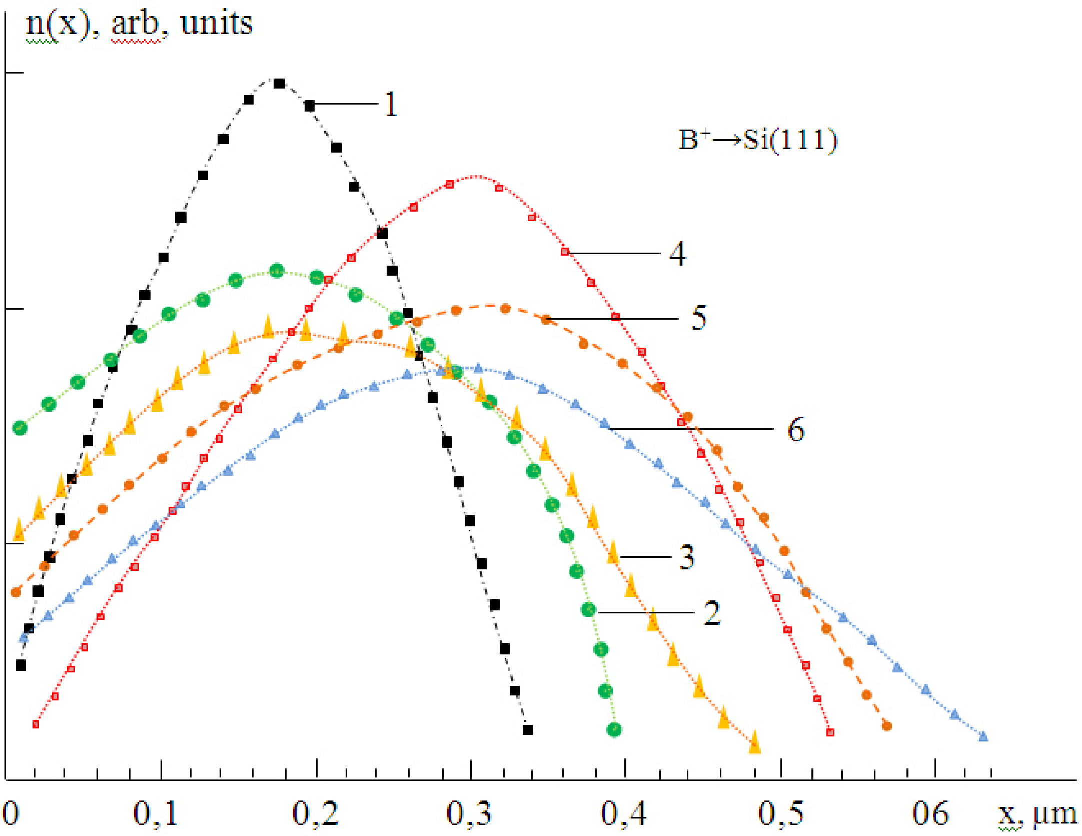

Figure 3. The distribution profiles of B atoms implanted in Si(111) with E_0 =20 keV (1), after IR annealing (2) of thermal annealing at T=1100 K (3) and with E_0 =80 keV (4), after IR annealing (5), thermal annealing at T=1100 K (6).

