



Jolanta STUPAKOVA

**PHYSICAL PROPERTIES OF POROUS SILICON
NANOSTRUCTURES UNDER INFLUENCE
OF MICROWAVE RADIATION**

**Summary of Doctoral Dissertation
Physical Sciences, Physics (02P),
Condensed Materials: electronic structure;
electric, magnetic and optical properties;
superconductors; magnetic resonance; relaxation;
spectroscopy (P 260)**

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Vilnius  **2007**

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VILNIAUS GEDIMINO TECHNIKOS UNIVERSITETAS

Jolanta STUPAKOVA

**AKYTOJO SILICIO NANODARINIŲ FIZINĖS
SAVYBĖS, VEIKIANT SUPERAUKŠTO DAŽNIO
ELEKTROMAGNETINE SPINDULIUOTE**

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General Characteristic of the Dissertation

Topicality and problem of the work. Just after discovery of porous silicon (PSi) there was clarified that its wide application in various fields opens new unexpected possibilities. One of the possibilities of products of porous silicon in microwave (MW) technique is carried out in the USA now. The propagation of MWs in PSi layers is under investigation. It has been shown that radio and optoelectronic connectors made from this material have low losses and can be applied to improve technique of cellular phone communication as well as other high frequency technique. It is obvious that the next element following the connector has to be the sensor of microwave radiation. The most practicable way would be to use porous silicon in the production of it. There are known MW detectors of crystal silicon for operating under the effects of hot charge carriers. Sensitivity of the sensors usually depends on the dimensions of separate parts of it. In general, sensitivity increases while reducing the mentioned above dimensions. The technology of porous silicon presents the advantage since the specific dimensions of PSi stem could be reduced up to the nanometre sizes. After having introduced PSi technology in production of sensors which require certain diminutive dimensions, it is possible to expect significant increase of the sensitivity of such sensors. Additional advantages are expected to be achieved from the quantum confinement effect. To realize promises of application of PSi in MW technique it is of relevance to investigate physical properties of PSi layers and structures under the action of MW radiation. Neither the effect of MWs on the characteristics of PSi nor the MW sensors of PSi haven't been analysed so far. Research dealing with PSi investigations is closely connected with modern, relevant fields of nanotechnology.

The aim of the work. To investigate the effect of microwave electromagnetic radiation on to electrical and physical characteristics of PSi nanostructures and to evaluate the possibility of practical application in compiling sensors of microwave radiation.

Tasks of the work

1. To select and optimise the technology of formation of porous silicon structures as well as to produce samples adapted to the experiments in the field of microwave electromagnetic radiation.
2. To carry out morphological research on the surface of porous silicon structures and photoluminescence tests of its layers.
3. To make comparative analysis of electrical conductivity of nanocrystal

porous silicon structures with different formations and evaluate their suitability or the achievement of the targeted aim of the work.

4. To investigate the effect of the microwave radiation on porous silicon structures and to reveal the physical origin of the observed effects.
5. To evaluate the possibility of practical implementation of the obtained results.

Scientific novelty

1. For the first time there were investigated samples of porous silicon and heterogeneous crystal silicon specified themselves by symmetrical current-voltage characteristics and having porous silicon doped with acceptor boron by thermal diffusion.
2. For the first time the research of the microwave radiation effect on the properties of porous silicon two terminal structures was carried out.
3. There was shown that microwave radiation causes activation of electric conductivity of the porous silicon structures.
4. There was demonstrated that influence of microwave radiation on the structures of porous silicon induces electromotive force, the character of which and quantitative parameters depend on the design of the porous silicon structure as well as on the power of microwave radiation.
5. The model of hot charge carriers was proposed to describe the appearance of electric conductivity and electromotive force in the structures of porous silicon under the action of microwave radiation.

Practical value. The obtained results could be implemented in compiling microwave sensors. The tested laboratory sensor samples exhibited 10^3 to 10^5 time's higher sensitivity than in the analogous samples of crystal silicon.

Defended propositions

1. The transport of the electric charge activated by the microwave radiation possible in the structures of porous silicon there associated with free charge carrier heating in the microwave electromagnetic field, under the conditions of relatively large fluctuations of density of states and the potential in the fractal network of porous silicon stem.
2. Microwave radiation induces electromotive force in the structures of porous silicon causes, due to the reason of charge carrier heating and their redistribution under the influence of microwave electromagnetic field.
3. The revealed properties of porous silicon in the microwave field could be implemented in development of microwave sensors of radiation.

Approval of the results. 8 scientific publications have been manifested on the subject of the dissertation, 2 of them in the journals with ISI Web of Science citation index, 1 paper in the journal with ISI Master Journal List citation index, 1 paper in the revised materials of presentations if the international conference referred in ISI Proceedings database. The results of dissertation have been discussed of 5 international, 2 national and 4 republican conferences. 4 papers have been published in the collections of conference presentations.

The scope of the scientific work. The dissertation consists of the introduction, 5 main chapters, conclusions, list of 125 references, and list of publications on the subject of the dissertation. The total scope of the dissertation – 103 pages, 58 pictures and 5 tables.

The content of the dissertation

Introduction motivates the analysed problem and the topicality of the work, the main aim of the work, the solved problems, scientific novelty, practical value and the statements to be defended are indicated here.

1. Review of literature

The main models of PSi as well as technologies of production are reviewed here. Extensive analysis of the works of investigation of the dependence of porosity of PSi on the composition of electrolyte, on density of etching current, on resistivity of silicon plate and on duration of etching is presented. The main characteristics of PSi are described. The range of possibilities of application of PSi layers is reviewed, from light emitting diodes to explosive loads and fuel cells for the control of cosmic objects.

