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Research Article

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Hot-Film Sensors based on Silicon with Nanoclusters of Nickel Atoms to Determine the Speed Gas Flow

Sh. B. Utamuradova, Sh. X. Daliev, S. S. Nasriddinov, Sh. A. Ismoilov, D. M. Esbergenov

Research Institute of Semiconductors and Microelectronics under National University of Uzbekistan, Tashkent, Uzbekistan,- 100000

Abstract The description of a new thermoanemometric sensor based on silicon with nanoclusters of Nickel atoms with high sensitivity and stability of the output parameters is given. The mode of diffusion of Nickel into silicon to create a thermoanemometric sensor is considered. The electrophysical parameters of the thermoanemometric sensor are investigated.

Keywords thermoanemometer, transducer, thermal sensor, silicon, Nickel, temperature, diffusion, sensitivity, resistivity

Introduction

It is known that the use of various measuring instruments depends on their functionality - on the ability to control a large number of input influences of a different nature, using processed measurement results based on microprocessor technology. One such microelectronic measuring device is a hot-wire anemometric sensor [1-4]. The foundations for the development of anemometric sensors were laid as early as the beginning of the 20th century and formulated in [1].

There are many design solutions for measuring the speed and volume of gas and liquid flows. For example, Sitrans P [2] uses a throttle to create a speed sensor. The authors of [2] propose a thermo-anemometric sensor using a zigzag-shape platinum thread that overlaps the cross section of the pipeline. This technical solution allows you to measure gas flow with an error of up to ± 2.5%.

The use of thermos-anemometers is promising not only for measuring the velocity or flow rate of a gas stream, but also for intermediate transformations of various non-electric parameters into an electrical signal, including compensation methods of measurement in automatic control and monitoring systems [3-9]. A thermo-anemometer usually means a thermo-anemometric device, including an inlet pneumatic transducer, receiving heat-sensitive and heating elements, and also an output electrical circuit. The input parameter of such a converter is the mass flow rate of gas, and the output is an electrical signal in the form of current, resistance or other electrical parameters.

In order to increase the sensitivity of the temperature sensor, reduce gas consumption and power consumption, and provide the required output characteristics, various throttling or control elements that change the magnitude of the velocity or direction of gas flow are usually used in the input channel of the hot-wire anemometer. Hot-wire transducers with input channels containing the above structural elements are called ink-jet hot-wire anemometers [3-6]. A significant drawback of such structures is the low speed of their sensitive element.

Theoretical Analysis

The aim of this work is to create a thermo-anemometer sensor based on silicon with nanoclusters of nickel atoms, which has high sensitivity and stability of the output parameters.

It is known that the use of a temperature sensor is included in the bridge circuit, the bridge is usually powered by a current source or voltage source [7]. With increasing ambient temperature, the resistance of the measuring temperature sensor decreases, this leads to an increase in the dissipated power at the temperature sensor, which in turn leads to greater heating of the thermistor by its own current. Therefore, at high temperatures and low nominal resistance, the temperature of the thermistor will differ from the temperature of the medium, i.e. The thermistor will measure some effective temperature different from the true temperature. To avoid these problems it is necessary to use thermistors based on materials with high resistivity. To obtain such a material, we used doping of silicon with nickel; introducing nickel into silicon in the increasing temperature mode allows us to obtain a material with stable electrophysical parameters both at low (300 ° C) and at relatively high initial temperatures (600 ° C), without affecting to its original parameters.

Experimental Results

To obtain such a material, nickel was diffused in a silicon mode of increasing temperature at a rate of 5 ° C / min in the temperature range 300 ÷ 1250 ° C, as shown in Fig. 1. The diffusion temperature was controlled by a platinum-platinum-rhodium thermocouple located directly next to the ampoule. Incremental heating was carried out for 110 minutes, and then kept at maximum temperature for 10 minutes, after which the ampoule with the samples was taken out of the furnace and quenched.

