Investigating the Strain Effect in Nickel- and Tin-Doped Silicon Schottky Barrier Diodes Under Hydrostatic Pressure

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Abstract: This work investigates the strain-sensitivity of Schottky barrier structures fabricated on silicon pre-doped with isovalent impurities and subsequently compensated with deep-level nickel impurities. The study demonstrates that while isovalent impurities themselves typically do not alter electrophysical parameters, the presence of deep-level nickel impurities significantly enhances the semiconductor's sensitivity to mechanical stress. The research was conducted under all-round hydrostatic pressure (AHP) to evaluate the piezoresistive properties of these structures. A key challenge addressed is the creation of Schottky barrier diodes (SBDs) that combine high strain-sensitivity - requiring high-resistivity compensated material - with a significant contact potential difference, which necessitates low-resistivity material for effective barrier formation. We show that pre-doping silicon with isovalent tin impurities inhibits uniform nickel diffusion, resulting in Si<P,Sn,Ni> structures with a non-uniform resistivity profile. This engineered structure features a highly compensated region for enhanced strain sensitivity and a near-surface low-resistivity zone for forming an effective Au-Sb Schottky barrier. Current-voltage characterization under AHP reveals that the relative change in forward current ($\Delta I/I_0$) in Si<P,Sn,Ni>-based SBDs shows a strong voltage dependence with a characteristic peak, attributed to pressure-induced voltage redistribution between the potential barrier and compensated base region. Significantly, enhanced strain-sensitivity is achieved even in high-resistivity (10^4-10^5 Ω·cm) Si<P,Sn,Ni> structures, a result unattainable in uniformly compensated Si<P,Ni> samples. These findings establish that controlled non-uniform impurity distribution through isovalent pre-doping is crucial for developing highly sensitive piezoresistive semiconductor devices.

1 INTRODUCTION

It is known [1] that isovalent impurities do not affect the electrophysical parameters of the semiconductor. Despite this, doped semiconductors with isovalent impurities are attracting great interest of the scientists all over the world. For example, the presence of isovalent impurities in the silicon volume does not affect the electrophysical states of the basic atoms can create internal mechanical stress.

It is known [2], [3] that semiconductor materials are highly sensitive to external mechanical effects. By doping with different impurities it is possible to change their strain sensitivity in a very wide range [4]. Doping semiconductors with impurities that create deep energy levels in its forbidden band will make them very sensitive to all kinds of external influences [5]. And devices based on such semiconductors have much higher strain-sensitivity coefficients than the strain-sensitivity of their base material [6], [7].

The authors [6] investigated the strain - electric properties of semiconductors with nickel impurities under static action of all-round hydrostatic pressure. The authors showed that with the introduction of deep-lying nickel impurities significantly increase its strain sensitivity to external mechanical action. According to the authors, the increase in tenso-sensitivity of semiconductors with deep energy centres, associated with the possibility of such impurities in a partially ionized state even at room temperature.

At diffusion of silicon by impurity atoms of nickel due to the large solubility [8], [9] is approximately uniformly distributed over the whole volume of silicon. Therefore, the compensated Si<P,Ni> samples have approximately the same resistivity throughout the thickness. To get a structure with a Schottky barrier with a high contact potential difference it must be made on the basis of a semiconductor with low resistivity. And to obtain a structure with a high strain sensitivity coefficient, the base material must have a high resistivity (high degree of compensation). For this purpose, compensating impurities should be distributed in the silicon volume not uniformly. That is, one near-surface area of silicon with strong compensation and decreasing in thickness on the other surface becomes uncompensated. To make the structure of metal-semiconductor contact on one surface of the base semiconductor is applied a layer of metal, which creates an ohmic contact and on the other surface a layer of metal, which creates a potential barrier.

The authors [3], [10] showed that the presence of tin atoms in silicon introduced in advance during growth by the Czochralskii method significantly slows down the diffusion rate of nickel impurities in Si<P,Sn>. According to the authors, this leads to a non-uniform distribution of nickel impurities in the thickness of silicon.