2. Fabrication of porous silicon structures and technique of investigation

The formation technology of the porous layers and the technique of the research are presented there. Crystalline silicon (cSi) plates of p-type 0,4 $\Omega \cdot \text{cm}$ resistivity were used for the production of PSi structures. The cell and the equipment of electrochemical etching are described there. The operations as well as conditions for production of the structure having two porous silicon layers PSiL1 and PSiL2 are presented. The technology of ohmic Al contacts is described. By applying the described technologies there were produced the samples of different types. The technology of their production differed by applying a certain number of operations and their sequence. The schemes of the samples are presented in Figure 1. A-type samples had no doped areas. B- and B'-type samples had additionally doped close-to-the-contact p^+ areas, respectively, only on the substrate side and on the both sides. Additional doping of C-type samples was performed after the production of PSi sample.

Also in this chapter the technique of morphology research of PSi structures

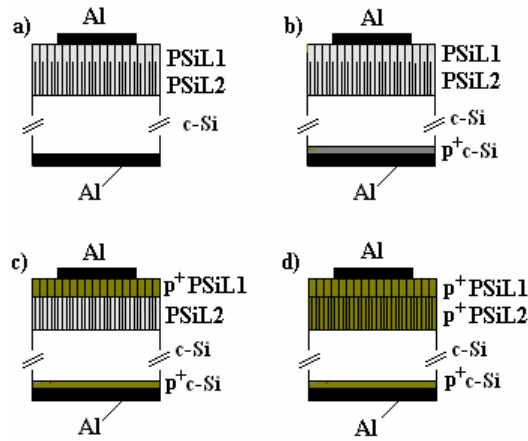


Fig 1. A-type (a); B-type (b); (c) B'-type and C-type (d) samples of porous silicon

is described, namely the method of scanning electronic microscopy (SEM), atomic forces microscopy (AFM) as well as photoluminescence (PL) method. The methods of research of the electric characteristics of the samples as well as of their properties under the influence of microwave radiation are described.

3. Investigation of morphology and contexture of porous silicon structures

Morphology of PSi porous layers and their structure are described there. The SEM research revealed that during the anodization a composite layer of PSi is formed on the surface of silicon plate there. While observing the cross-section of the structure (Fig 2) it was determined, that PSi layer was composed of two areas different porosity. SEM data on PSi structure were proved by AFM investigations (Fig 3). To assess the dimensions of the elements of PSiL2 area of PSi stem the investigations of FL spectra were carried out (Fig 4). The position of PSi FL spectra is unambiguously connected with the dimensions of PSi nanoparticles. This PSi feature was used to evaluate the dimensions of nanoparticles of PSiL2

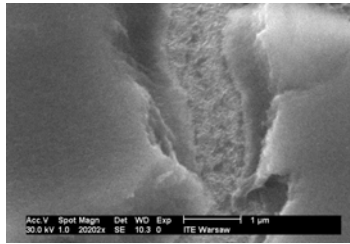


Fig 2. SEM microphotograph of the surface of porous silicon

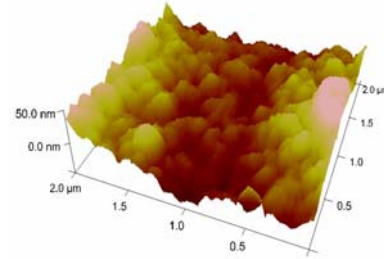


Fig 3. Porous silicon surface layer morphology obtained by AFM tests

stem. It was revealed from the position of the spectrum that the dimensions of particles compiling PSi stem network are within the interval of (3÷5) nm. Wide band of the spectrum, hints that distribution of the particles with respect to thin dimensions is wider than in homogeneous PSi layers (Fig 4).

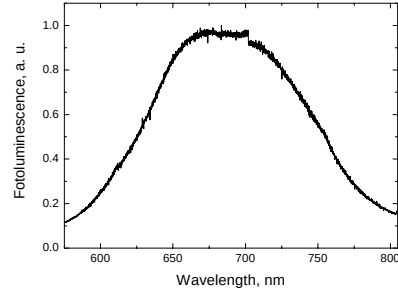


Fig 4. Photoluminescence spectrum of porous silicon structures

On the basis of PSi morphology research and FL analysis there was compiled the scheme of energy bands in the direction of the sample cross section (Fig 5). Metallic Al contacts are on the ends of the sample. The figure presents the forbidden energy bands E_i for the separate parts of the sample, σ_i is the electric conductivity, ε_i is the dielectric permittivity. The thicknesses of separate parts are indicated there. The Al contact located on the surface of PSiL1 layer is separated by a tunnel transparent layer of oxide. There is a supporting PSiL1 layer under the contact. The area of PSiL1 is additionally doped by boron. Its electric conductivity is $\sigma^+ > \sigma$ cSi. Quantum confinement effects in the PSiL1 layer do not express themselves that is why the width of the forbidden energy band in it is equal to E_g , the width of the forbidden energy band of cSi.

