East European Journal of Physics. 3. 309-313 (2025)
DOI:10.26565/2312-4334-2025-3-28 ISSN 2312-4334

STATICAL CURRENTS OF p-Si–n-$Si_{1-\delta}Sn_\delta$–n^+-$Si_{1-\delta}Sn_\delta$ ($0 \le \delta \le 0.04$)-STRUCTURES WITH TIN QUANTUM DOTS

Avazbek Sh. Ikromov[a], Azizbek A. Abdurakhmonov[b], Khurshidjon M. Madaminov[a]*
[a]*Andijan State University, 129 Universitet st., Andijan, Uzbekistan*
[b]*Ferghana State University, 19 Murabbiylar st., Ferghana, Uzbekistan*
**Corresponding Author E-mail: khurmad@mail.ru*
Received May 25, 2025; revised July 13, 2025; accepted July 21, 2025

In this work, the current-voltage characteristics of p-Si-n-$Si_{1-\delta}Sn_\delta$ structures at room temperature were investigated to clarify the role of injection effects in the formation of electrical properties of heterostructures obtained based on the $Si_{1-\delta}Sn_\delta$ ($0 \le \delta \le 0.04$) solid solution. It is shown that the sub linear sections observed on the current-voltage characteristics are well described within the framework of the theory of the injection depletion effect. The value of the parameter "a" was determined directly from the sub linear section of the current-voltage characteristic, which in the following allowed determining the concentration of deep impurities responsible for the appearance of the sub linear section. With this it was proved that the investigated structure can be considered as p-Si-n-$Si_{1-\delta}Sn_\delta$–n^+-$Si_{1-\delta}Sn_\delta$ ($0 \le \delta \le 0.04$) - a junction with a high-resistance n-$Si_{1-\delta}Sn_\delta$ layer. An analysis of the results obtained allowed us to conclude that in this $Si_{1-\delta}Sn_\delta$ ($0 \le \delta \le 0.04$) solid solution, scattering of charge carriers not only on complex complexes, but also on nanoformations plays a significant role in the formation of electro physical properties. Based on the results of the studies, it was concluded that the use of epitaxial films of $Si_{1-\delta}Sn_\delta$ ($0 \le \delta \le 0.04$) solid solutions, obtained on silicon substrates, as promising materials, when developing diodes based on them, operating in the double injection mode.
Key words: *Liquid-phase epitaxy; Solid solution; Current-voltage characteristic; Sub linear region; Effect of injection depletion*
PACS: 73.40.Lq, 77.55.df, 61.82.Fk

INTRODUCTION

In connection with the development of nanotechnology and the relevance of research into nano-objects, in particular, the production of semiconductor quantum dots is of interest both for fundamental physics and for potential applications in micro- and nanoelectronics devices [1-3]. This situation has led to intensive research into growing, for example, crystalline perfect solid solutions (SS) of "silicon + tin" with quantum dots (QDs) [4].

Semiconductor p-n-n^+ structures based on the "silicon+tin" solid-state transistor are of significant interest for solid-state electronics and it is very important to have a clear understanding of the current-voltage characteristic (CVC) of these structures [5-6]. Interest in these objects is due to their unique physical properties associated with the atomic-like energy spectrum of QDs and the possibility of producing various semiconductor devices based on them [7-8].

Based on this, the goal of this work was set to study the features of the room CVC of p-n-n^+ structures based on the solid solution "silicon+tin".

The studied p-n-n^+ structures were produced by liquid-phase epitaxy from a tin melt solution [9]. To improve structural perfection, growth was carried out at temperatures below 1100^0 C. The solution-melt composition for low-temperature epitaxy was determined from phase diagrams, which showed that the most suitable component was antimony. In addition, the addition of antimony to the melt solution ensures reliable pouring of the melt solution into the gap between the silicon substrates and the necessary wet ability. The substrates were KDB washers, 40 mm in diameter, oriented in the (111) direction. The growth was carried out from a solution-melt confined between two horizontally located substrates. The grown layers had n-type conductivity with a specific resistance of 0.8 Ohm·cm and a current carrier concentration of 10^{17} cm^{-3}, at room temperature.

