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A STRAIN SENSOR RESISTENT TO PROTON IRRADIATION

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Abstract: Influence of proton irradiation on the properties of $Si_{1-x}Ge_x$ whiskers as strain sensors is studied in this work. On the basis of secondary signal processing the possibility of using such whiskers as a strain sensor's sensitive element resistant to proton radiation is shown.

Key words: proton irradiation, whisker, strain, measuring system, digital signal processing.

1. Introduction

To create irradiation resistant sensors it is important to study the influence of high energy radiation, in particular proton radiation, on a sensitive element of the sensor. A $Si_{1-x}Ge_x$ whisker was chosen as a sensitive element because it possesses a high gauge factor, and in comparison with a Si whisker it has higher irradiation resistance [1, 2]. High structural perfection of the $Si_{1-x}Ge_x$ whiskers gives us a possibility of modeling defects in crystals due to irradiation influence. It should be noted that earlier proton irradiation influence was studied in the work [2]. But these investigations were made only for quantities of radiation limited to $5\times10^{15}p^{+}/\text{см}^{2}$ which have a low influence on the whisker conductivity, and no high-temperature annealing was made. But, a stable defective subsystem is known to be formed only after high-temperature annealing. So, in this work the influence of proton irradiation up to $1\times10^{17}p^{+}/\text{см}^{2}$, and the high-temperature annealing at the temperatures between 100 ^{o}C and 300 ^{o}C on the conductivity of $Si_{1-x}Ge_x$ whiskers with dopants concentration near metal-insulator limit in the temperature range 4,2-300 K and in magnetic fields up to 14T was studied to use them as strain sensors. It is shown that using digital signal processing allows improving the output characteristics of such a sensor and checking its adequacy relative to the dose received.

2. Experimental procedure

The $Si_{1-x}Ge_x$ whiskers were grown from the gas phase in a closed system in the form of hexagonal prisms with longitudinal axis in the crystallographic direction <111> and transverse size of 20-60 microns. There were chosen several parties of the crystals with boron dopants concentration proximity to the dielectric side of the metal insulator limit for studying conductivity of the p-type $Si_{1-x}Ge_x$ whiskers in a wide temperature range. Temperature resistance dependence of the samples was conducted in a wide temperature range (4.2-300) K, using a system based on helium cryostat in the range of magnetic fields up to 14T.

The proton irradiation was carried out in a nuclear reactor (protons energy 6.8MeV). The irradiation dose was evaluated in comparison with the reference, and increased in proportion to irradiation time. For the experiments there were chosen samples, irradiated by protons at the following doses: $5\times10^{13}p^{+}/cm^{2}$, $5\times10^{15}p^{+}/cm^{2}$, $1\times10^{16}p^{+}/cm^{2}$, and $1\times10^{17}p^{+}/cm^{2}$.

3. Experimental results

Studies of the electrical properties of the samples irradiated with the doses up to $5\times10^{15}p^{+}/cm^{2}$ showed that there were not any significant changes observed in the temperature dependence of resistance (Fig. 1). The irradiation dose of $5\times10^{15}p^{+}/cm^{2}$ caused significant changes in the magnetoresistance (see Fig. 2, 3).

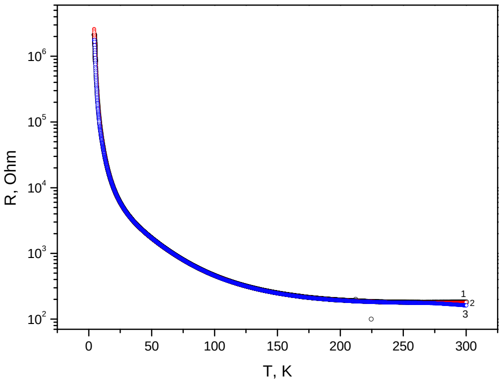

Fig.1. Resistivity temperature dependence of $Si_{1-x}Ge_x$ whiskers with ρ_{300K}=0.025Ohm×cm irradiated by protons with energy E=6.8 MeV at T=40 °C: 1 - $F=0p^{+}/cm^{2}$, 2 – at the dose $F=5\times10^{15}p^{+}/cm^{2}$ after annealing at 100 °C 3 – at the dose $F=5\times10^{15}p^{+}/cm^{2}$ after annealing at 280 °C.