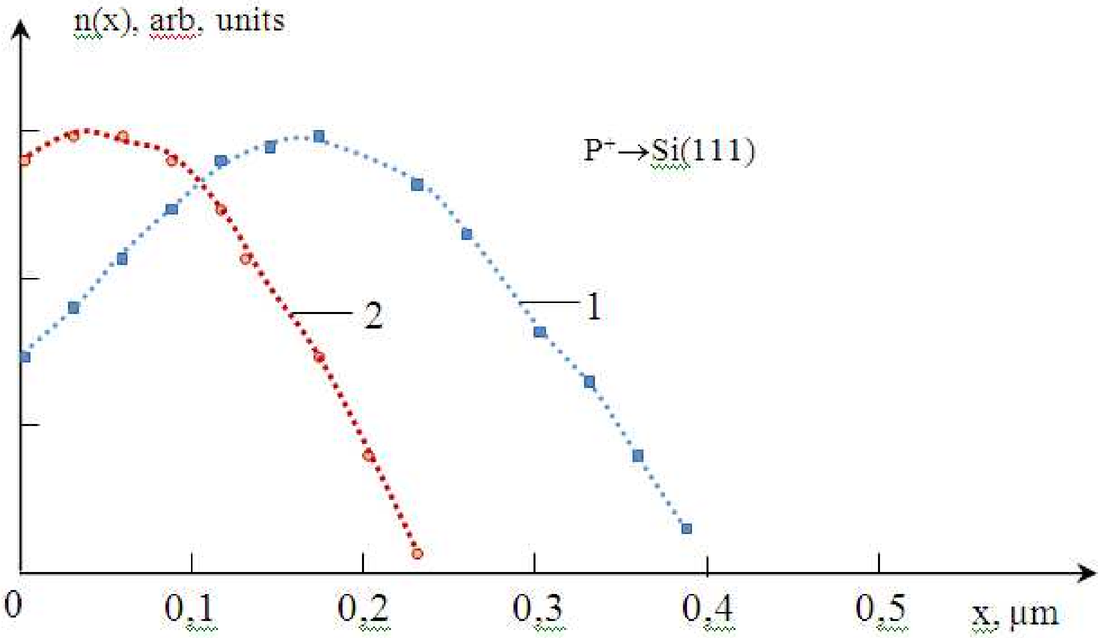

Figure 4. Distribution profiles of phosphorus atoms over depth x, implanted into Si(111) with (1) energy E_0 =80 keV and dose D=$1.8 \cdot 10^{16}$ cm^{-2} and (2) E_0 =20 keV and D=$1.8 \cdot 10^{15}$ cm^{-2} .

In the case of boron, the optimal conditions for implantation and annealing are the following: first, implantation of B^{+} ions at E_0 =80 keV and D=$0.9 \cdot 10^{16}$ cm^{-2}, then with E_0 =20 keV and D=$3 \cdot 10^{15}$ cm^{-2} and finally with E_0 =10 keV and $D=1.8 \cdot 10^{16}$ cm^{-2}, annealing with infrared radiation should also be carried out after each stage of ion implantation (Figure 5).

As can be seen from the above Figures 4 and 5, carrying out ion implantation and subsequent annealing in the manner described above makes it possible to obtain an almost uniform distribution of P atoms in a layer $x \approx 0.4$ µm thick, and B atoms in a layer with $x \approx 0.6$ µm.

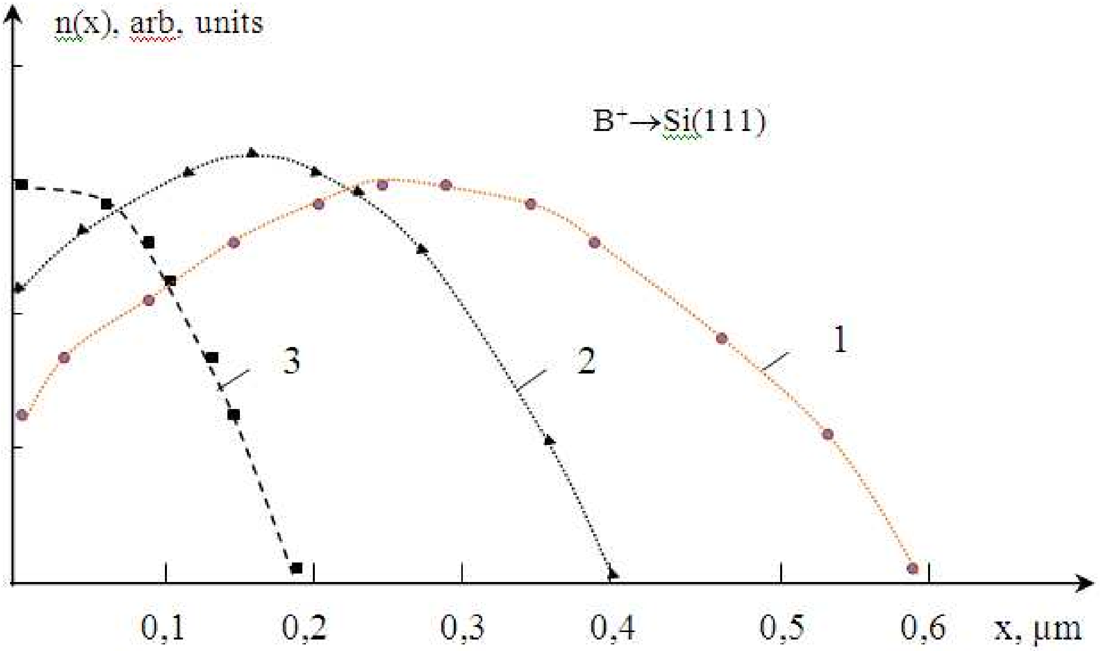

Figure 5. Distribution profiles of boron atoms over depth x, implanted into Si(111) with (1) energy E_0 =80 keV and dose $D=0.9 \cdot 10^{16}$ cm^{-2}, (2) E_0 =25 keV and $D=3 \cdot 10^{15}$ cm^{-2}, and (3) E_0 =10 keV and $D=1.8 \cdot 10^{15}$ cm^{-2}.