MATERIALS AND METHODS

Formation of solid solutions of "silicon – tin". It is appropriate to add here that before this work we did not find any data in the literature on the synthesis of a substitution solid solution based on silicon (Si) and tin (Sn) [9].

Taking into account the charge state and geometric factors of the components, we discuss the possibilities of forming a solid solution based on $Si_{1-\delta}Sn_\delta$. To do this, we will first consider the possibilities of forming solid substitution solutions based on Si and Sn, associated with the conditions for the formation of continuous solid substitution solutions based on molecular-statistical and crystallochemical concepts. These conditions are given in the work [9] in the form

$$\Delta z = \sum_{i=1} z_i^m - \sum_{i=1} z_i^n = 0 \quad (1)$$

$$\Delta r = |\sum_{i=1} r_i^m - \sum_{i=1} r_i^n| \le 0.1 \sum_{i=1} r_i^m = 0 \quad (2)$$

where z_i^m, z_i^n - valency, r_i^m, r_i^n covalent radius of the atoms of the solvent m and dissolved n chemical element or elements that form the molecules of the solvent and dissolved compounds, respectively, *i=1, 2, 3, 4.*

Cite as: A.Sh. Ikromov, A.A. Abdurakhmonov, Kh.M. Madaminov, East Eur. J. Phys. 3, 309 (2025), https://doi.org/10.26565/2312-4334-2025-3-28

Condition (1) presupposes the electrical neutrality of the dissolved chemical elements or compounds in the solvent semiconductor material. It is satisfied when the dissolved elements are isovalent with respect to the solvent semiconductor.

Condition (2) provides for the proximity of the geometric parameters of the solvent m and soluble n compounds, which excludes the occurrence of significant distortions of the crystal lattice in solid solutions. The smaller, the smaller the energy of elastic distortions of the crystal lattice and, consequently, the greater the crystalline perfection of the solid solution and the solubility n in m. When the difference in the sum of the covalent radii of the atoms of the molecules forming the solution is greater than 10%, the formation of a solid substitution solution of these components is insignificant. Based on the equality of the sum of the valences of the atoms of the Si_2 and SiSn molecules, it is easy to verify that the conditions of electroneutrality (1) are met for them:

$$\Delta z = (z_{Si} + z_{Si}) - (z_{Si} + z_{Sn}) = 0, \tag{3}$$

where z_{Si} and z_{Sn} - valences of silicon and tin atoms, respectively. The sums of the covalent radius of the atoms of the Si_2 and Sn molecules have close values, then from condition (2) we can obtain:

$$\Delta r = \left|(r_{Si} + r_{Si}) - (r_{Si} + r_{Sn})\right| = \left|2.34\text{Å} - 2.51\text{Å}\right| = 0.17\text{Å} \approx 0.073 \cdot (r_{Si} + r_{Si}) < 0.1(r_{Si} + r_{Si}), \tag{4}$$

where r_{Si} and r_{Sn}covalent radius of silicon and tin atoms according to Pauling, respectively.

From (4) it is evident that the difference in the sum of the covalent radii of the atoms of the Si_2 and SiSn molecules is about 7.3%, therefore, these components satisfy the condition for the formation of a continuous substitution solid solution presented in [10]. Thus, the substitution of Si_2 by a SiSn molecule does not greatly deform the crystal lattice, while the energy of elastic distortions of the crystal lattice will be insignificant and the substitution solid solution in the form of $Si_{1-\delta}Sn_{\delta}$ is a stable solid phase.

A model explaining the formation of tin quantum dots. It is in this process that the driving force of synthesis is the gradient of chemical potentials of the atoms of the crystallized substance in two phases: liquid (μ_L) and solid (μ_S).

