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INVESTIGATION OF SENSITIVE THERMAL SENSORS BASED ON Si<Pt> and Si<Pd>

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In this work, new sensitive thermal sensors based on Si<Pt> and Si<Pd> were developed. Single-crystal n- and p-type silicon samples doped with phosphorus and boron during growth were used for the study. These samples were first doped with platinum and palladium, then subjected to ohmic contact with nickel. To manufacture temperature sensors based on n-Si<Pd> and obtain an ohmic contact, this material was subjected to appropriate mechanical and chemical treatments. Metallic nickel with a thickness d = 1 μm was chemically deposited on its surface, followed by thermal annealing in a vacuum at T = 400-450°C for t = 10 - 15 minutes. To compare the created temperature sensors, a special measuring device, a thermostat, was developed to ensure uniform heat transfer.
Keywords: *Temperature sensor; Silicon; Platinum; Palladium; Doping; Sensitivity*
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INTRODUCTION

Without sensitive and fast-acting thermal sensors, it is difficult to imagine a successful solution to modern technical and environmental problems. In this case, of particular interest is the development of temperature sensors that allow remote control and monitoring of the temperature of an object. Existing temperature sensors based on semiconductor materials have practically exhausted their capabilities in terms of sensitivity and speed [1-4]. Therefore, to create a new generation of sensitive sensors, new materials or new physical phenomena should be used. In this regard, the functionality of a doped semiconductor is of great interest.

Thermal sensors are used in almost all sectors of the national economy, as well as in automated systems. Therefore, the main requirements for a temperature sensor are to increase sensitivity, speed, reduce energy consumption and stability of parameters under various conditions. Existing temperature sensors that use additional amplification circuits have almost reached their maximum efficiency, especially since they do not allow remote monitoring of the temperature of objects [5-7]

In most modern automatic electronic devices, temperature sensors are key elements that convert light and thermal energy into electrical vibrations. Without them, high-speed fiber-optic communication channels, automatic and security systems, and fire alarm devices are unthinkable today. Moreover, every year their implementation in all spheres of human activity becomes more intense. Existing thermal sensors, manufactured on the basis of traditional semiconductor materials, no longer meet modern requirements for thermal sensors. Therefore, new temperature sensors with more improved parameters are relevant [8,9].

In this regard, the main goal of this work is to develop a technology for producing silicon with platinum and palladium impurities, select the optimal impurity, determine the optimal concentrations and nominal resistances of temperature sensors, develop a good and reliable ohmic contact, as well as select a material for sealing that allows the use of a temperature sensor in various aggressive conditions and environments.

EXPERIMENTAL PART

Silicon wafers of n- and p-type conductivity with a resistivity of 40 Ohm cm (KEF-40 brand) and 20 Ohm cm (KDB-20) were used as the objects under study. The wafers were cut from silicon ingots grown by the Czochralski method. Diffusion doping of silicon with platinum and palladium was carried out from a layer of metal Pt and Pd deposited on the silicon surface in evacuated quartz ampoules at temperatures of 1200°C for 2 hours. Subsequent cooling of the samples was carried out using the thermal regimes given in [10, 11].

After doping, the type of conductivity and resistivity of the doped samples were determined using a thermal and quadruple probe (Table 1).

From the table it can be seen that after doping with palladium atoms, the resistivity increases significantly and the type of conductivity changes (from n to p). Doping with platinum atoms leads to a decrease in resistivity in both types of samples.

It was shown in [12,13] that electronically active palladium exists in silicon in the form of two independent particles. The first, designated Pd_1, is amphoteric and has an acceptor level 0.22 ± 0.01 eV below the conduction band edge, as well as a donor level 0.33 ± 0.01 eV above the valence band edge. The second species, designated Pd_2, has an acceptor level

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0.32 ± 0.1 eV above the valence band edge. The ratio of Pd_1 to Pd_2 embedded in silicon varies from 40 to 5 for diffusion temperatures from 900 to 1200°C, respectively. Platinum is also considered an amphoteric element with good conductivity and has an acceptor and donor level in the band gap of silicon.

Table 1. conductivity and resistivity of the doped samples

No	Brand	Samples	Doping temperature (°C)	Conductivity type	Resistivity (Ohm cm)
1	KEF-40	n-Si	-	n	39.8
3		n-Si<Pd>	1200	p	1665
5		n-Si<Pt>	1200	n	17
6	KDB-20	p-Si	-	p	20
8		p-Si<Pt>	1200	p	3

From these results, we selected n-Si<Pd> p-Si<Pt> samples for the development of temperature sensors. To manufacture temperature sensors based on n-Si<Pd> and obtain an ohmic contact, this material was subjected to appropriate mechanical and chemical treatments. Metallic nickel with a thickness d = 1 μm was chemically deposited on its surface, followed by thermal annealing in a vacuum at T = 400-450°C for t = 10 - 15 minutes. For temperature sensors based on p-Si<Pt>, silver liquid was used to increase the resistance of the material. To compare the created temperature sensors, a special measuring device, a thermostat, was developed to ensure uniform heat transfer.

RESULTS AND DISCUSSIONS

We know that the resistance of semiconductor materials decreases with increasing temperature, and we measured its change using a digital multimeter. The results obtained are presented in Table 2. For comparison with our temperature sensors, we also obtained the temperature dependence of the resistance of the Chinese MF52 temperature sensor.