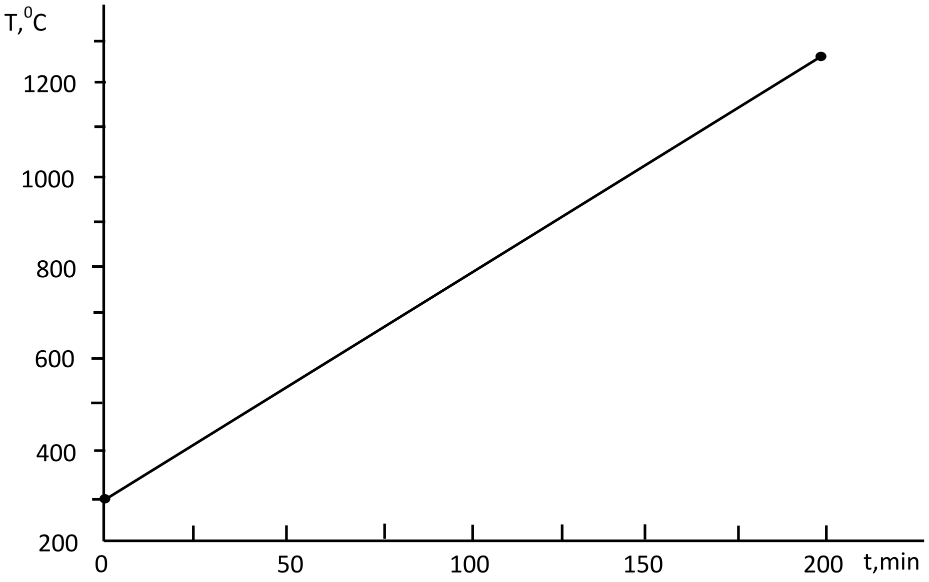

Figure 1: Temperature regime of diffusion

The difference between this alloying method consists in conducting diffusion at lower initial temperatures (25 °C), followed by an increasing temperature increase (900 ÷ 1250) °C with different heating rates (5 ÷ 7 °C / min).

Thus, the most optimal material for creating effective temperature sensors is highly compensated n-type silicon with a specific resistance of $10^4 \div 10^5$ Ohm · cm. The diffusion parameters for obtaining this material in the particular case based on silicon alloying with nickel have the following values: alloying temperature 1150 °C, vapor pressure 0.5 atm. A method has been developed for the diffusion of nickel with built-in nanoinclusions in silicon, which consistently raises the temperature at a rate of 5 deg / min. and then cooled at a speed of 100 deg/s.

We have developed a technology for manufacturing temperature sensors for measuring temperature in a wide temperature range from -100 to 180 degrees Celsius;

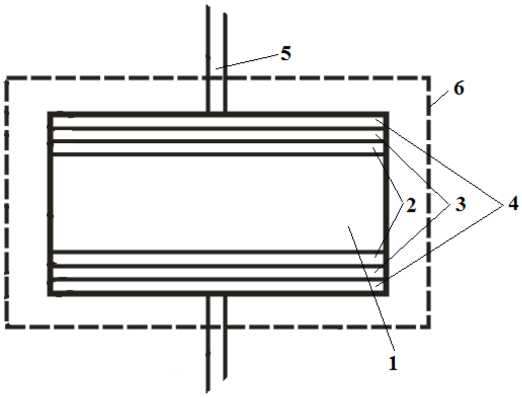

Figure 2: a) 1-base of silicon, 2-n + -regions, 3-layer of nickel. 4-layer tin, 5-leads, 6-compound

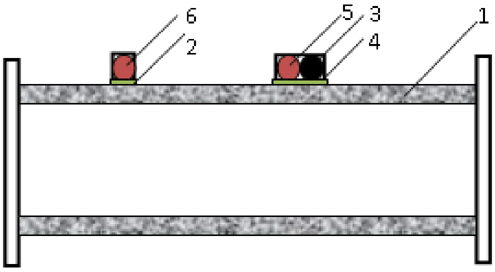

Figure 3: Sectional view of device design. 1-pipe wall, 2- dielectric layer, 3-heating resistor, 4-layer dielectric, 5-sensitive semiconductor resistor, 5-sensitive element, 6-additional semiconductor-nickel resistor

