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EFFECT OF MICROWAVE RADIATION ON CONDUCTIVITY OF POROUS SILICON NANOSTRUCTURES *

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An attempt was made to find out the possible influence of microwave radiation on the conductivity of structures containing porous silicon layers. Samples have been made of boron doped p-type, (100) oriented, $\rho = 0.4\ \Omega\cdot$cm specific resistance silicon wafers by technology involving electrochemical etching in HF : ethanol = 1 : 2 electrolyte, and subsequent preparation of contacts. Two kinds of prepared samples have been characterized by nonlinear and linear current–voltage characteristics. Electric conductivity of the samples was investigated under the action of 10 GHz frequency microwave radiation. Activation nature of porous silicon conductivity was revealed. Model of hopping conductivity in the vicinity of Fermi level in the lattice of a porous silicon grid, considering the fractal character of porous silicon skeleton, has been applied to explain experimental results. Three activation energies were found: E_0', E_0'', and E_0''' ($E_0' < E_0'' < E_0'''$), caused by fractal character of a porous silicon grid. Activation of conductivity occurs because of charge carrier heating in porous silicon structure by microwave radiation.

Keywords: porous silicon, microwave, hot carriers

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1. Introduction

Silicon, the base material of microelectronics, the second element by its abundance in the Earth crust after oxygen, is easily accessible and a cheap semiconductor. It is no wonder therefore that the search for its qualitatively new forms like porous silicon (PSi) has made a splash in a number of works on the most versatile researches of properties and attempts for practical use. Significant Canham's work [1] made a push for research of PSi. The author has indicated for the first time that the occurrence of unusually intensive visible radiation in PSi can be due to the effect of dimensional quantization in the sponge-like system of quantum wires and clusters formed in the course of electrochemical etching of crystalline silicon (cSi). Soon this assumption has been confirmed in works [2, 3] and numerous subsequent researches. By present time a huge number of works devoted both to physical properties of PSi and to creation of devices on its basis is published. There are detailed reviews and monographs on these subjects [3–7]. However, there is a lack of works on interaction of porous silicon with microwave (MW) radiation. Investigations of dielectric characteristics of PSi in an electromagnetic field are the most advanced among similar ones. The basic stimulus of such researches is effective dielectric constant of porous silicon, which depends on degree of porosity and can be made much lower than dielectric constant of monolithic silicon (cSi) [7]. Besides, the resistance of PSi can increase by 5–10 orders at high value of porosity in a highly doped material [8, 9]. The latter two properties define small dielectric losses of MWs in PSi. Therefore, PSi is successfully used in a role of substrates for various MW devices, for creation of electroisolating layers and areas. Recently it has been shown that structures containing porous silicon can be used as sensitive elements for microwave radiation sensing without demanding any external bias [10]. Though these sensors work in an electromotive force (emf) mode, it is obvious; however, that MW radiation not only causes the rise of emf, but probably also changes other parameters of the structure, in particular, its electric resistance. As we know, these questions have not been

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discussed in the literature and still remain open. Action of MW radiation on physical properties of volume semiconductors is manifested through effects of heating of charge carriers, as a rule [11]. Detectors of MW radiation on the base of cSi are known to operate on this principle. They are successfully used to record MW radiation of high as well as of sufficiently low power [12, 13]. Bipolar barrier-less elements working on the basis of free carrier heating effect are worth noting [13]. They show high speed, high sensitivity, and linearity of voltage–power characteristic, and have an advantage of absence of a p–n junction area, which is potentially damaged by high power radiation. Specifics of technology of porous silicon gives additional possibilities to improve parameters of such elements. However, looking through plenty of works on the PSi bipolar structures we did not find the papers devoted to research of action of microwave radiation on such structures. Therefore in the given work we make an attempt to answer a question about possible influence of MW radiation on the conductivity of structures containing PSi layers.