Since the lattice constant of the quantum dot material a_2 (a_{Sn}) differs significantly from the lattice constant of the base semiconductor a_1 (a_{Si}), shear mechanical stresses arise at the boundary of subcrystallites (blocks) and epitaxial layers during the formation of QDs [1]. These mechanical stresses can be expressed through the elastic energy *U(x)* per one QD atom with coordinate x, where $0 \le x \le R$, *R*– is the radius of the QD base [3]. Then the difference in chemical potentials will be determined by the expression [11]:

$$\Delta\mu_{ST} = \mu_L - \mu_S - U(x) = \Delta\mu - U(x)$$

Under condition $\Delta\mu < U(x)$, the crystallization process is replaced by a dissolution process, since $\Delta\mu_{ST}$ becomes a negative value.

The equality $\Delta\mu = U(x)$ defines the maximum allowable mechanical stresses in a quantum dot. Under these growth conditions, the lattice parameter of the base semiconductor a_{Si} and the quantum dot material a_{Sn} do not depend on temperature. It is in this situation, when calculating the maximum value of the radius of the base (R) of the nascent quantum dot, that we use the expression determined from the condition $\Delta\mu = U(R)$, given in the literature [3]:

$$R = \sqrt{\frac{N_S\Delta\mu(a_1+a_2)a_1a_2}{G(a_1-a_2)^2}}, \tag{6}$$

here N_S is the number of atoms per unit surface area; *G* is the shear modulus.

Since the nuclei formed at the boundary of subcrystallites (blocks) of epitaxial layers are spherical segments whose radius of curvature corresponds to the radius of a homogeneous critical nucleus formed in the liquid phase under the same crystallization conditions, the calculation of the radius of curvature of the nucleus is calculated using the formula:

$$r = \frac{2\sigma M}{\rho R_C T} ln\frac{C_0}{C}, \tag{7}$$

where σ is the interfacial surface energy in the liquid phase; ρ, M are the density and molar mass of the nucleus substance, respectively; R_C is the universal gas constant; C, C_0 are the concentrations of the base semiconductor (Si) and QD (Sn) in supersaturated and equilibrium solutions, respectively. Then the height h of the heterogeneous CT nucleus will be determined by the expression:

$$h = r\left[1 - \left(1 - \frac{R^2}{r^2}\right)\right]. \tag{8}$$

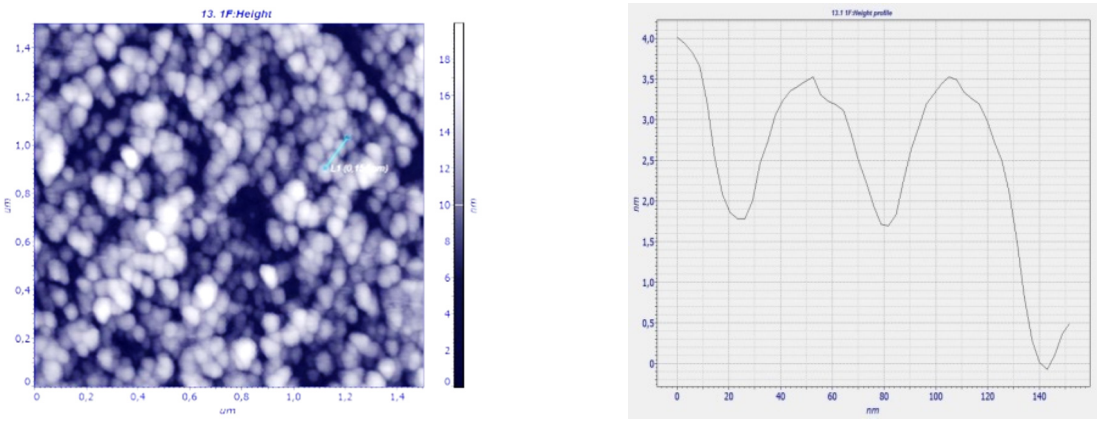
During the growth of the QD nucleus, the mechanical stresses in the QD material layer (Sn) adjacent to the heterointerface increase to values corresponding to the elastic constants of the bulk Si layer [11].