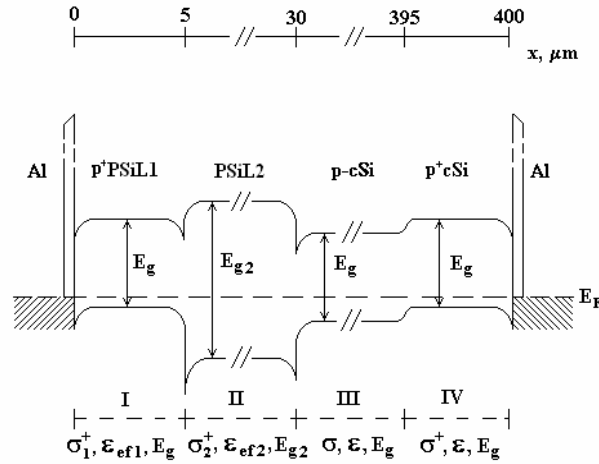


Fig 5. Band diagram of nanostructure PSi layers

Dielectric permittivity has an effective value ϵ_{efl} , because the layer is composed of hollow cavities and crystal stem network. Deeper is located the porous layer PSiL2. Its conductivity is σ_2 , dielectric permittivity is ϵ_{ef2} , and the width of the forbidden band is E_{g2} . As the FL research indicates, E_{g2} is wider than the E_g of cSi and is within the interval $E_{g2} \in (1,6 \div 1,9)$ eV. In general the layers of high porosity have the reduced electric conductivity that is why the Fermi level could be in the middle of E_g . The PSiL2 is about $(20 \div 25)$ μm of thickness. Deeper is located the non etched cSi with its own parameters σ , ϵ and E_g , but at the base of the contact again is additionally doped p^+ cSi layer having the conductivity σ^+ . Within the boundaries of PSiL2 and cSi, PSiL1 and PSiL2 there exist the potential barriers because of the differences of the width of the forbidden energy bands in the layer of PSiL2 and cSi. The attention has to be paid to the fact that the two barriers are directed towards opposite directions. That is why the energy band diagram of our samples satisfies the scheme of two oppositely connected isotypic barrier junctions. A similar scheme is widely used when explaining the characteristics of PSi two terminal structures. The essential difference of the scheme in comparison with the ones used in the known scientific works is that the role of the first diode usually is attributed to the contact of metal and PSi. In the samples investigated by us both are considered to be energetically symmetrical barriers due to quantum confinement effect and are located at the ends of PSiL2 layer.

4. Electrical properties of porous silicon structures

It presents the current-voltage (I-V) characteristics of all types of samples. The I-V characteristics of several samples of A-type are presented in Fig 6. I-V is considered nonlinear, asymmetrical, with the expressed rectifying effect. Such an I-V form is inherent for Schottky metal-semiconductor barrier, or for very asymmetric isotypic $p-p^+$ or $n-n^+$ junction, where the spatial charge area is

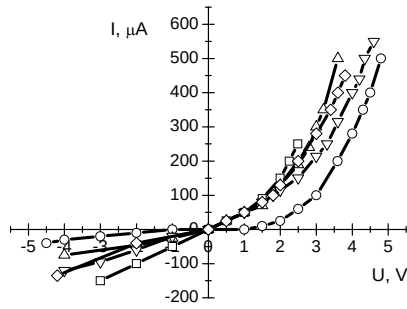


Fig 6. Current-voltage characteristics of A-type samples

working in the larger resistance semiconductor. However, the I-V form differs more or less from the characteristics of an ideal diode. This certainly is determined by the complicated PSi structure in the volume of the sample and on the surface. The potential barriers exist in the volume of the sample at the ends of PSiL2 region. On the surfaces of A-type samples Schottky type barriers at the contacts of Al/PSiL2 and Al/cSi possible. Taking

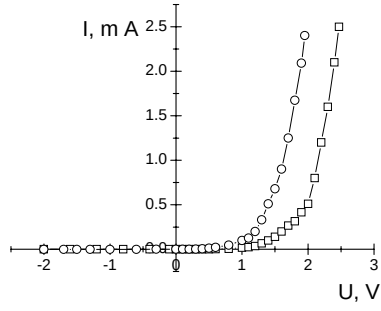


Fig 7. Current-voltage characteristics of B-type samples

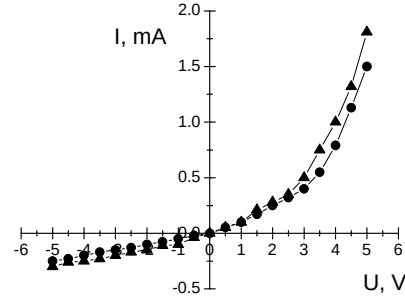


Fig 8. Current-voltage characteristics of B'-type samples

into consideration the morphology of PSi surface it is possible to consider that the Al layer of the upper contact site is in contact not only with PSiL1 layer, but also with PSiL2 layer. Then the spatial charge areas in PSiL1 region could be shunted by Al layer. There are also possible local strong field effects and nonlinearities determined by them. Taking into account these peculiarities it is very difficult to assess and analyse the shape of I-V characteristics of A-type samples. It also stimulates earlier chosen way of modification of the samples and method of consistent comparison in order to receive more transparent results.

B-type samples differed from A-type in such a way that in the bottom part of the plate there was p^+ layer, to improve the quality of the contact at the base. As the I-V characteristics (Fig 7) indicated, B-type samples are really more perfect than A-type samples. The I-V characteristics are asymmetrical as it was in the first case, but the rectifying effect in them is expressed more strongly. The shape of the forward part of the characteristics is more similar to the I-V characteristic of diode having a thin layer of PSi. They are described by means of the following expression:

$$I = I_0 \exp \left[\frac{e}{mkT} (V - IR_s) \right], \quad (1)$$

where the potential barrier is taken into account (it is included in the expression of electrical current I_0), V is voltage, e is an electron charge, m is the coefficient of ideality of a diode, k is Boltzman constant.

Similar characteristics were received when carrying out the research on the samples of B'-type series (Fig 8). The advance doping of PSiL1 pre-surface

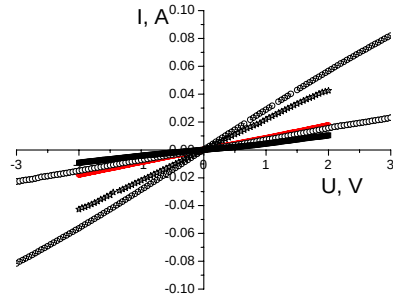


Fig 9. Current-voltage characteristics of C-type samples

region rather notably changes the I-V characteristics, reduces the effect of voltage rectification. It indicates that the rectification effect in B-type samples is determined not only by the volume of the structure, which remained the same in both cases, but also by the region at the upper contact of the structure, which in the structures of B'-type is doped highly. In the samples of B'-type there remains the barrier within the boundary of PSiL2 and

cSi and it determines the rectifying effect. The I-V measurements prove the model of PSi as diode structures (Fig 1 and Fig 5), where the barriers are set in the volume of the structure, in the interface of nanostructured layers with cSi or PSi layer, but without the effect of quantum confinement.