2. Experimental

Boron-doped, p-type conductivity, (100) oriented cSi wafers of $\rho = 0.4$ Ω·cm resistivity and 0.35 mm thickness were used for preparation of PSi structures. Anode etching of initial plates was carried out in the teflon electrochemical cell with the platinum cathode. Mix of fluoric acid (48% HF) with ethanol (96% C_2H_5OH) in the ratio 1 : 2 was used as an electrolyte. Etching current has been applied in the form of a pulse-train with 5 seconds intervals to withdraw hydrogen formed during the reaction. The density of current during the etching cycle was 10 and 80 mA/cm^2, and duration of etching was 5 and 10 minutes, accordingly. The first, denser auxiliary porous silicon layer (PSiL1) has been formed at the surface in the beginning of the etching cycle. It was made for the evaporated contact metal to penetrate less into the pores at the subsequent vacuum evaporation of metal contacts and thus to avoid shunting of subsequent basic PSi layer. Estimated porosity of an auxiliary layer was about 55%. Basic porous layer PSiL2 was formed in the second phase of the cycle of etching. Estimated thickness of the basic layer was about six times the thickness of the auxiliary layer. Calculations of geometry and porosity of the layers were based on data depending on density of the dc current and duration of etching [14, 15]. Contacts were made by vacuum evaporation of aluminium

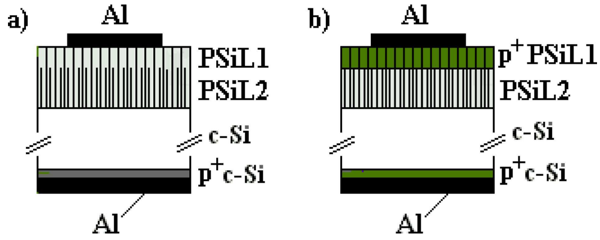

Fig. 1. Schematic drawing of porous silicon containing structures: (a) A-type, additionally boron-doped bottom, (b) B-type, boron-doped top and bottom.

and subsequent annealing at temperature of 450 °C in nitrogen atmosphere. Additionally doped p^+-layer was formed on the back surfaces of all plates to obtain ohmic not rectifying contacts (temperature 1100 °C in an extent of 1 hour). On the top surface of the porous silicon layer ohmic contacts were similarly produced, only in this case instead of continuous metal layer the aluminium contact platforms of 100 microns in diameter have been evaporated in vacuum through a mask. Two kinds of samples were fabricated. In the first case (A), the boron diffusion has been made only on the bottom of a plate. Contact platforms of aluminium were evaporated on PSiL1, which was not doped additionally (Fig. 1(a)). In the second case (B), boron diffusion has been made on both surfaces of a plate (Fig. 1(b)). The samples of size 0.5×0.6 mm^2 were cut out from the plates. Quality of the contacts was checked by measurement of resistance and current–voltage (I–V) characteristics. Measurements were carried out by universal measuring device "Agilent 4156C" or by characteriograph TR-4805. MW measurements were performed in the section of rectangular waveguide of $f = 10$ GHz frequency microwave radiation. The signal was taken from the basic contact of the sample, whereas the contact platform to PSi layer has been earthed [13]. MW radiation fell on the sample in the form of rectangular pulse with duration of 2 μs, repetition frequency of 40 Hz, and maximum power of 1 kW. The samples were connected in series with a loading resistor, and a bias of 5 V was applied to investigate the influence of microwave radiation on conductivity of PSi. From loading resistor the signal corresponding to change of conductivity of PSi structure was taken to oscilloscope "Agilent 5464-2A". Measurements have been carried out at room temperature.

3. Results and discussion

Investigations of I–V characteristics have shown basic difference between the A-type and B-type structures. I–V characteristics of the A-type structures