Due to the fact that the stresses in the QD have a gradient directed along the normal to the plane of the base semiconductor, a curvilinear etching front of the lateral surface of the QD is formed at the base of the QD at $\mu_{ST} < 0$. This in turn changes the condition of local phase equilibrium near the heterointerface compared to a flat etching front [12].

Thus, when a mechanically stressed wetting layer is formed, arrays of QDs of the surface regions of the base semiconductor are formed.To confirm the above-described model, an analysis of surface images obtained using AFM was carried out [13].

To confirm the above, the surface properties of these films were investigated using an industrial atomic force microscope (AFM) “Solver-NEXT”, which allows studying the surface relief.

Figure 1 shows a two-dimensional image (a) and a surface profilogram (b) of an epitaxial film of substitution solid solutions $Si_{1-\delta}Sn_\delta$. It is evident (Fig. 1a) that individual nanoislands of different sizes are formed on the surface of the films. Analysis (Fig. 1b) showed that the diameter of the base of the nanoislands varies in the range from 50 to 70 nm, and the height from 3 to 15 nm.

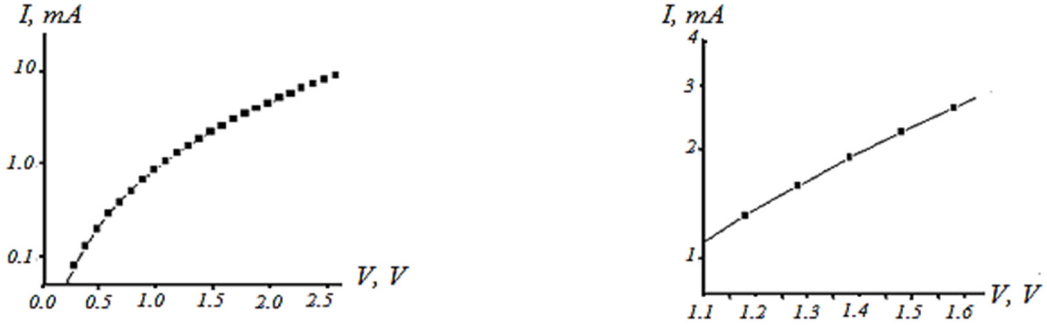


a) b)

Figure 1. Two-dimensional image (a) and surface profilogram (b) of an epitaxial film of $Si_{1-\delta}Sn_\delta$ solid solutions

The data obtained by the atomic force microscope show that at the growth stage, the Sn nanoislands in the $Si_{1-\delta}Sn_\delta$ solid solution have a geometric shape of a dome, the so-called dome islands with a characteristic lateral size of 50-70 nm with a round base. The appearance of such forms of tin nanoislands is usually explained by strong relaxation of elastic stresses in the dome- phase configuration. According to the data presented in [13], these nanoclusters are called hut-clusters with lateral dimensions of 15 ... 25 nm, they are absorbed by dome-clusters. Such a process is often accompanied by a bimodal distribution of islands by size, corresponding to the coexistence of hut- and dome-phases [14]. Based on these data, it can be concluded that the observed nanoislands on the surface of epitaxial layers are caused by Sn quantum dots with dimensions R = 25 ÷ 35 nm and height h = 3 ÷ 15 nm.

Sample preparation and research methods. As is known, a very important indicator of a p-n junction is its current-voltage characteristic. The appearance of the current-voltage characteristic curves allows us to reason about certain properties of the p-n junction. Since usually, the creation of p-n junctions is complicated by the formation of various types of surface states, which sharply reduce the electrical parameters of devices manufactured on their basis. The resulting p-n junction in a single technological cycle causes a decrease in the density of surface defects. Taking this circumstance into account, the studied pSi-n$Si_{1-\delta}Sn_\delta$ structures were obtained in a single technological cycle using the liquid-phase epitaxy method [9-10].



a b

Figure 2. Straight branches of the VAX of pSi–n$Si_{1-\delta}Sn_\delta$ heterostructures (a) and their sublinear sections (b) at room temperature