Annealing of defects (by thermal heating or laser, or IR radiation) is evident along with the change in the distribution profiles of the P and B atoms, as well as their chemical state, should lead to a change in the electronic structure of the near-surface region of ion-implanted Si(111).

The selected modes of ion implantation and subsequent annealing for electrical activation ensured a stepwise distribution of the atoms P and B, as well as a sharp interface between the impurity and base regions of Si. Estimation of the concentration of electrically active atoms by the AES method shows that $N_P = 10^{21}$ cm^{-2} and $N_B = 2 \cdot 10^{21}$ cm^{-2}. Similar results are obtained if, after each stage of ion doping, annealing is performed with pulsed laser radiation with an energy density of $W=3$ J$\cdot$cm^{-2} (wavelength=1.06 µm, pulse duration 10 nanoseconds). That is, as a result of such ion implantation, it is possible to obtain a p-i-n structure with a high concentration of electrically active impurities and a sharp boundary between the p-i and i-n regions of Si. Note that a high concentration of carriers in the p and n regions of Si is also necessary in order to smooth the temperature dependence of the contact region of devices based on the p–i–n junction. The HEED study of the crystal structure of Si(111) surfaces after the above-mentioned ion implantation and subsequent annealing showed that both surfaces of the p–i–n junction have a single crystal structure.

Thus obtained by us, p-i-n structure is a diode with hole conductivity of the base i-region. To study the current-voltage characteristics of the p–i–n diode, metal contacts were deposited on both surfaces of the crystal.

The diode surface was metallized by vacuum deposition of Ti and Ni atoms in the UVN-2M installation under high vacuum conditions at the substrate temperature T=600 K. At first, Ti and then Ni atoms were deposited.

The Figure 6 shows the current-voltage characteristics of the p–i–n diode obtained by us, taken at different temperatures. As can be seen from the figure, the current – voltage characteristics have the traditional form characteristic of diode structures and the direct voltage drop across the p–i–n structure depends on the temperature of the diode. The thickness of the TiNi films on the surfaces of the p–i–n structure was (100–200) Å.

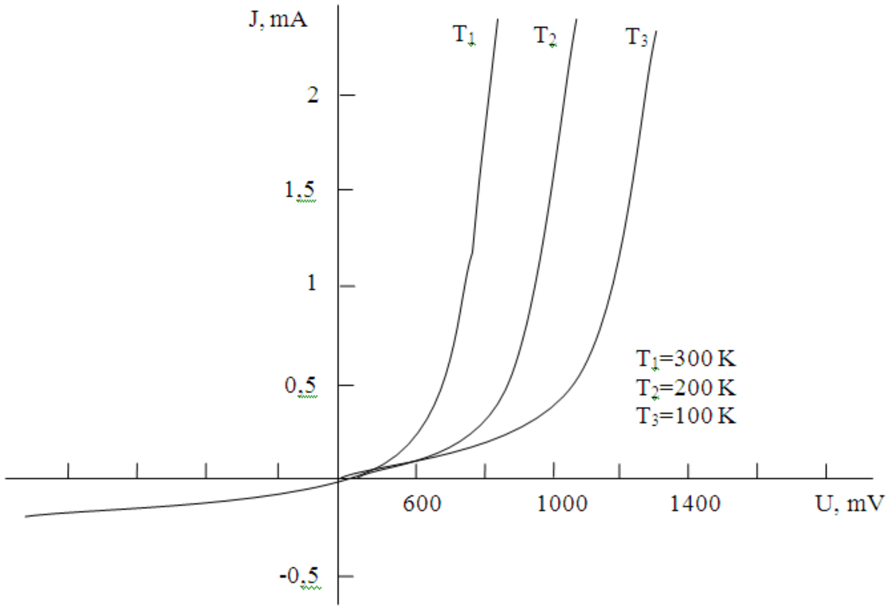

Figure 6. Volt - current characteristics of p-i-n –diode, taken at different T: 100, 200, 300 K.

The Figure 7 shows the direct voltage drop across the p-i-n - transition from the heating temperature for Si(111) with a specific resistance ρ = 6000 Ohm $\cdot$ cm (curve 2) and 3000 Ohm $\cdot$ cm (3).