2 METHOD

The alloying of Si<P>, Si<P,Sn> with nickel was carried out from the diffusant layer deposited on the silicon surface by vacuum spraying on VUP-4 units. Metallic Ni with special purity of 99.999 % was used as a diffusant. Diffusion annealing was carried out in electric furnaces of SUOL-4 M type (temperature up to 1200÷1250 °C) The temperature in the furnace was controlled by measuring the thermal EMF with a platinum - platinum rhodium thermocouple.

The obtained n-Si<P,Ni> samples after diffusion had resistivity in the range of $10^2÷10^5$ Ohm cm. Measurement of surface resistivity by four-probe method showed that the samples n-Si<P,Ni> on both surfaces had approximately the same resistivity in contrast to the samples n-Si<P,Sn,Ni>.

All samples n-Si<P,Sn,Ni> after diffusion doping of nickel had non-uniform resistivity along the thickness. One near-surface region in all samples had resistivity in the range of 90-120 Ohm cm. And the other near-surface region of the studied samples had resistivity in the range of $10^2 ÷ 10^5$ Ohm cm.

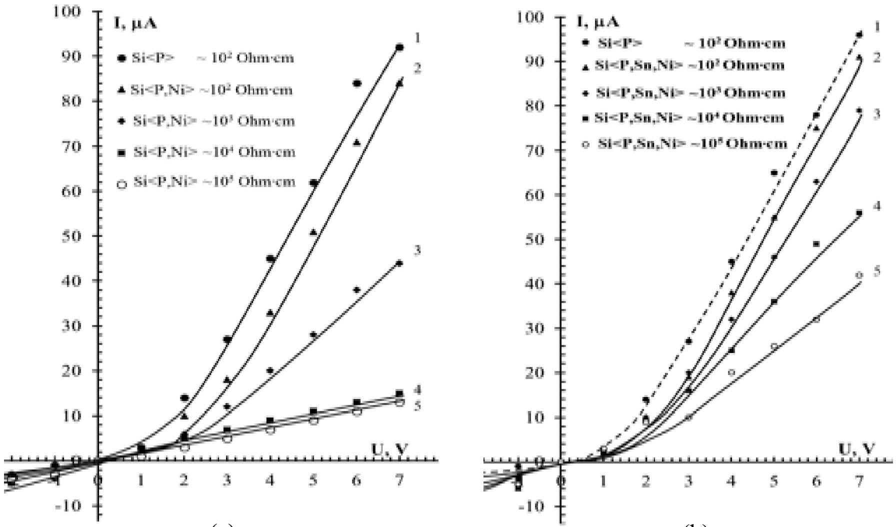
To study the strain electrical properties of structures with Schottky barrier such as Au-n-Si<P,Ni>-Sb and Au-n-Si<P,Sn,Ni>-Sb with different degrees of base materials compensation. These structures differ from each other by the fact that in Au-n-Si<P,Sn,Ni>-Sb structures the base samples are compensated by nickel impurities only on one side and on the other side they are practically uncompensated. In Au-n-Si<P,Ni>-Sb structures, the base samples have approximately the same resistivity throughout the thickness.

3 RESULTS

In this work we investigated the electrophysical and strain electrical properties of Schottky surface barrier structures based on n - Si<P>, n - Si<P,Ni> and n-Si<P,Sn,Ni> with resistivities of $10^2÷10^5$ Ohm cm under all-round hydrostatic pressure (AHP).

To compare the diode characteristics of the obtained structures, the Volt Ampere characteristics (VAC) of Au-n-Si<P,Ni>-Sb (Fig. 1a) and Au-n-Si<P,Sn,Ni>-Sb (Fig. 1b) structures were investigated. As can be seen from the figure, the VAC of structures with Schottky barrier made on the base of compensated silicon n-Si<P,Ni> with resistivity ~$10^4÷10^5$ Ohm cm (Fig. 1a curves 4-5) have almost linear character. This shows that contact potential differences have not formed in these structures. And VACs of structures made on the basis of n-Si<P,Ni> with resistivity $10^2÷10^3$ Ohm cm have a noticeable exponential form (Fig. 1a curves 2-3). As shown in Figure 1a curves 1,2 in the VAC of structures based on the initial sample n-Si<P> with resistivity 10^2 Ohm cm (Fig. 1a curve 1) and based on n-Si<P,Ni> with resistivity 10^2 (Fig. 1a curve 2) Ohm cm are very close to each other.