The irradiation dose of about 1×10^{16} p^{+}/cm^{2} led to a significant decrease in whiskers resistance in the temperature range 4,2–40 K (see Fig. 4, 5) and minor changes of the whiskers magnetoresistance (Fig. 6). It should be noted that the resistance changes at 4.2 K are more significant in samples with higher concentration of free carriers: the resistance decreases almost twice in whiskers with a resistivity ρ_{300K}=0,018 Ohm×cm (Fig. 4), whereas it decreases only by 10 % in crystals with ρ_{300K}=0.025 Ohm×cm (Fig. 5). At higher doses there is a significant increase in resistance of the irradiated $Si_{1-x}Ge_x$(x=0.03) whiskers comparing with the non-irradiated samples (Fig. 7).

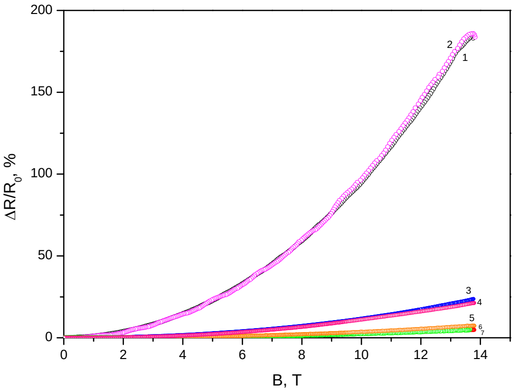

Fig. 2. Magnetoresistance field dependence of $Si_{1-x}Ge_x$ whiskers with ρ_{300K}=0.025 Ohm×cm irradiated by protons w ith energy E=6.8 MeV at T=40°C at the dose $F=5\times10^{15} p^+/cm^2$: 1 – at 4.2 K without annealing, 2 - at 4.2 K after annealing at 100°C, 3 – at 13 K without annealing, 4 – at 13 K after annealing at 100 °C, 5 – at 30 K after annealing at 100 °C, 6 – at 50 K without annealing, 7 – at 50 K after annealing at 100 °C.

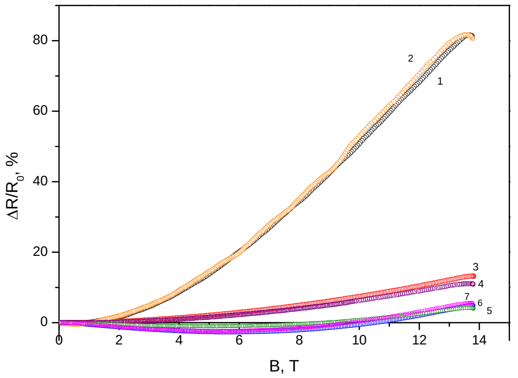

Fig. 3. Magnetoresistance field dependence of $Si_{1-x}Ge_x$ whiskers with ρ_{300K}=0.028 Ohm×cm irradiated by protons with energy E=6.8 MeV at T=40°C at the dose $F=5\times10^{15} p^+/cm^2$: 1 – at 4.2 K without annealing, 2 – at 4.2 K after annealing at 100 °C, 3 – at 50 K without annealing, 4 – at 50 K after annealing at 100 °C, 5 – at 30 K after annealing at 100 °C, 6 – at 13 K without annealing 7 – at 13 K after annealing at 100 °C.

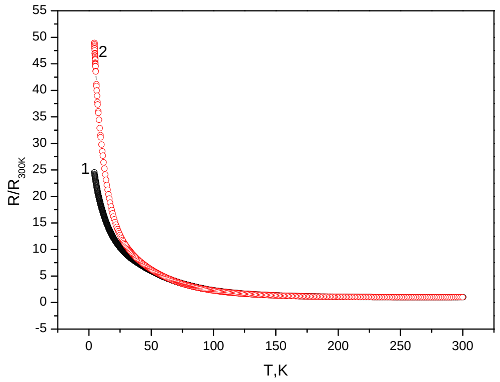

Fig. 4. Relative resistance change temperature dependence of $Si_{1-x}Ge_x$ whiskers with ρ_{300K}=0,018 Ohm×cm irradiated by protons with energy E=6.8 MeV at T=40 °C: 1 – irradiation dose F=0, 2 – irradiation dose $F=1\times10^{16} p^+/cm^2$.