Therefore, to determine some electrophysical characteristics of pSi-$Si_{1-\delta}Sn_\delta$ structures, experiments were conducted to measure the I–V characteristics. For this purpose, pSi-n$Si_{1-\delta}Sn_\delta$ ($0 \le \delta \le 0.04$) structures with a base n-layer thickness of $d \approx 20\ \mu m$ were fabricated. During the study, ohmic contacts were created to the structure using the vacuum deposition method of silver - solid on the back side and quadrangular with an area of 12 mm^2 on the side of the epitaxial layer. During the experiments, dark CVC were measured (Fig. 2). The I–V measurements were carried out at room temperature

T = 293 *K* in the forward current mode (Fig. 2a). The direct direction of current in the structure was considered to be when a positive potential was applied to the contact from the rear side.

RESULTS AND DISCUSSION

According to the obtained experimental results, CVC of the studied samples contains a sublinear region. Figure 2b shows the sublinear region CVC reconstructed on a semi-logarithmic scale. It is easy to see that in these coordinates the sublinear section straightens out. This indicates that it is satisfactorily described by an exponential dependence of the type

$$V \approx V_0 \cdot \exp(JA). \tag{9}$$

Theoretical studies of the processes of ambipolar transport of nonequilibrium carriers in p-n-n^+ structures show that VAX, described by expression (9), can arise under the conditions of the injection depletion effect, first predicted by Leiderman, Karageorgiy-Alkalaev [15].

This effect occurs under conditions of developed carrier accumulation at the n-n^+- junction of the n-base, causing opposite directions of diffusion and drift. In this case, due to the injection modulation of the charge of deep impurities, there is a decrease in the concentration of nonequilibrium current carriers n, a linear increase in the ambipolar drift velocity v_a with an increase in current in the form

$$v_a = a \cdot D_p \cdot J, \tag{10}$$

$$a = (2qN_tD_n)^{-1}, \tag{11}$$

where q is the electron charge, D_n, D_p are the diffusion coefficients of electrons and holes, respectively; N_t is the concentration of deep impurities.

As shown in [16, 17], the coefficient A in (9) is determined by the formula

$$A = a \cdot d, \tag{12}$$

where W is the length of the n-base.

The I(V) graph in Fig. 2b allows us to estimate the parameter “a” using the formula

$$a = \frac{\ln(V_2/V_1)}{(I_1 - I_2)\cdot d} \tag{13}$$

where S is the cross-sectional area of the sample. Calculation using formula (11) shows that the values of the parameter $a = 6.58\cdot10^3$ cm/A and the concentration of deep impurities responsible for the appearance of the sublinear section in the form (9), at room temperature, the value of which was $N_t = 5.3\cdot10^{12}$ cm^{-3}.

It is appropriate to add here that the specific resistance of the epitaxial layer, determined by the Hall method, is 0.8 Ohm·cm, but all the characteristics obtained indicate that a layer with other characteristics is formed between the epitaxial film and the substrate, otherwise such VAX are not observed, and, therefore, the exponential dependence (9) cannot be observed.

This allows us to reason that the studied structure can be considered as a p-Si–n-$Si_{1-\delta}Sn_\delta$-n^+-$Si_{1-\delta}Sn_\delta$ ($0 \le \delta \le 0.04$) junction with a high-resistance n-$Si_{1-\delta}Sn_\delta$ layer (Fig. 3).

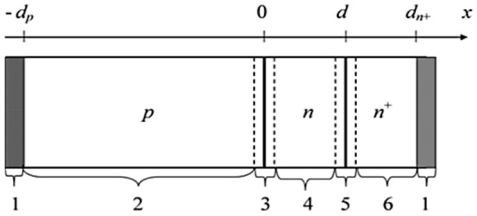


Figure 3. Scheme of pSi-n$Si_{1-\delta}Sn_\delta$-$n^+Si_{1-\delta}Sn_\delta$– structures
1 – ohmic current collector contacts; 2 – pSi layer (substrate); 3 – pSi-n$Si_{1-\delta}Sn_\delta$ junction volume charge region; 4 – high-resistance epitaxial layer of pSi - n$Si_{1-\delta}Sn_\delta$ solid solution; 5 – n$Si_{1-\delta}Sn_\delta$- n+$Si_{1-\delta}Sn_\delta$ junction volume charge region; 6 – low-resistance epitaxial layer of pSi - n$Si_{1-\delta}Sn_\delta$ solid solution