Figure 1b shows the VACs of Schottky barrier structures made on the basis of n-Si<P,Sn,Ni> with resistivity $10^2÷10^5$ Ohm cm. As can be seen from the figure, the VACs of all investigated structures of Au-n-Si<P,Sn,Ni>-Sb type have a noticeable exponential form. It means that in all investigated structures with Schottky barrier of Au-n-Si<P,Sn,Ni>-Sb type certain contact potential differences have been formed.



(a) (b)

Figure 1: Volt-Ampere characteristics of structures with Schottky barrier based on a) n-Si<P,Ni> and b) n-Si<P,Sn,Ni>.

Figure 2 shows the dependences of the relative change in the forward current of structures with Schottky barrier at AHP (I/Io=f(U), P=0.5 GPa) on the applied external electric voltage. As shown by the results of investigations, the relative change in the forward current of diode structures with Schottky barrier based on n - Si<P,Ni> with resistivity ~10^2 (Fig. 1 curve. 2) and 10^3 (Fig. 2 curve. 3) Ohm cm. at constant AHP depends on the applied external electric voltage. With increasing external electric voltage, the relative change in the forward current of the studied structures increases at the start, then reaches its maximum value and begins to decrease with further increasing of the electric voltage.

As shown in Figure 2, the dependence of the relative change in the forward current at AHP on the electric voltage can be divided into three characteristic sections. In section I, the value of I/Io at constant AHP equal to P=0.5 GPa increases with increasing electric voltage. The value of I/Io at section II decreases and at section III it becomes constant.

We suppose that this character of dependence of the relative change in the forward current at constant AHP on the electric voltage is due to the presence of compensating impurities with deep energy levels in the volume of the base material of the investigated structures with Schottky barrier. In our case, the base materials are compensated silicon with nickel impurities. The base materials of our investigated structures are highly resistive (~10^2 and 10^3 Ohm cm). Therefore, the applied electrical voltage in the structures is distributed between the potential barrier and the base material. At the start, the effective resistance of the potential barrier height is much higher than the resistance of the base region of the structures. At the same time, most of the external electric voltage falls on the effective resistance of the potential barrier. Therefore, at low electrical voltages, the effect of redistribution of electrical voltage between the barrier and the base region is smaller and consequently the relative change in forward current will also be smaller. It is known, that [10] the dependence of the potential barrier height on the electric voltage is expressed by the following formula.

$$\varphi = \varphi_b - eU \qquad (1)$$

Where - $\Delta\varphi_b$ is the metal-semiconductor contact potential difference, e - is the electron charge, U - is the external voltage applied to the contact.

As the external electric voltage increases, the height of the potential barrier decreases and this leads to a decrease in its effective resistance. At the same time, the distribution of the applied electric voltage between the barrier and the base region changes. As the external electric voltage increases, its contribution in the base region increases. Accordingly, the effect of voltage redistribution (Fig. 2, section I) between the barrier and the base region under all-round hydrostatic pressure increases.