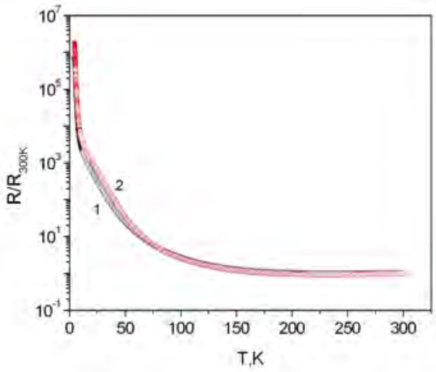

Fig. 5. Resistance relative change temperature dependence of $Si_{1-x}Ge_x$ whiskers with ρ_{300K}=0.025 Ohm×cm irradiated at T=40 °C by protons with energy E=6.8 MeV at the dose: 1 – F=0, 2 – $F=1\times10^{16} p^+/cm^2$.

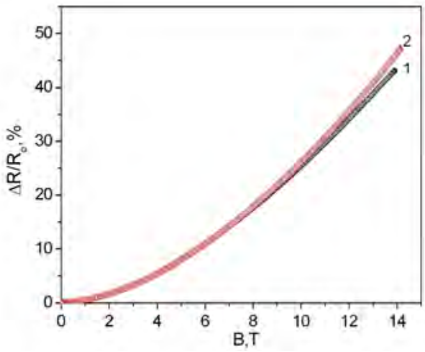

Fig. 6. Magnetoresistance field dependence of $Si_{1-x}Ge_x$ whiskers with ρ_{300K}=0.018 Ohm×cm protons irradiated at T=40 °C with energy E=6.8 MeV: 1 – irradiation dose F=0, 2 – irradiation dose $F=1\times10^{16} p^+/cm^2$.

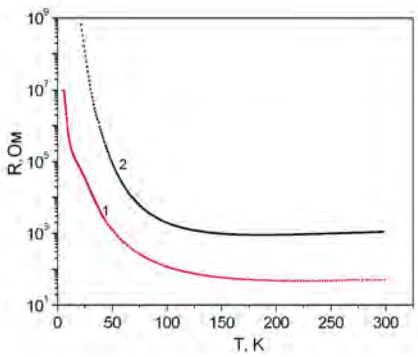

Fig.. 7. Resistivity temperature dependence of $Si_{1-x}Ge_x$ whiskers with ρ_{300K}=0.025 Ohm×cm irradiated at T = 40 °C by protons with energy E=6.8 MeV: 1 – irradiation dose F=0, 2 - $F=1\times10^{17} p^+/cm^2$.

The above results cannot be the basis for the determination of dose dependences. However, we can assume that the radiation dose (~ $1\times10^{16} p^+/cm^2$) caused the appearance electrically active radiation defects that in turn caused the appearance of additional carriers in the conduction band of the crystal [3]. As a result, $Si_{1-x}Ge_x$ (x=0.03) whiskers resistance should decrease.

This situation involves an unclear fact of discovering some large changes of resistance at low temperatures in more strongly doped crystals (we can compare Fig. 4 and Fig. 5).

Appearance of the additional carriers due to irradiation should cause greater changes in high-resistance crystals. We can see an opposite situation. It is therefore logical to assume that irradiation does not lead to the emergence of additional carriers, but rather lead to the redistribution of the energy-level density in the impurity band of the crystal. As a result of these explosure doses impurity atoms get excited which simultaneously capture two charge carriers with antiparallel spins. The consequence of the exposure may be inverse population of the excited impurity levels. In these conditions, the dominant type of conductivity should be hopping conductivity in the upper Hubbard band with the activation energy E2 [4].