The samples of C-type series demonstrated different electrical characteristics. C-type samples were made by electrochemical forming of the layers PSiL1 and PSiL2 at first. Only then the operation of boron diffusion was performed. Their resistance was lower by several orders than the resistance of A-type and B-type samples. The I-V characteristics of C-type samples were linear (Fig 9). Nonlinearities that could be associated with the potential barriers in the close-to-contacts regions due to possible oxide layers or in the volume of the samples due to heteroenergetic junctions were not observed. Taking into account the linear current-voltage characteristics of C-type samples and their low resistance, the energy band diagram of C-type structures has to vary slightly from the scheme presented in Figure 5. The main difference could be as follows. The Fermi level has to be pinned in the regions of inter-layers due to local surface states, and the doped p^+ region holds on about $(100 \div 150) \mu\text{m}$ towards the base of cSi. However, as PL spectra indicate, the increase of E_g caused by quantum confinement effect in PSiL2 layer still remains in this type of the samples.

5. Investigation of porous silicon structures under the action of microwave radiation

There are presented the results of the research on the influence of MW radiation on the PSi structures. In the results of the influence of MW radiation on the PSi electric resistance are presented. The experiments demonstrated that under the action of MW radiation the resistance of the samples is reduced, and its change ΔR is negative (Fig 10). The dependence of ΔR on P is nonlinear.

It is relatively more expressed in the samples with lower resistance. The effect of microwave radiation in semiconductors is usually interpreted via the effects of charge carriers heating by MW electric field. The heating of charge carriers (increase of their energy) changes the processes of dissipation and has a direct influence on the mobility of charge carriers. Via the mobility the electric conductivity is influenced. It is usually considered that when charge carriers are heated under the effect of the electric field E , their mobility $\mu(E)$ satisfies the following expression:

$$\mu(E) = \mu_0 (1 + \beta E^2), \quad (2)$$

where μ_0 is the initial mobility, β is the coefficient of nonlinearity. The coefficient of nonlinearity depends on the mechanism of the dissipation of the charge carriers, and can be both negative and positive. That could be demonstrated in the summarized expression of mobility with the spread dependence on the energy of charge carriers:

$$\mu = \frac{e}{m^*} \tau_0 (T) (kT)^{\frac{1}{2}-r} E^{r-\frac{1}{2}}, \quad (3)$$

where r is the factor of dissipation; $r = 0$ for dissipation by acoustic phonons, $r = 2$ – for dissipation by impurities ions. The dissipation of charge carriers in semiconductors is integrated and is determined by the synchronic effect of several processes of dissipation. Thus the coefficient of nonlinearity under particular conditions and in advance is very hard to be determined accurately. In the case of weak heating is mostly $\beta < 0$. In accordance with this model we could expect the opposite effect than it is observed during the experiment. The dependence of conduction increase $\Delta\sigma$ on the pulse power is nonlinear (Fig 11; in our case $\Delta\sigma \approx \Delta R/R_0^2$), when according to the expression (2) the expected

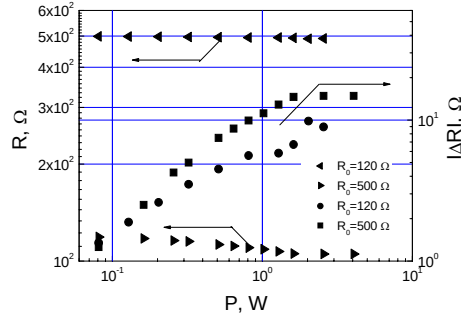


Fig 10. Dependence of the resistance R of PSi structures and the modulus ΔR of its change versus MW radiation pulse power P . R_0 – is the initial resistance of the samples

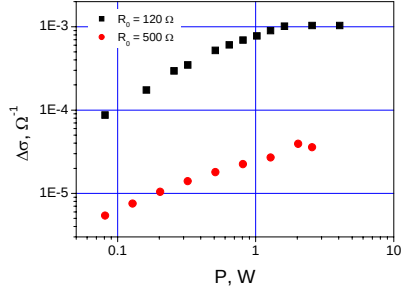


Fig 11. Dependence of the increase of PSi structures conductivity on the pulse power of MW radiation

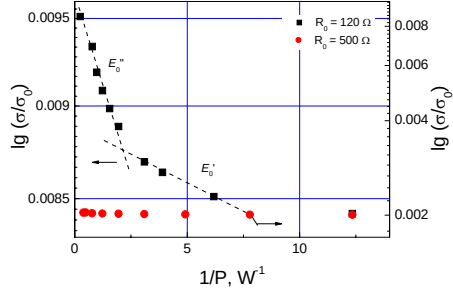


Fig 12. Dependence of PSi structures conductance on the reciprocal pulse power (semilogarithmic plot)

dependence has to be linear. The obtained results indicate that MW radiation rises (activates) the conduction of PSi layers. The percolation model of activated electric conduction very extensively describes the electrical properties of PSi. That is why it is wise to discuss the possibilities it has in the given case. According to the model the electric conduction in the layers of PSi is determined as a very complicated process of hopping conductivity in the vicinity of Fermi level in the net of fractal crystallites including spatial quantum effect. The following expression was obtained for the direct current electric conductivity:

$$\sigma = \sigma_0 \exp(-E_0 / kT), \quad (4)$$

where σ_0 is a complicated function of specific parameters of PSi. When stating that the temperature is proportional to the absorbed microwave energy $T \sim P\Delta t_{\text{imp}}$, the equation (4) could be transformed in the following way:

$$\sigma = \sigma_0 \exp(-E_0 / k'P), \quad (5)$$

where k' is a certain analogue of Boltzman constant proximately related to the temperature of holes T_h and to power P of the radiation pulse. In Figure 12 there is presented the dependence $\lg\sigma(P^{-1})$ for the sample with $R_0 = 120 \Omega$ and it could be approximated by two straight lines $\lg\sigma \sim P^{-1}$ with different slopes. It means that there have been clarified two different energies of activation E_0' and E_0'' . By increasing the power P of MW pulse the temperature T increases. Progressively the increased temperature activates the carriers to the higher