Table 2. Temperature dependence of the resistance of the temperature sensors

T, °C	$R_{Si<Pt>}$ Ohm	$R_{Si<Pd>}$ Ohm	R_{MF52} Ohm
34	228000	307	6320
35	206000	278	5750
36	183000	259	4920
37	177300	244	4370
38	167200	227	4300
39	160400	216	4010
40	153700	210	3740
…..			
50	87200	148	1560
51	87000	145	1560
52	83200	145	1510
53	81600	128	1500
54	79500	130	1380
55	59700	124	1280
…..			
75	22500	99.2	420
76	21700	88	347
77	21300	79	336
78	20400	80.5	326
79	20000	79.1	314
80	20300	77.4	307

During the comparison process, each temperature sensor was measured separately, and measurements were carried out in the range from room temperature to 80°C. To determine the temperature sensitivity of these temperature sensors, their temperature sensitivity coefficients β were analyzed. Table 3 shows the β coefficients of temperature sensors.

Table 3. Sensitivity coefficient (β) of temperature sensors

No	Thermal sensors	Sensitivity factor(β) °K	Temperature °C	Sensitivity factor(β) °K	Temperature °C
1	Si<Pt>	5700	34-80	7500	50-60
2	Si<Pd>	3200	34-80	5210	50-60
3	MF52	7200	34-80	5000	50-60

As can be seen from this table, we see that among temperature sensors in the temperature range 34-80℃, the sensitivity of the MF54 temperature sensor made in China is high. It can be seen that the sensitivity of the temperature sensor developed on the basis of Si<Pt> in the temperature range of 34-80℃ is better than that of temperature sensors developed on the basis of Si<Pd>, but worse than that of the MF52 temperature sensors developed in China.

As a rule, temperature sensors developed on the basis of silicon are designed to operate in the temperature range from -50 to +150℃, and depending on the purpose and operating temperature of each sensor, they can also be used in short temperature ranges [14, 15]. For example, we developed temperature sensors based on Si<Pt>, Si<Pd> and set ourselves the task of using them in a microelectronic device that controls the temperature (in the range of 50-60℃) of a water desalination system. If we take into account temperature control in the range of 50-60℃ in this system using a microelectronic device, as can be seen from Table 3, then we can see that temperature sensors made on the basis of Si<Pt>, Si<Pd> have much better temperature sensitivity in the range of 50-60 ^{0}C compared to MF52 temperature sensors. It has been established that temperature sensors developed on the basis of Si<Pt> have the best temperature sensitivity (7500 K).

The authors [16] developed highly sensitive thermal sensors in their work. For the material they chose highly compensated silicon with manganese atoms. The thermal sensitivity of the presented temperature sensors is very high, it was 25-50 times greater than that of the existing most sensitive ones. As a result of theoretical calculations and analysis of the parameters of temperature sensors made on the basis of uncompensated silicon with intrinsic conductivity, obtained by crucibleless zone melting with $\rho \sim 2\cdot10^4$ Ohm·cm, it was found that the sensitivity of these temperature sensors is also 50-70% lower than that of the developed us thermal sensors.

Other authors [17] have developed temperature sensors based on silicon doped with nickel. The article says that temperature sensors with a maximum nominal resistance have a very high thermal sensitivity value β in which reaches 7400-7500 K; such temperature sensors are capable of controlling the temperature of an object with an accuracy of 0.005 K.

Based on [16,17], it can be assumed that it is possible to develop highly sensitive silicon-based thermal sensors with transition elements.

CONCLUSION

The resistivity and conductivity of silicon samples doped with platinum and palladium atoms were determined by four-probe and thermal probe methods. To develop high-sensitivity thermal sensors, the necessary samples were selected and nickel atoms were deposited on the surface of silicon samples to obtain ohmic contacts.

As a result of research, it has been established that the temperature sensitivity of the MF52 thermometer made in China is higher in the temperature range of 34-80℃, and in the temperature range of 50-60℃ the temperature sensitivity of temperature sensors based on Si<Pt> is higher In the future, we plan to use these thermometers in a microelectronic device that controls the temperature of a water desalination system.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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ДОСЛІДЖЕННЯ ЧУТЛИВИХ ТЕРМОСЕНСОРІВ НА ОСНОВІ Si<Pt> і Si<Pd>

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У цій роботі розроблено нові чутливі термосенсори на основі Si<Pt> і Si<Pd>. Для дослідження використовували монокристалічні зразки кремнію n- і p-типу, леговані фосфором і бором під час росту. Ці зразки спочатку легували платиною і паладієм, потім піддавали омічному контакту з нікелем. Для виготовлення датчиків температури на основі n-Si<Pd> та отримання омічного контакту цей матеріал піддавався відповідній механічній та хімічній обробці. На його поверхню хімічно осаджували металевий нікель товщиною d = 1 мкм з наступним термічним відпалом у вакуумі при T = 400-450°C протягом t = 10 – 15 хвилин. Для порівняння створених датчиків температури був розроблений спеціальний вимірювальний прилад – термостат, який забезпечує рівномірний теплообмін.

Ключові слова: *датчик температури; кремній; платина; паладій; легування; чутливість*