In this case, the exposure should lead to greater resistance changes in the samples with higher impurities concentration as observed experimentally. According to these experiments we can conclude that $Si_{1-x}Ge_x$ whiskers can be used as strain sensors up to $5\times10^{16}p^+/cm^2$ proton irradiation doses and in the temperature range 70-300 K.

4. Measuring System

Strain characteristics of the sensor are as follows:

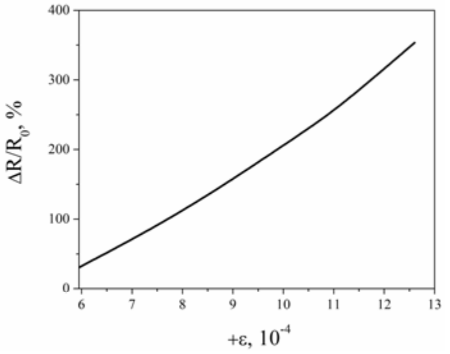

Fig. 8. Strain characteristics of the typical $Si_{1-x}Ge_x$ *sensor.*

For a linear, adjusted to temperature output signal of the sensor, a secondary signal processing scheme based on the programmable system on a chip was proposed [5]. It allowed performing analog and digital data processing directly from the sensor. In the existing system precision 20 bit sigma-delta ADC and 4 programmable analog blocks that perform initial amplification of the sensor are used in a single chip.

After analog-to-digital conversion of the signal, it in turn is subject to digital processing (digital filtering with 4-th order filter and signal correction according to a temperature sensor). Accuracy of the result is estimated according to an irradiation dose sensor signal. Having been processed, the signal is displayed. The digital signal processing allowed extending the range of operating temperatures and linearizing the output signal of the sensor.

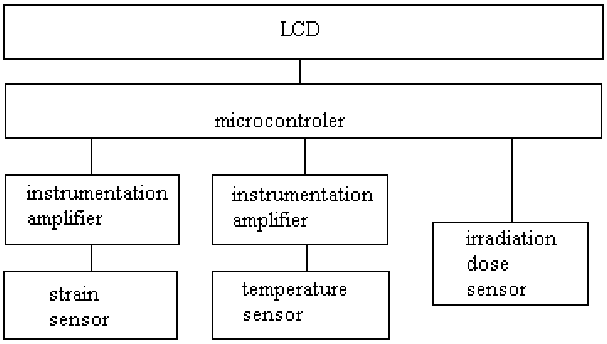

Fig. 9. Designed measuring system schematic diagram.

7. Conclusions

The effect of proton irradiation with energy of 6.8 MeV and doses up to $1\times10^{17}p^+/cm^2$, and annealing at the temperatures of 100–300 °C on the $Si_{1-x}Ge_x$ whiskers with the concentration of impurities near the metal-insulator limit in the temperature range 4,2–300 K in magnetic fields up to 14T induction. The irradiation doses up to 5×10^{15} p^+/cm^2 have been founded not to change the conductivity of crystals, however, lead to significant magnetoresistance changes (changing values both positive and negative magnetoresistances). The irradiation dose of $1\times10^{16}p^+/cm^2$ led to a significant decrease in $Si_{1-x}Ge_x$ resistance in the temperature range 4,2–40 K. But conductivity change at higher temperatures caused by proton irradiation is not significant. So, we can recommend $Si_{1-x}Ge_x$ whiskers as strain sensors of proton irradiation resistant up to $5\times10^{16}p^+/cm^2$ doses. A seconary signal processing scheme is proposed for linearizing output signals and for controlling a received irradiation dose.

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СЕНСОР ДЕФОРМАЦІЇ, СТІЙКИЙ ДО ДІЇ ПРОТОННОГО ВИПРОМІНЮВАННЯ

Анатолій Дружинін, Юрій Ховерко,
Ігор Островський, Андрій Вуйцик

В даній роботі проаналізовано вплив протонного випромінювання на ниткоподібні кристали Si$_{1-x}$Ge$_x$ які використовуються в сенсорах механічних величин та зроблено висновки про стійкість таких сенсорів до дії протонного випромінювання. Також запропоновано інтелектуальну інтерфейсну плату для обробки сигналу від вимірювального перетворювача.

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