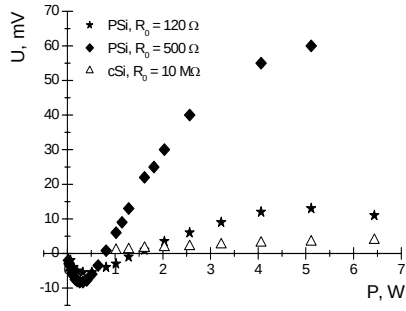


Fig 13. Electromotive force dependence on the power of microwave radiation pulse of C-type samples

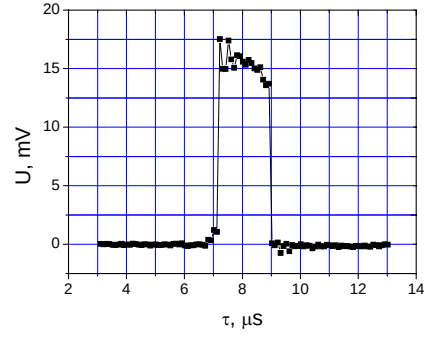


Fig 14. Electromotive force response in the C-type samples

activation energies, so we obtain $E_0'' > E_0'$.

There are presented the results of the research of electromotive force (EMF), induced under the action of pulses of MW radiation on to the PSi structures. The response of the EMF was observed in the samples of all four types and in control samples. To explain the appearance of the EMF in A-, B- and B'-type samples it is not enough to take into account only the potential barriers. By increasing the power of MW pulse the response amplitude is growing more suddenly than it is expected. That is why the interpretation of the experiment on these samples is complicated and ambiguous. More transparent conditions were achieved when C-type samples were manufactured, where the potential barriers were shunted by the surface states of doped PSi stem. In C-type samples the EMF signal appears at much lower MW pulse powers if compared with A-, B- and B'-type samples. However, at the lowest power the EMF response was negative, i.e. had sign opposite to that observed in the previous tests (Fig 13). The response repeated the form of MW pulse, namely it was fast (Fig 14). By increasing the pulse power the amplitude of EMF had a tendency to grow, reached the maximum, later decreased to zero and changed its sign. When the response sign changed, the analogous run of the amplitude was observed in the samples of A-, B- and B'-types. The EMF amplitude was by one – two orders higher than the amplitude in the control samples of monolith is silicon. There was demonstrated that the appearance of two responses of EMF with opposite signs can be explained by the scheme of two sources connected one in front another, taking into consideration the structure of C-type PSi samples. The inner structure of the formation is caused by the

above-mentioned three regions. The middle region PSiL2 is considered the place, where the effect of spatial quantum confinement is functioning, as well as the regions PSiL1 and cSi (Fig 5) located on both sides of it. Spatially the junctions of PSiL2 layer with PSiL1 and cSi are directed opposite to each other. It is indicated that PSiL1/PSiL2 and PSiL2/cSi boundaries differ from each other in several parameters (Fig 5). These differences determine the coherent order of the EMF appearance.

The application of the model of charge carrier heating by the MWs in the porous silicon is grounded by explaining the results of PSi electric conductivity and tests on EMF under the field of MW radiation. The quantum energy of the MW radiation is too low to induce any really possible quantum jumps in semiconductors. The energy of 10 GHz frequency radiation quantum is $E \approx 40\mu\text{eV}$. That is why MW radiation cannot generate carriers even from the shallowest impurity levels. Thus for PSi, as well as for cSi, the influence of MW field is manifested via the effects of charge carrier heating. The effects of hot charge carriers are easily separated from the thermal effects of the lattice with respect to the relaxation time. The observed practically non inert response to the MW radiation in the low resistance samples of C-type is a good reason approving that the observed phenomena are determined by the effects of hot

Table 1. Temperature changes of the samples at different MW powers

The pulse power, W	1	10	10^2	10^3
The pulse energy, J	$2 \cdot 10^{-6}$	$2 \cdot 10^{-5}$	$2 \cdot 10^{-4}$	$2 \cdot 10^{-3}$
ΔT_0 , °K	10^{-2}	10^{-1}	1	10

charge carriers. There was evaluated the possible heating of the sample within the interval of pulses power of the applied MW radiation. The temperature change ΔT_0 of the sample during the pulse was evaluated under adiabatic approximation. The carried out calculations indicate that due to short duration of the MW radiation pulse ($t_{\text{imp}} = 2 \mu\text{s}$) the pulse of power of 1 kW heats the sample not higher than by $\Delta T_0 = 10 \text{ }^\circ\text{K}$ (Table 1). That is comparatively small change of the lattice temperature to explain the increase of electric conductivity of 0,45 eV activation energy. Taking into account the ΔT_0 evaluations, experimentally observed results of the electric conductivity and the EMF, there is derived the conclusion that the observed phenomena are caused by the heating of holes under the action of MW radiation. Based on that, the temperature in the expression (4) is equalized to the temperature of hot holes $T_h = T_0 + \Delta T_h$.

Assuming the model of activation percolate conductivity within the fractal

net of PSi stem, based on the literature, the observed experiment was explained by the reduction of the resistance of PSi samples under the influence of MW radiation. Considering that the hole temperature is $T_h \sim P$, then we write the expression of PSi electric conductivity:

$$\sigma = \sigma_0 \exp(-E_i / kT_h), \quad (6)$$

where the temperature T_h of the holes is in the denominator of the exponent. Two activation energies $E_0'' > E_0'$ are established from the diagram $\lg \sigma(T_h^{-1})$ (Fig 15). When analysing the reason of appearance of the electromotive force it is assumed that for the hot charge carrier EMF there exist the same general initial expressions as for the ordinary thermo–electromotive force in semiconductors, just with hole temperature T_h instead of lattice temperature T_0 . The total electromotive force is written in the following:

$$U = \left(\frac{\partial U_\phi}{\partial T_h} + \frac{\partial U_d}{\partial T_h} \right) \Delta T_h, \quad (7)$$

where $\partial U_\phi / \partial T_h$ is the coefficient of thermo EMF due to the existence of possible potential barriers, and $\partial U_d / \partial T_h$ is the coefficient of thermo EMF due to the diffusion of hot and “cold” holes. The presence of temperature gradients is based on different MW pulse energy absorption within the ASi areas having different electrical properties. Since the I-V characteristics of C-type samples are linear, i.e. the potential barriers do not express themselves, the conclusion is derived that in the expression (7) $\partial U_\phi / \partial T_h = 0$, but $\partial U_d / \partial T_h \neq 0$. This means that pulse response of the EMF appears due to the different diffusion of hot and relatively cold holes. The heated holes “overpass” the “percolation threshold” (“mobility threshold”). They are released from the localized state and can participate in the diffusion transfer. Since MW radiation is unequally absorbed in different space areas of PSi structure, so

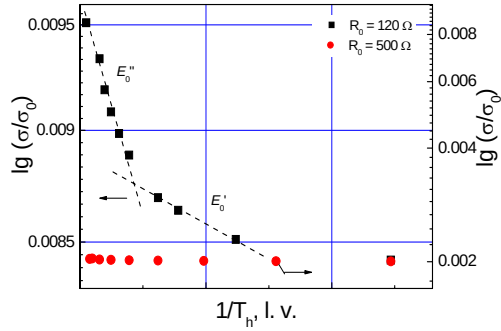


Fig 15. Dependence of PSi structures conductivity on the inverse temperature of holes $1/T_h$

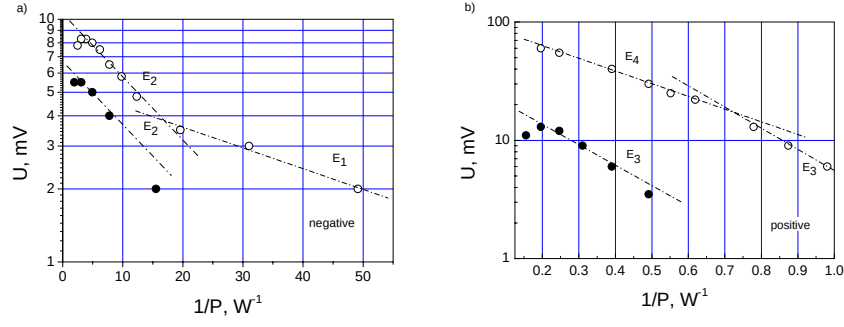


Fig 16. Dependence of electromotive force on reciprocal pulse power: a) – negative part of response, and b) – positive part of response

the areas with different temperature of the holes T_h are formed in the structure, and correspondingly the temperature gradients ∇T_h appear. Because of that the flows of the holes increase from the “hot” areas to the “cold” ones. The absence of hole flow balance causes pulsed response of hot hole EMF on to MW pulse. As in the case of electric conductivity the magnitude of the electromotive force depends on the number of holes that “overpass” the percolation threshold. Analogously to the expression (6) it is possible to write the following:

$$U \sim \exp\left(-\frac{E_i}{kT_h}\right). \quad (8)$$

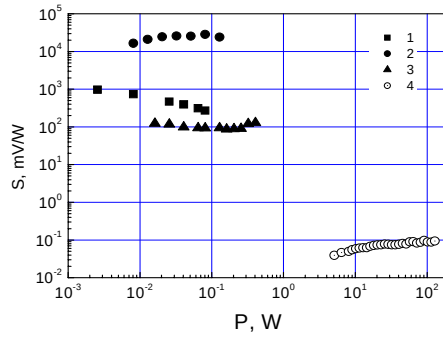


Fig 17. Sensitivity of sensors made from PSiL structures (1, 2, 3 – sensors with PSiL structures, 4 – control cSi sensors)

For the approval of the statement, the experimental data of the dependence of positive and negative response of EMF on the power of MW radiation pulse are presented in the semilogarithmic scale (Fig 16). As the temperature of holes is $T_h \sim P$, then the dependence presented in Figure 16 satisfies the formulae (8). The figure indicates that both the positive and negative response parts

reflect the activation type of EMF. The activation energies are E_1 , E_2 , E_3 and E_4 are identified. Energies E_2 and E_3 are observed in both samples. On the basis of analysis of the experimental results there is derived the conclusion that the EMF appearing in the structures of porous silicon of C-type is considered as the thermal electric EMF of hot charge carriers. The reason of its appearance is the increase of the holes temperature due to absorbed energy of MW radiation.

It is shown that on the base of nanostructures of porous silicon it is possible to manufacture MW sensors with sensitivity not lower than 100 mV/W (Fig 17). The voltage–power sensitivity of sensors with porous silicon structures is from 10^3 to 10^5 times higher than the sensitivity in cSi control samples. The range of their operation is shifted by two – three decades towards the side of lower power values of the MW radiation. The dynamic range of the operation of the sensors covers one – two decades.

General Conclusions

1. The results of morphological and photoluminescence tests showed that in the samples under investigation porous silicon was composed of two layers – one of lower porosity and another, which is in contact with crystalline silicon, of higher porosity.
2. Additional doping of porous silicon layers with boron significantly influenced the electric characteristics of the structure. The influence of the doping manifests itself by significant increase of electric conductivity of the porous silicon layer and by the linear current-voltage characteristics of heterogeneous porous and crystalline silicon samples.
3. Structures of porous silicon that are characterized by symmetrical current–voltage characteristics show activated transfer of the electric charge is associated with the heating of holes ensemble in the microwave electromagnetic field.
4. Microwave radiation induces electromotive force response in the structures of porous silicon, the parameters and the amplitude of which depend on the contexture of the structure and on the microwave pulse power.
5. The response of electromotive force in the porous silicon structures is caused by heating of holes ensemble under the action of microwave radiation.
6. The physical properties of porous silicon in the electromagnetic field of microwave radiation can be applied in developing of microwave radiation sensors.