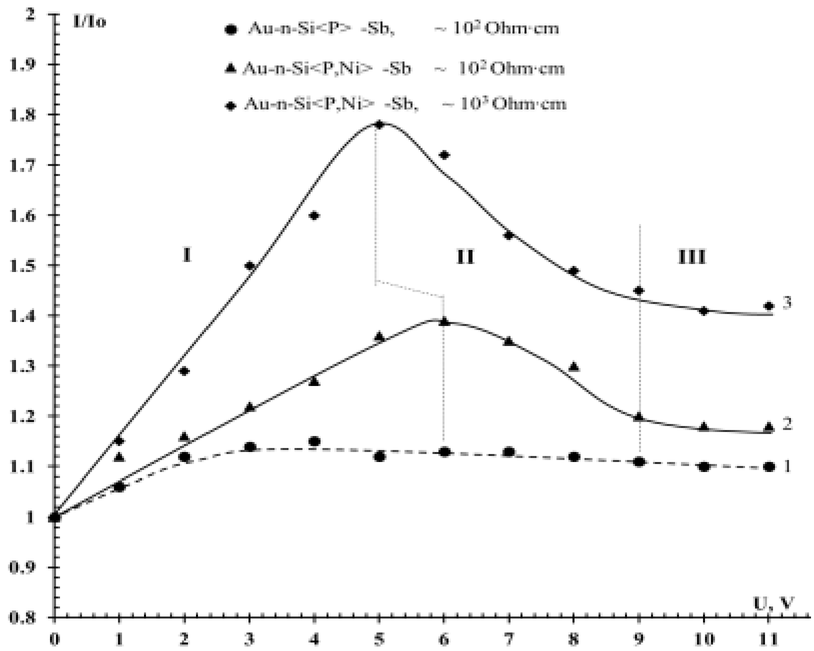


Figure 2: Relative change of the forward current of Schottky barrier structures made on the basis of initial (1) silicon and Si<P,Ni> (2, 3) under all-round hydrostatic pressure as a function of the applied electrical voltage.

When the effective resistance of the potential barrier becomes comparable to the resistance of the base region, the redistribution effect under AHP becomes maximum. Further, due to the lower effective resistance of the potential barrier, the redistribution effect starts to decrease (Fig. 2 area II) as the external electric voltage increases. When the height of the potential voltage becomes equal to zero the strain - effect in the studied structures will cease to depend on the external voltage (Fig. 2 area III).

It was shown in [2], in structures with Schottky barrier based on compensated semiconductors n-Si<P,Ni> with resistivity $10^2 \div 10^3$ Ohm cm are formed significant contact potential differences. And in structures made on the basis of compensated n-Si<P,Ni> samples with resistivity $10^4 \div 10^5$ Ohm cm the presence of contact potential difference is practically no noticeable.

The above results show that the strain - effect in structures with Schottky barrier depends on the effect of redistribution of external electric voltage. In order to observe the effect of redistribution of external electric voltage, the studied structures must have a high degree of compensation and a large height of the potential barrier. To create such a diode structure with Schottky barrier, the base material should have a strong compensation on one surface and a poor compensation on the other surface. In such samples, the surface with a high degree of compensation is used to create an ohmic contact and the other surface with a weak compensation can be used to create a contact potential difference.

To investigate the strain effect in Schottky barrier structures based on compensated silicon with non-uniform resistivity along the thickness, Schottky barrier structures based on n-Si<P,Sn,Ni> were prepared. The basic samples of our structures on the ohmic contact side had resistivities in the range of 10^2–10^5 Ω·cm, and on the barrier contact side, in all structures, on the order of ~10^2 Ω·cm. According to our assumptions, in all investigated Schottky barrier structures, the contact potential differences should be close in value to each other.

In Figure 3, the relative changes in the forward current of Schottky barrier structures based on n-Si<P,Sn,Ni> as a function of the applied voltage at constant hydrostatic pressure are shown.

As shown by the results obtained, in all structures there is a significant effect of redistribution of the electric voltage between the base region and the potential barrier. Even in Schottky barrier structures based on n-Si<P,Sn,Ni> with resistivity of 10^4–10^5 Ω·cm, there are significant relative changes (Fig. 2, curves 4–5) in the forward current, in contrast to structures made on the basis of n-Si<P,Ni> with similar resistivity.