CONCLUSIONS

The obtained results allow us to conclude that the presence of a sublinear region in VAX p-n-n^+ structures based on silicon-tin solid solutions is associated with the effect of injection depletion [18].

Thus, the epitaxial films of $Si_{1-\delta}Sn_\delta$, solid solutions obtained on silicon substrates that we studied, can be used as an active element for developing injection diodes. The structures obtained on this basis and the description of the mechanisms of physical processes occurring in them are of both theoretical and practical interest for semiconductor materials science [19].

As a result, it can be assumed that the epitaxial films of $Si_{1-\delta}Sn_\delta$ solid solutions studied in the work may be promising materials for the manufacture of diodes operating in the double injection [4, 20].

ORCID
A.Sh. Ikromov, https://orcid.org/0009-0009-3145-1326; **A.A. Abdurakhmoov**, https://orcid.org/0009-0007-6758-2585
Kh.M. Madamiov, https://orcid.org/0000-0003-0117-9316

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СТАТИЧНІ СТРУМИ p-Si–n-$Si_{1-\delta}Sn_\delta$–n^+-$Si_{1-\delta}Sn_\delta$ (0≤δ≤0.04)-СТРУКТУР З КВАНТОВИМИ ТОЧКАМИ ОЛОВА

Авазбек Ш. Ікромов[a], Азізбек А. Абдурахмонов[b], Хуршиджон М. Мадамінов[a]
[a]*Андижанський державний університет, вул. Університетська, 129, Андижан, Узбекистан*
[b]*Ферганський державний університет, вул. Мураббійлар, 19, Фергана, Узбекистан*

У цій роботі досліджено вольт-амперні характеристики структур p-Si-n-$Si_{1-\delta}Sn_\delta$ за кімнатної температури з метою з'ясування ролі ефектів інжекції у формуванні електричних властивостей гетероструктур, отриманих на основі твердого розчину $Si_{1-\delta}Sn_\delta$ (0≤δ≤0,04). Показано, що сублінійні ділянки, що спостерігаються на вольт-амперних характеристиках, добре описуються в рамках теорії ефекту виснаження інжекції. Показано, що сублінійні ділянки, що спостерігаються на вольт-амперних характеристиках, добре описуються в рамках теорії ефекту виснаження інжекції. Значення параметра «а» визначалося безпосередньо з сублінійної ділянки вольт-амперної характеристики, що надалі дозволило визначити концентрацію глибоких домішок, що відповідають за появу сублінійної ділянки. Цим було доведено, що досліджувану структуру можна розглядати як p-Si-n-$Si_{1-\delta}Sn_\delta$–n^+-$Si_{1-\delta}Sn_\delta$ (0≤δ≤0,04) – перехід з високоомним шаром n-$Si_{1-\delta}Sn_\delta$. Аналіз отриманих результатів дозволив зробити висновок, що в цьому твердому розчині $Si_{1-\delta}Sn_\delta$ (0≤δ≤0,04) розсіювання носіїв заряду не лише на складних комплексах, але й на наноутвореннях відіграє значну роль у формуванні електрофізичних властивостей. На основі результатів досліджень було зроблено висновок про використання епітаксійних плівок твердих розчинів $Si_{1-\delta}Sn_\delta$ (0≤δ≤0,04), отриманих на кремнієвих підкладках, як перспективних матеріалів при розробці діодів на їх основі, що працюють у режимі подвійної інжекції.

Ключові слова: *рідкофазна епітаксія; твердий розчин; вольт-амперна характеристика; сублінійна область; вплив виснаження інжекції*