The transverse section sensor of the developed silicon-based temperature sensor is shown in Fig. 2. In it, each area of the same name is obtained in a single process, where the base region 1 is a high-resistance silicon with a thickness of 350 µm, alloyed with nickel. Low resistance, heavily doped, 2 n + -type regions with a thickness of 2 µm were formed on its both surfaces by annealing at 600 ° C. For 30 minutes, chemically deposited nickel was deposited on the front and back surfaces of a silicon wafer with a diameter of 76 mm, metal thin layers of nickel 3 with a thickness of 3 µm were obtained by chemical the deposition of nickel from solution on the entire surface of the silicon wafers in a single process serving as the basis of ohmic contacts. To solder the leads, tin layers with a thickness of 50 µm 4 were obtained by sputtering over nickel layers, after which a silicon crystal with corresponding contacts was cut into discrete structures with an area of 1 mm^2, then conclusions 5 were soldered to them and filled with compound 6 for sealing.

As a result, 40 temperature sensors were obtained from one plate. Electrophysical studies were carried out on these finished temperature sensors. The sensor contains a piece of pipe on the outer surface of which there is a heating resistor and two semiconductor resistors, one of which is a sensitive element, and the other serves for temperature correction. The heating resistor is located next to the sensitive element (SE) and is isolated from it by a layer of aluminum oxide Al_2O_3 or a diamond-like film. The design of the sensor provides a significant reduction in energy consumption (at least by 1 order) with optimal mechanical strength and temperature resistance. Figure 3 shows a section of the design of the proposed device. A heating resistor 3 made of polysilicon or refractory metal is made on the surface of the tube on a SiO_2 layer, the surface of which is protected by an Al_2O_3 dielectric layer or diamond-like film 4. A sensitive semiconductor resistor 5 is located next to the heating resistor 3 on the dielectric layer 4. The heating resistor 3 is located next to the sensitive element 5 and isolated from it by an ideal heat-conducting layer of Al_2O_3 or a diamond-like film, which allows a good energy-saving connection between the resistors. An additional semiconductor resistor 6 is installed on the wall of the pipe 1 for temperature correction, which responds to changes in the temperature of a liquid or gas. The energy consumption of such a resistor is significantly lower in comparison with conventional resistors, and its speed is higher, which is extremely important in relation to the measurement conditions in the boundary layers to eliminate the influence of the design temperature on the measured gas temperature. The sensor operates on the hot-wire principle [4].The semiconductor resistor 5 is a sensitive element. Its thermal mode provides a heating resistor 3. An additional semiconductor resistor 6 has a low thermal time constant and corrects the measurement system with rapid changes in flow temperature.

The block diagram of the electronic block of the hot-wire air mass flow sensor is shown in Fig. 4. The electronic unit includes: resistive first electric bridge I, containing the sensing element R, 5 - air flow meter; the second resistive electric bridge II, containing a semiconductor resistor R6 temperature correction value of the flow rate due to changes in gas temperature.

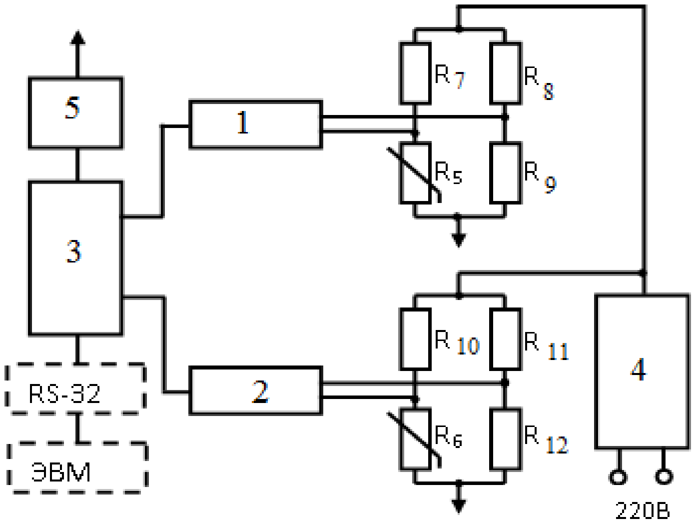

Figure 4: The block diagram of the electronic block of the hot-wire air mass flow sensor

In figure 4, blocks 1, 2 - signal amplifiers from the corresponding measuring bridges. Block 3 - a microprocessor that performs the program analog-to-digital conversion of signals from amplifiers 1, 2 and mathematical processing of signal values according to a given algorithm, the issuance of digitized information values from bridges through a standard data channel (RS-232) to a computer (IBM PC), which allows you to record, save and process the analog-time characteristics of the device during debugging and calibration. Block 4 is the secondary power source of all blocks and bridges of the device. Block 5 - shaper of the output signal transmitted to the actuator or display device. Block 5 - shaper of the output signal transmitted to the actuator or display device.