Studying the dependence of the direct voltage drop Upr on temperature during the formation of the p–i–n structure by implanting P and B ions into Si with a gradual decrease in the energy and ion dose showed that the dependence U_{pr}=f(T) turns out to be nonlinear (curve 1). After the initial stage of ion implantation (with E_0=80 keV and D=$0.9\cdot10^{16}$ cm^{-2}) and annealing, the dependence U_{pr}=f(T) becomes linear in the low-temperature region of 250 K, and after the final stage of ion implantation (with E_0=20 keV and D=$0.9\cdot10^{15}$ cm^{-2} of phosphorus and with E_0=10 keV and D=$0.9\cdot10^{15}$ cm^{-2} of boron and subsequent annealing, this dependence becomes linear throughout the entire range of temperature variation.

Note that given in Figure 7 the dependences are obtained by passing a current I_n=1 mA through the p-i-n structure and connecting it to the circuit in the current stabilization mode (I_n=const). As can be seen from Figure 7, the sensor performance also depends on the resistivity of the original silicon, i.e. is determined by the processes in the base region of the p-i-n-diode. With a decrease in ρ of the

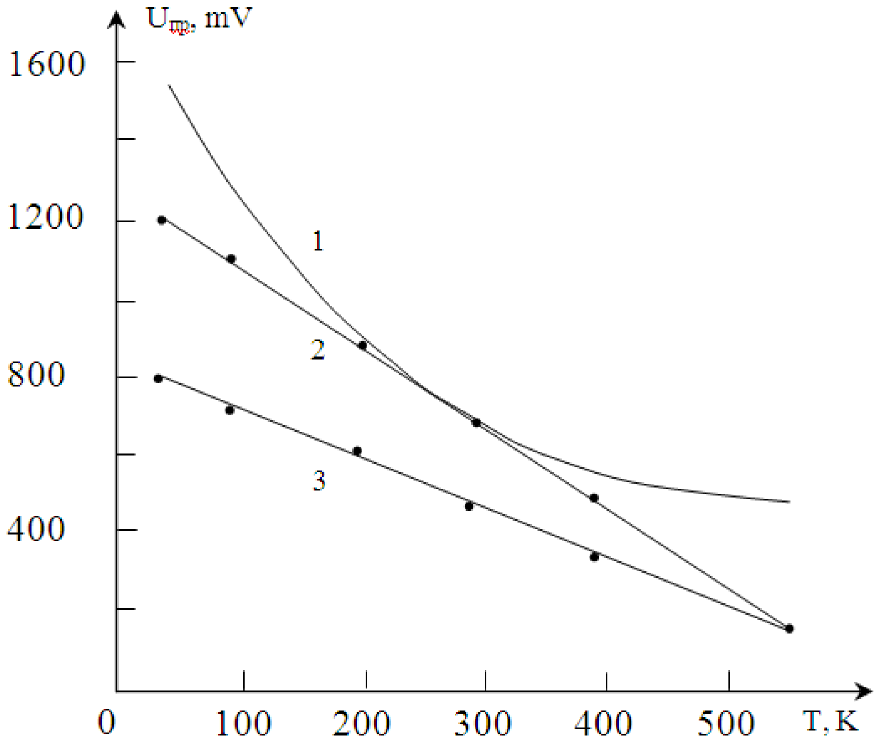

Figure 7. The dependence of the direct voltage drop on the p-i-n - transition from the heating temperature for Si(111) with a specific resistance ρ =6000 Ohm · cm (1) and 3000 Ohm · cm (2).

original silicon, the sensitivity of the sensor decreases slightly. Figure 8 shows a general view of a multichannel device for measuring temperature. The picture of the temperature-sensitive element is shown in Figure 9.