List of Publications on the Topic of the Dissertation

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3. SHATKOVSKIS, E.; GRADAUSKAS, J.; STUPAKOVA, J.; ČESNYS, A.; SUŽIEDĖLIS, A. Effect of Microwave radiation on conductivity of porous silicon nanostructures, *Lithuanian J. Phys.*, 2007, Vol. 47, N. 2, p. 169–173. ISSN 1648–8504.

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6. STUPAKOVA, J.; GRADAUSKAS, J.; ŠATKOVSKIS, E. Akytojo silicio ir aliuminio darinių savybių tyrimas superaukšto dažnio elektriniame lauke. Iš 8-osios Lietuvos jaunųjų mokslininkų konferencijos „Lietuva be mokslo – Lietuva be ateities“ medžiagos, 2005, p. 103–106. ISBN 9986–05–853–8.
7. STUPAKOVA, J.; KOZIČ, A.; MANEIKIS, A.; ŠATKOVSKIS, E. Akytojo silicio sluoksnių sandaros ir morfologijos tyrimai. Iš 9-osios Lietuvos jaunųjų mokslininkų konferencijos „Mokslas – Lietuvos ateitis“ medžiagos, 2006, p. 135–138. ISBN 9986–05–989–5.

8. STUPAKOVA, J.; ŠATKOVSKIS, E.; GRADAUSKAS, J. Karštųjų krūvininkų atsakas į superaukšto dažnio spinduliuotės poveikį akytojo silicio nanodariniuose. Iš *10-osios Lietuvos jaunųjų mokslininkų konferencijos „Mokslas – Lietuvos ateitis“ medžiagos*, Vilnius: Technika, 2007, p. 139–147. ISBN 978–9955–28–136–8.

About the author

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AKYTOJO SILICIO NANODARINIŲ FIZINĖS SAVYBĖS, VEIKIANT SUPERAUKŠTO DAŽNIO ELEKTROMAGNETINE SPINDULIUOTE

Bendras disertacinio darbo apibūdinimas

Tiriamoji problema ir darbo aktualumas. Atradus akytąjį silicį (ASi) paaiškėjo, kad daugelyje sričių jo panaudojimas atveria naujas netikėtas galimybes. Viena galimybių panaudoti akytojo silicio gaminius mikrobangų technikoje tirama JAV. Tiriamas mikrobangų sklaidimas ASi sluoksniuose. Parodyta, kad radijo- ir optoelektroninės jungtys iš šios medžiagos yra mažų nuostolių ir tinka panaudojimui tobulinant mobilaus ryšio ir kitą superaukštų dažnių techniką. Sekantis po jungties elementas turėtų būti superaukšto dažnio spinduliuotės jutiklis. Patogiausiai būtų jį gaminti iš tos pačios medžiagos – akytojo silicio. Yra žinomi kristalinio silicio mikrobangų spinduliuotės detektoriai, kurių fizinis veikimo pagrindas – karštųjų krūvininkų efektai. Jutiklių jautris priklauso nuo tam tikrų jo dalių matmenų. Jautris didėja mažinant minėtus matmenis. Akytojo silicio technologija suteikia tą privalumą, kad ją pritaikius ASi kamieno charakteringieji matmenys gali būti sumažinami iki nanometrų dydžio. Pritaikius ASi gamybos technologiją jutikliuose, kuriuose pageidaujama kaip galima mažesnių tam tikrų matmenų, galima tikėtis žymiai padidinti tokių jutiklių jautrį. Papildomų privalumų galima laukti ir iš pasireiškiančio ASi erdvinio kvantinio ribojimo (pagavimo) efekto. Tam, kad galima būtų spręsti apie ASi darinių panaudojimo superaukšto dažnio (SAD) technikoje perspektyvą, aktualu ištirti ASi sluoksnių ir darinių fizines savybes, veikiant juos SAD spinduliuotės lauku. Nei superaukšto dažnio spinduliuotės

poveikis ASi savybėms, nei, tuo labiau, ASi SAD spinduliuotės jutikliai iki šiol nebuvo tiriama.

Darbo tikslas. Ištirti superaukšto dažnio elektromagnetinės spinduliuotės poveikį akytojo silicio nanodarinių elektrofizinėms savybėms ir įvertinti jų praktinio panaudojimo galimybę kuriant mikrobangų spinduliuotės jutiklius.

Darbo uždaviniai

1. Parinkti ir optimizuoti akytojo silicio darinių formavimo technologiją bei pagaminti bandinius, pritaikytus tyrimams superaukšto dažnio elektromagnetinės spinduliuotės lauke.
2. Atlikti akytojo silicio paviršiaus morfologinius bei jo sluoksnių kontrolinius fotoluminescencinius tyrimus.
3. Atlikti skirtingos sandaros nanokristalinio akytojo silicio darinių palyginamuosius elektrinio laidumo tyrimus ir įvertinti jų tinkamumą numatytam darbo tikslui pasiekti.
4. Ištirti mikrobangų spinduliuotės poveikį akytojo silicio dariniams ir atskleisti stebimų efektų fizinę prigimtį.
5. Įvertinti gautų tyrimo rezultatų praktinio panaudojimo galimybę.

Mokslinis naujumas

1. Pirmą kartą tirti akytojo ir kristalinio silicio heterogeniniai dariniai, pasižymintys simetrinėmis voltamperinėmis charakteristikomis, kuriuose į aktyvųjį sluoksnį difuzijos būdu įvesta akceptorinė boro priemaiša.
2. Pirmą kartą atlikti superaukšto dažnio spinduliuotės poveikio elektrocheminio ėsdinimo būdu pagaminto akytojo silicio dvipolių darinių savybėms tyrimai.
3. Parodyta, kad superaukšto dažnio spinduliuotė aktyvuoja akytojo silicio darinių elektrinį laidumą.
4. Parodyta, kad, veikiant akytojo silicio darinius mikrobangų spinduliuote, atsiranda elektrovara, kurios charakteris ir kiekybiniai parametrai priklauso nuo akytojo silicio darinio sandaros bei mikrobangų galios.
5. Pasiūlytas karštųjų krūvininkų modelio taikymas, aiškinant elektros laidumo padidėjimą ir elektrovarą, stebimus superaukšto dažnio elektromagnetiniame lauke.