The new sensor design provides higher performance, at least an order of magnitude lower power consumption, and standard manufacturing methods make it easy to integrate the sensor with framing schemes. Thermal conversion processes in a thermo-anemometer sensor are described by the following formulas:

$$I_{нэ}^2 R_{нэ} = \alpha F(T_5 - T_6) \tag{1}$$

where $I_{нэ}$ $R_{нэ}$ – current and resistance of the heating element, α –heat transfer coefficient, F - heat transfer surface.

From the heat balance formula (1), we determine the temperature difference:

$$(T_5 - T_6) = \frac{I_{нэ}^2 R_{нэ}}{\alpha F} \tag{2}$$

The temperature of the semiconductor resistor R_5 according to the formula (3)

$$T_5 = T_6 + \frac{I_{нэ}^2 R_{нэ}}{\alpha F} \tag{3}$$

It can be seen that the temperature of the resistor R_5 depends on the heat transfer coefficient which is a function of the gas flow rate (Fig. 5.)

$$\alpha = f(V) \tag{4}$$

In the initial position at a speed of V = 0 m / s, the resistances of the bridge I are chosen so that the output voltage of the bridge I is zero.

In the presence of a gas flow rate ($V \neq 0$), the heated semiconductor resistor R_5 enters into heat exchange with a controlled gas flow and changes its temperature and, as a result, the output voltage of bridge I changes, according to Fig. 4:

$$R_5 = R_7 = R_8 = R_9$$

In the microprocessor 3 using a semiconductor thermistor R_6 is compensated for the change in temperature of the controlled air flow. In this design, as a thermo-anemometer sensor (5,6), a new nanostructured semiconductor thermal resistance based on nickel-doped silicon is used [5].A temperature sensor containing a thermosensitive high-resistance i-region based on single-crystal silicon and equipped with electrical contacts, characterized in that the i-region is enclosed between two heavily doped n^+ regions, made by doping with metal atoms to form an n^+ - I – n^+ structure, with the outer surface each n^+ - region is nickel-plated and forms an ohmic transition between the n^+ - region and the corresponding electrical contact, and layers are introduced between nickel-plated surfaces and electrical leads tin.

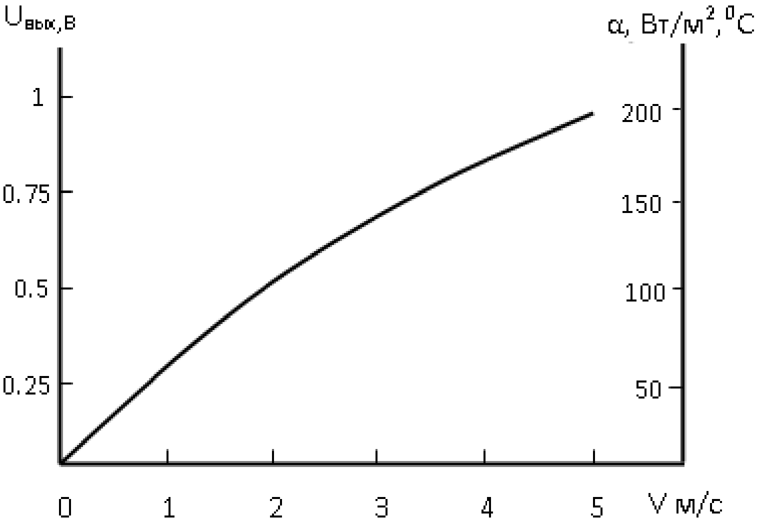

Figure 5: Dependence of output voltage and heat transfer coefficient on gas flow rate