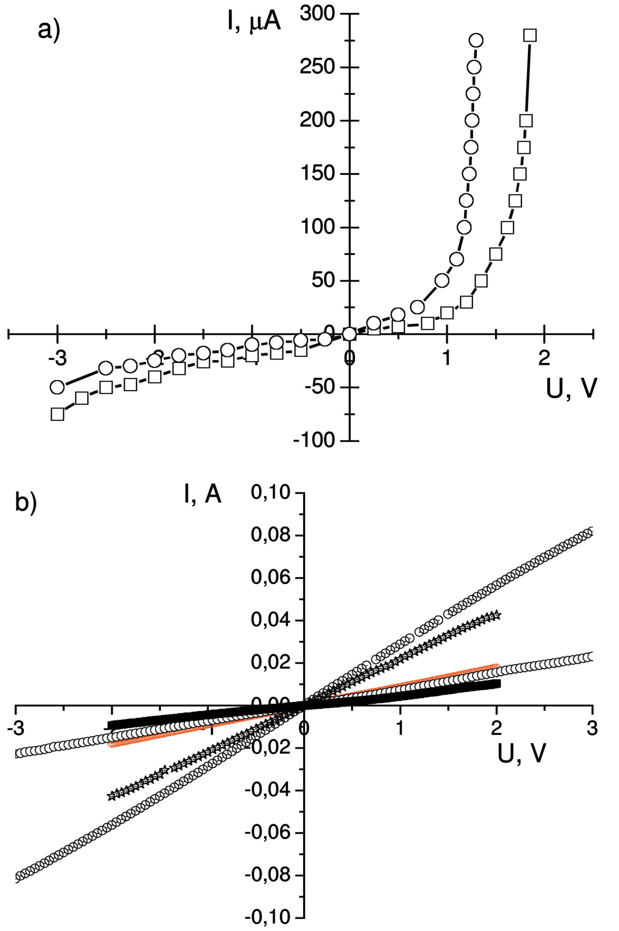

Fig. 2. Current–voltage characteristic of (a) *A*-type and (b) *B*-type structures.

are asymmetrical, with typically rectifying shape (Fig. 2(a)). Backward direction is realized when a positive potential is applied to the contact platform to porous silicon, and that coincides with picture observed in other papers [3–5]. Thus, I–V characteristics specify presence of a potential barrier (Schottky barrier on border Al // PSiL1, or heterojunction on borders PSiL1 // PSiL2 or PSiL2 // cSi) [3–5, 16, 17]. At forward bias (negative potential on a contact platform to PSi) the deviation from linearity and extreme current growth is observed at voltage higher than 1 V. The residual series resistance of the sample thus evaluated was hundreds of ohms. Such value agreed with numerical estimation carried out on the basis of technological parameters and taking into account the factor of porosity of PSi layers. The ideality factor m of the I–V characteristic found according to the expression for the nonideal diode $I \sim \exp(eU/mkT)$ (here e is charge of electron, U is external voltage, k is Boltzmann constant, T is absolute temperature), varied around 10, what is typical for aluminium // PSi structure contacts [4]. Unlike the samples considered above, the I–V characteristics of B-type structures were practically ideally linear (Fig. 2(b)). It meant that usual potential barriers did not reveal themselves neither on the borders of silicon–metal (Al // p^+PSiL1 and p^+cSi // Al borders) nor on two borders inside the structure (PSiL1 // PSiL2 and PSiL2 // cSi). The resistance of the structures to a dc current varied within 100–800 Ω. Assuming the thickness of PSi layer equal to 30 microns, we have estimated resistivity of the porous layer $\rho^* \sim 50$ Ω·cm. It is by two orders higher than the resistivity of the initial cSi material. Nevertheless, the increase in resistivity is lower than 5–8 orders specified for PSi in literature [8, 9]. We notice, however, that there the material of n-type was investigated and that the strong increase of resistivity was marked only for rather high-resistance material [8]. For low-resistivity material with $\rho \sim 0.01$ Ω·cm only the 1.2–1.7 times increase is marked in the same work. Thus, considering an intermediate value ρ of our initial material and taking into account different conductivity type, the observed moderate growth of PSi resistivity agrees with the data from literature. More surprising is the observed practically ideal linearity of the I–V characteristic. The essence is that while it is possible to explain the absence of potential barriers on external borders of the structures by the presence of highly doped p^+ areas, at the same time the absence of heterojunction on the borders of layers of different porosity PSiL1 // PSiL2 and PSiL2 // cSi is rather unexpected. It is especially surprising that these heterojunctions most likely are responsible for the rise of response in an emf mode [10]. We believe that despite the undertaken precaution that PSiL1 were denser and consequently less permeable both for boron during the doping operation and for aluminium during the evaporation of contact platforms, it appears insufficient for prevention of penetration of one or even both mentioned technological components deeply into the porous structure. Moreover, there are some works in which more intensive diffusion of doping elements is found in PSi compared to cSi, together with reduction of its activation energy [18, 19]. In the works specified, however, diffusion for the creation of p-n junction in PSi is carried out in other conditions. Therefore we cannot directly take advantage of the conclusions drawn there. At present it is possible only to state that the technological stage of additional doping of PSi creates not only highly doped auxiliary p^+PSiL1 layer, but also changes the properties of basic porous layer PSiL2. Linearity of I–V characteristics of B-type samples makes it convenient to investigate the action of MW radiation on PSi conductivity, in contrast to