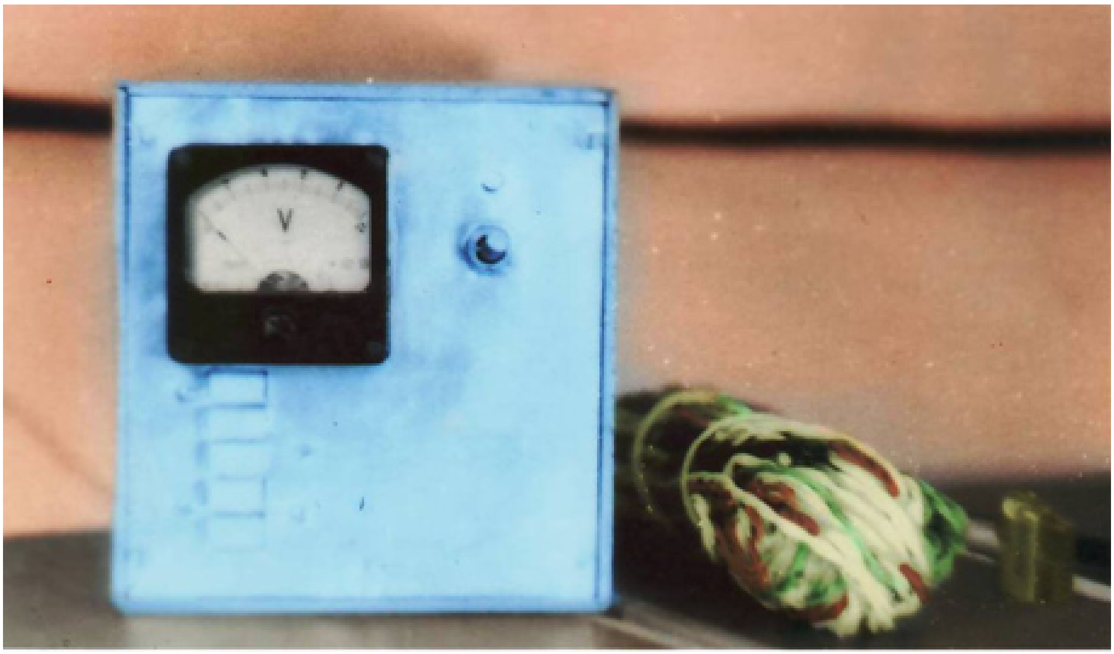

Figure 8. Multichannel temperature measuring device.

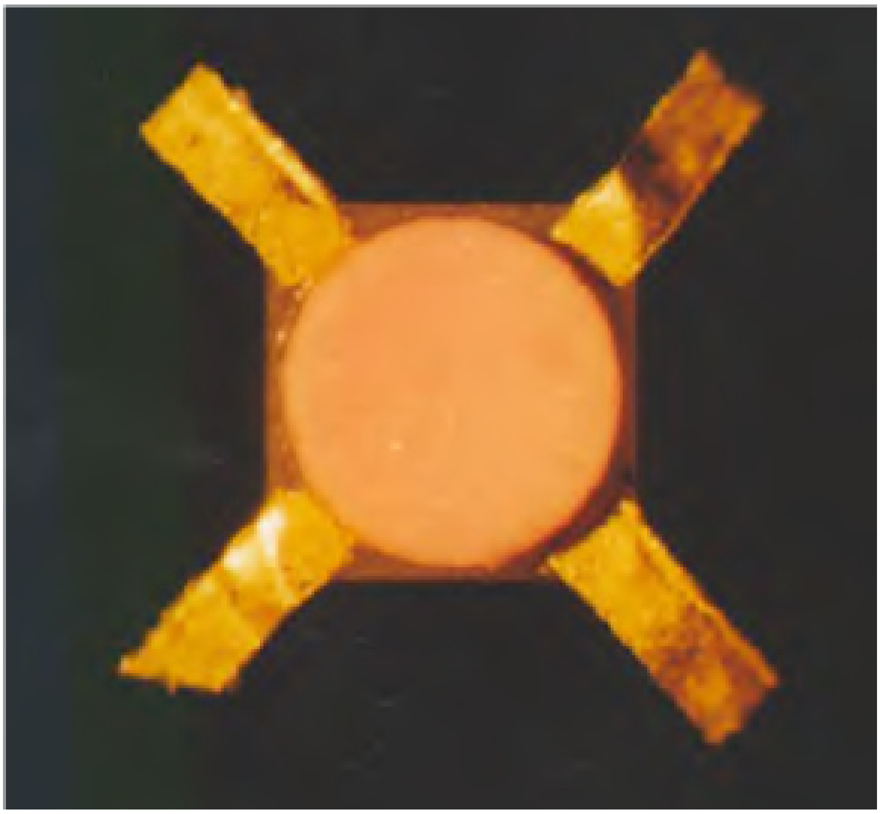

Figure 9. Diode c p - i-n – junction.

Conclusion

In the method of high-phase ion implantation of P^+ and B^+ to different sides of monocrystal silicon we obtained p-i-n- structure, which has a high thermal sensitivity of 2.3 mV/K in a broad band temperature of (20 ÷ 550) K. We studied the distribution profile P and B atoms implanted in the Si gradually decreasing energy. The effect of the subsequent thermal and annealing IR profile on the distribution of the atoms and the characteristics of the temperature sensor was studied.

Thus, the above technological modes of ion implantation and pulsed IR annealing are optimal for obtaining a thermal sensor with the following parameters:

1) the range of measured temperatures: from 20 to 500 K. In the whole range, the dependence U_{pr} =f(T) is linear;

2) temperature sensitivity is 2.1 $mV \cdot K^{-1}$;

3) supply current from 100 μA to 1 mA.

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