As the starting material for the base region of the temperature sensor, industrial monocrystalline silicon of n-type conductivity of the KEF brand with a resistivity of $\rho = 10 \div 100$ Ohm·cm was used. The choice of such a material is due to the need for a controlled task in it of the concentration of electroactive nickel atoms by the compensation method, since nickel in silicon acts as an acceptor impurity. In Fig. 6 presents the distribution of the concentration of electroactive nickel atoms in silicon obtained in the regime with increasing temperature, the final value of which coincides with the fixed temperature of conventional technology. That is, in the second case, the samples placed in the ampoules were installed in the furnace with the accumulated final diffusion temperature, and the diffusion time was 2 hours. It follows from the Fig. 6 that the concentration of electroactive nickel atoms is approximately 7–10% higher (curve 1) than in samples obtained by conventional technology (curve 2).

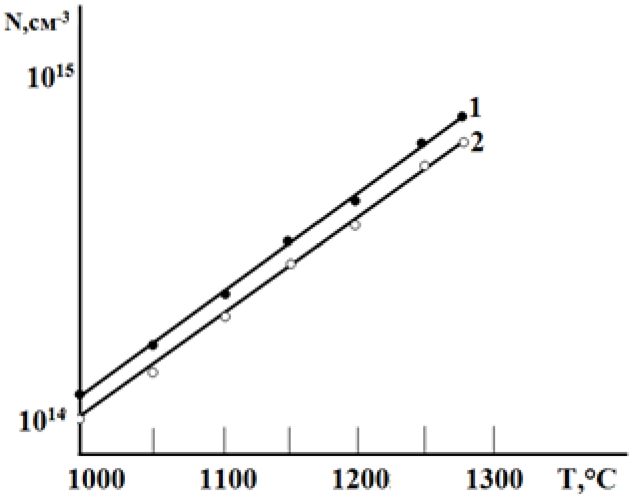

Figure 6: Temperature dependence of the concentration of electroactive atoms of impurities
1- Si <P, Ni> obtained by new technology; 2-Si <P, Ni> obtained by conventional technology

The main difference between nickel diffusion in an increasing temperature regime is that it takes half as much time to obtain a given carrier concentration in the diffusion process. So, according to the relation

$$D_{Ni}=2,3\cdot 10^{-3}\exp(-0,47/kT)\ [см^2/с], \tag{5}$$

$$N_{Ni}=1,4\cdot 10^{25}\exp(-2,3/kT)\ \ [см^{-3}], \tag{6}$$

at a temperature of T = (600÷900) °C, the solubility of nickel should be N_{Ni}~10^{14} cm^{-3}, and the diffusion coefficient should have a value of D = (10^{-4}÷10^{-7}) cm^2/s. Then, in order to uniformly alloy samples with a thickness of 1 mm, it would take about t = 7 hours, and in our case, the entire diffusion process takes 3 hours. The concentration of nickel atoms in the bulk was N_{Ni}~10^{14} cm^{-3}, i.e. more than expected.

Conclusion

Based on the results obtained, it can be concluded that in the temperature increasing mode, nickel diffusion does occur along interstices, and impurity atoms are in interstitial states. An additional proof of this situation is that in this case, the concentration of vacancies, - N_v, is of the order of 10^7 cm^{-3}, i.e. it is almost 10^7÷10^8 orders of magnitude less than the concentration of nickel atoms in the interstices. The concentration of vacancies was calculated by the formula

$$N_v \approx N_s\exp(-3/kT), \tag{7}$$

where N_s is the number of silicon atoms in the lattice (N_s~ $5\cdot 10^{22}$ cm^{-3}) [8].

Thus, the parameters of the initial silicon (ρ = 10 ÷ 100 Ohm·cm) intended for the base region of the temperature sensor were brought to the required level (ρ = $3\cdot 10^2$÷10^5 Ohm·cm) by nickel diffusion in the growing temperature mode and further subjected to technological processing to create a therm-anemometric sensor. The hot-wire anemometer is used not only to determine the speed of movement or gas flow, but also for intermediate conversions of various non-electrical parameters into an electrical signal, including compensation methods of measurement in automatic control and regulation systems.

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