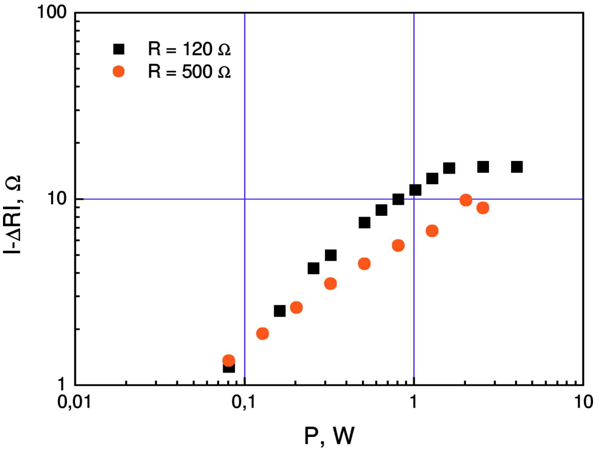

Fig. 3. Change of resistance of the PSi layer containing samples under the action of MW radiation pulse.

A-type samples where the presence of potential barriers complicates the analysis of conditions. Experimental results of measuring the influence of MW radiation on PSi resistance are presented in Fig. 3 for two *B*-type samples with resistivity R_0 of 120 and 500 Ω. Apparently the resistance of the samples decreases with MW power increase. Appreciable change in resistance (∼1%) is observed already at power value of ∼0.1 W. Dependence of the change of resistance ΔR is almost linear for both samples in the studied power range. It is a little weaker in one of them.

Usually the heating of charge carriers in semiconductors in strong electric fields affects their scattering and leads to a change of mobility μ. According to standard considerations, mobility of the charge carriers at heating by strong electric field E is $\mu = \mu_0(1 + \beta E^2)$, where the value of coefficient β is rather sensitive to many conditions and can be both negative and positive. β <0 in the range of weak heating [20]. So, following this model we should expect an opposite result to that observed in the experiment because we actually observe a reduction of the resistance of PSi structure at excitation by microwave pulses (Fig. 3). So, MW radiation activates conductivity in porous silicon.

Activation character of conductivity in PSi will be explained by the model offered and developed in [17]. According to it the carrier transport in porous silicon represents a complicated process of hopping conductivity in the vicinity of Fermi level in the lattice of PSi grid, considering the fractal character of PSi skeleton (model is somewhat similar to the Poole–Frenkel mechanism of conductivity). According to the model the dc conductivity of PSi

$$\sigma_{\mathrm{dc}} = \sigma_0 \exp\left(\frac{-E_0}{kT}\right). \tag{1}$$

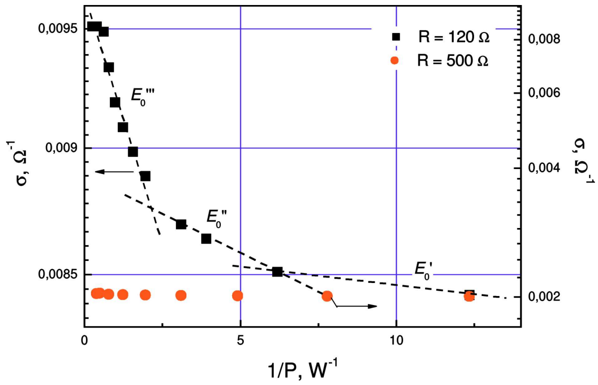

Fig. 4. Semilogarithmic dependence of conductivity of PSi structure on MW excitation power P. Symbols E_0', E_0'', and E_0''' denote adequate activation energies.