Praktinė vertė. Gauti rezultatai gali būti panaudoti kuriant mikrobangų jutiklius. Išbandyti laboratoriniai jutiklių pavyzdžiai pasižymėjo nuo 10^3 iki 10^5 kartų didesniu jautriu negu analogiški kristalinio silicio bandiniai.

Ginamieji teiginiai

1. Akytojo silicio dariniuose galima mikrobangų spinduliuote aktyvuota elektros krūvio pernaša. Ji sietina su laisvųjų krūvininkų kaitimu superaukšto dažnio elektromagnetiniame lauke, esant stambiamasčiui potencialiniam barjerui.
2. Mikrobangų spinduliuotė akytojo silicio dariniuose sukelia elektrovarą, kurios priežastimi laikytinas krūvininkų kaitimas ir persiskirstymas superaukšto dažnio elektromagnetinio lauko poveikyje.
3. Atskleistos akytojo silicio savybės superaukšto dažnio spinduliuotės lauke gali būti panaudotos kuriant mikrobangų spinduliuotės jutiklius.

Rezultatų aprobavimas. Disertacijos tema paskelbtos 8 mokslinės publikacijos, iš jų 2 straipsniai žurnaluose su ISI Web of Science citavimo indeksu, 1 straipsnis žurnale ISI Master Journal List duomenų bazėje, 1 straipsnis tarptautinių konferencijų recenzuotų pranešimų leidinyje, referuotame MII duomenų bazėje (*ISI Proceedings*). Disertacijos rezultatai aptarti 5 tarptautinėse, 2 nacionalinėse ir 4 respublikinėse konferencijose. Išspausdintos 4 mokslinės publikacijos konferencijų pranešimų rinkiniuose.

Darbo apimtis ir struktūra. Disertaciją sudaro įvadas, 5 pagrindiniai skyriai, darbo išvados, nuorodos į 125 literatūros šaltinius, pateiktas 9 publikacijų disertacijos tema sąrašas. Iš viso 103 puslapiai teksto, 58 paveikslai ir 5 lentelės.

Pirmame skyriuje analizuojama literatūra apie akytojo silicio gamybos technologijas ir pagrindines akytojo silicio savybes. Antrame skyriuje aprašoma bandinių gamybos technologiją ir matavimų metodikos. Trečiame skyriuje aprašoma pagamintų akytojo silicio dvipolių darinių sluoksnių morfologija ir sandara. Pasiūlyta tokių bandinių energetinė diagrama. Ketvirtame skyriuje pateikti akytojo silicio dvipolių darinių elektrinių charakteristikų tyrimų rezultatai. Penktame skyriuje aprašyti elektros laidumo ir elektrovaros tyrimai veikiant akytąjį silicį superaukšto dažnio spinduliuotės impulsais.

Bendrosios disertacijos išvados

1. Akytas silicis tirtuose dariniuose, sprendžiant iš morfologinių ir fotoluminescencinių tyrimo rezultatų, susideda iš dviejų sluoksnių – mažesnio akytumo paviršinio ir didesnio akytumo sluoksnio, kontaktuojančio su kristaliniu siliciu. Akytojo silicio kamieną sudarančių elementų matmenys yra $(3\div 5)$ nanometrų ruože. Tirtų darinių juostinėse diagramose tarp šių sluoksnių galimi izotipinės heterogeninės sandūros būdingi potencialiniai barjerai.

2. Papildomas akytojo silicio sluoksnių legiravimas boru stipriai įtakoja darinio elektrinės savybės. Legiravimo poveikis pasireiškia žymiu akytojo silicio sluoksnio elektros laidumo padidėjimu, o heterogeninis akytojo ir kristalinio silicio darinys tiesinėmis voltamperinėmis charakteristikomis.
3. Akytojo silicio dariniuose, pasižyminčiuose simetrinėmis voltamperinėmis charakteristikomis, pasireiškia mikrobangų spinduliuotės aktyvuota elektros krūvio pernaša, sietina su skylių ansamblio kaitimu superaukšto dažnio elektromagnetiniame lauke.
4. Superaukšto dažnio elektromagnetinė spinduliuotė sukelia akytojo silicio dariniuose elektrovaros atsaką, kurio parametrai ir amplitudė priklauso nuo darinio sandaros ir mikrobangų impulso galios.
5. Elektrovaros atsako akytojo silicio dariniuose veikiant superaukšto dažnio elektromagnetine spinduliuote priežastis – skylių ansamblio kaitimas.
6. Akytojo silicio fizinės savybės superaukšto dažnio spinduliuotės elektromagnetiniame lauke gali būti panaudotos kuriant mikrobangų spinduliuotės jutiklius.

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**PHYSICAL PROPERTIES OF NANOPOROUS SILICON
STRUCTURES UNDER INFLUENCE OF MICROWAVE RADIATION**

Summary of Doctoral Dissertation

Physical Sciences, Physics (02P), Condensed Materials: electronic structure; electric, magnetic and optical properties; superconductors; magnetic resonance; relaxation; spectroscopy (P 260)

Jolanta Stupakova

**AKYTOJO SILICIO NANODARINIŲ FIZINĖS SAVYBĖS, VEIKIANT
SUPERAUKŠTO DAŽNIO ELEKTROMAGNETINE SPINDULIUOTE**

Daktaro disertacijos santrauka

Fiziniai mokslai, fizika (02P), kondensuotos medžiagos: elektroninė struktūra, elektrinės, magnetinės ir optinės savybės, superlaidininkai, magnetinis rezonansas, relaksacija, spektroskopija (P 260)

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