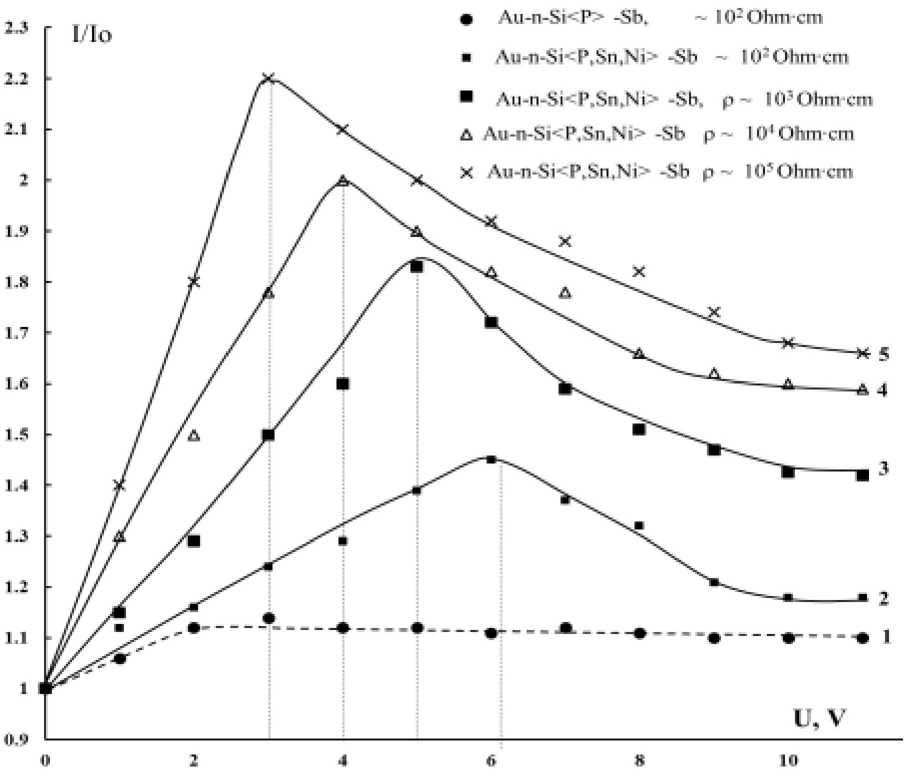


Figure 3: Relative change in the forward current of Schottky barrier structures fabricated on the basis of initial (1) silicon and Si<P,Sn,Ni> (2-5) under all-round hydrostatic pressure as a function of the applied electrical voltage.

Figure 3 shows that the peaks of the relative change in the forward current are shifted towards lower voltages. This is probably due to the fact that in Schottky barrier structures based on Si<P,Sn,Ni> with high resistivity, the effective resistance of the potential barrier becomes comparable to the resistivity of the base region at lower voltages.

4 CONCLUSIONS

This study demonstrates that Schottky barrier diodes (SBDs) fabricated on silicon compensated with deep-level nickel impurities exhibit a significant strain effect under all-round hydrostatic pressure. The key factor governing this effect is the mechanism of electric voltage redistribution between the potential barrier and the compensated base region of the semiconductor. The strain sensitivity was found to increase with the degree of compensation; however, a critical challenge was identified: achieving a high strain effect concurrently with a substantial contact potential difference, as highly compensated, uniform material (with resistivity of 10^4–10^5 Ohm·cm) yields a poorly defined Schottky barrier.

We have successfully addressed this challenge by introducing a controlled, non-uniform distribution of nickel impurities. Pre-doping silicon with isovalent tin atoms effectively inhibits nickel diffusion, resulting in Si<P,Sn,Ni> structures where one near-surface region remains lightly doped (enabling the formation of a high-quality Au-Sb Schottky barrier) while the bulk is highly compensated (providing enhanced strain sensitivity). This engineered structure allows for the creation of SBDs based on highly compensated silicon that still possess a significant and well-defined contact potential difference.

The most important practical outcome of this work is the development of a foundational technology for creating highly sensitive piezoresistive sensing elements [11]. The obtained structures exhibit a strong, voltage-dependent piezoresistive response, characterized by a pronounced peak in the relative current change, which is a hallmark of high sensitivity.

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