Here E_0 is activation energy; σ_0 is a multiplier with conductivity dimension as usual depending on density of states at Fermi level, on energy of activation E_0, on dielectric constant of material, and on several other specific factors [17]. In our case we have the temperature of charge carriers (holes) T_p instead of usual lattice temperature T. Introduction of T_p is rightful because the duration of microwave pulse exceeds characteristic times of the carrier energy and impulse relaxation in Si. Let us for simplicity use the adiabatic approach, that is we will assume $T_p \sim P$. Then, taking into account the mentioned reservations, on the basis of Eq. (1) we can write that in our case

$$\sigma_{\mathrm{dc}} = \sigma_0 \exp\left(\frac{-E_0}{k'P}\right), \tag{2}$$

where k' is some composite coefficient involving Boltzmann constant and coefficient of proportionality between T_p and P. According to common procedure for definition of activation energy, we have constructed the dependence $\Delta\sigma = f(P^{-1})$ in semilogarithmic scale, depicted in Fig. 4. Dependence $\ln\sigma \sim P^{-1}$ can be approximated well enough by straight lines with different slopes. For the first sample ($R_0 = 120$ Ω) the whole curve can be approximated by three straight lines, so we can distinquish three activation energies in the sample. We believe these are the activation energies of the area of PSi layer. As microwave pulse power P increases the temperature of holes grows. Accordingly, the energy of holes becomes sufficient to overcome the higher energy of activation, $E_0''' > E_0'' > E_0'$. One of the lines (of activation energy E_0') can be applied to extrapolate the dependence of the second sample with resistivity of $R_0 = 500$ Ω. However, activation energies E_0'' and E_0''' cannot be distinguished for this sample. We explained this fact by the presence of an additional ballast area in the second sample, which results in its higher resistivity. The applied MW electric field is divided in this sample between PSi layer and ballast area, whereas in the first sample the MW field is applied completely to PSi area.

In conclusion, the study of conductivity of the structures containing PSi layers reveals an activation nature in the change of conductivity under the influence of 10 GHz frequency microwave radiation. Three levels of activation energy $E_0' < E_0'' < E_0'''$ are distinguished. Activation of conductivity occurs due to charge carrier heating in PSi structure under MW radiation

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MIKROBANGĖS SPINDULIUOTĖS POVEIKIS AKYTOJO SILICIO NANODARINIŲ LAIDUMUI

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Santrauka

Atliktas pradinis bandymas siekiant išaiškinti galimą mikrobangų spinduliuotės poveikį akytojo silicio (ASi) elektriniam laidumui, pasireiškiantį dėl krūvininkų kaitimo. ASi bandiniams pagaminti panaudotos p tipo 0,4 Ω·cm specifinės varžos (100) plokštumos silicio plokštelės. ASi sluoksniai buvo gaminami elektrocheminio ėsdinimo HF : etanolis = (1 : 2) elektrolite būdu. Aliuminio kontaktai bandiniams pagaminti vakuuminio garinimo būdu, papildomai įterpiant boro priemaišų į paviršines sritis. Išmatuotos bandinių voltamperinės charakteristikos ir elektrinė varža. Vieni bandiniai pasižymėjo netiesinėmis, kiti – tiesinėmis voltamperinėmis charakteristikomis.

Atlikti bandinių su tiesinėmis voltamperinėmis charakteristikomis laidumo tyrimai, veikiant juos 10 GHz dažnio ir 2 μs trukmės spinduliuotės impulsais. Nustatyta, kad mikrobangų spinduliuotė mažina ASi darinių varžą. Parodyta, kad varžos pokytis atitinka aktyvacinį laidumo fraktaliniu ASi kamieno tinklu modelį. Nustatyta, kad yra trys skirtingi aktyvacijos energijos lygmenys $E_0' < E_0'' < E_0'''$. Konstatuota, kad akytojo silicio aktyvacinės kilmės elektrinis laidumas didėja dėl skylių kaitimo, veikiant mikrobangų spinduliuotei.