Lithuanian Journal of Physics, Vol. **51**, No. 2, pp. 143–146 (2011)

SENSITIVITY IMPROVEMENT IN POROUS SILICON MICROWAVE DETECTOR

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Received 13 March 2011; revised 19 April 2011; accepted 21 June 2011

Attempts to use microporous silicon structures in detection of microwave radiation were investigated. Point-contact-like samples containing microporous silicon layers were manufactured using traditional technique of electrochemical etching of p-type crystalline silicon. The response of the structures to microwave radiation of 10 GHz frequency was studied. It is shown that the microporous silicon containing samples exhibited sensitivity by several orders higher than that of similar detectors having no porous layers. The results were analysed within the model of hot carrier effects.

Keywords: porous silicon, microwave, detection, hot carriers

PACS: 61,43.Gt, 68.37.Hk, 72.30 +q

1. Introduction

Microporous silicon (μPSi) is a challenging material for nanotechnology which sometimes demonstrates unexpected properties and therefore opens a lot of new possibilities for a wide range of applications [1–3]. Unique sensor, photodetector, or other device can be manufactured by comparatively easy porous silicon (PSi) technology [1]. Still, applications of PSi in microwave technology are rather poor. It has been shown that losses of microwave power could be notably reduced if PSi were used in high frequency coplanar waveguides and interconnects [4, 5]. Interconnects produced of this material could be used to improve cellular phone communications as well as other high frequency technology. It is obvious that the next element following the connector has to be a sensor, and thus the most practical way would be to produce it of a porous silicon. In order to realize possibilities of application of PSi in microwave technology it is important to investigate physical properties of PSi layers and structures under the action of microwave radiation. The effect of microwave radiation on physical properties of μPSi structures has been studied recently [6, 7]. It was shown that μPSi containing structures exhibited electromotive force (emf) response with the shape and the sign of it depending on microwave radiation power as well as on the architecture of the device [6]. Influence of microwave radiation on electrical conductivity of μPSi was shown, too [7]. The study revealed activation-like nature of microwave conductivity in μPSi. It was suggested that the experimentally observed increase of conductivity and rise of electromotive force in μPSi structure could be explained assuming both the fractal character of μPSi skeleton and the concept of carrier heating by microwave radiation; quantum confinement effect should be also taken into consideration [8, 9].

Crystalline silicon (c-Si) microwave detectors operating due to effects of hot charge carriers are well known [10]. Sensitivity of these devices depends on the size of a point contact and, in general, higher sensitivity is achieved in detectors with lower contact dimensions [11].

The technology of porous silicon seems to have advantages since the specific dimensions of PSi stem can be reduced down to nanometre size. It is reasonable to expect significant increase of detector's sensitivity if PSi technology were introduced in its production. Additional advantages are expected due to the quantum confinement effect. In this paper we show that introduction of μPSi structures into a microwave detector leads to the enhancement of its sensitivity.

2. Experiment

Porous silicon layers were produced by a common electrochemical etching method. Single crystal p-type silicon plate of orientation (100) and resistivity of

ISSN 1648-8504

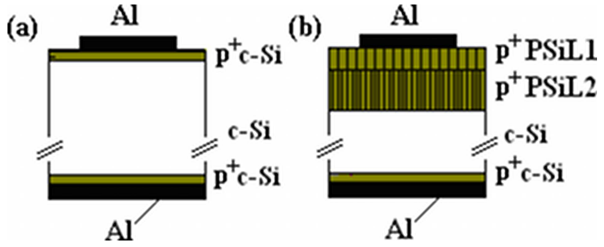

Fig. 1. Schematic drawings of two silicon structures with additionally boron-doped top and bottom: (a) crystalline silicon sample, (b) microporous silicon sample.

0.4 Ω cm was used for PSi formation. A mix of fluoric acid with ethanol in the ratio 1:2 was used as an electrolyte. The structure having two porous silicon layers, PSiL1 and PSiL2, was produced using operations and conditions presented below. Full cycle of etching (at room temperature) consisted of two phases: the density of anodic current was 10 and 80 mA/cm^2, and etching time was 5 and 5–10 min, respectively for each phase. Denser surface layer PSiL1 was formed in the first etching phase (Fig. 1(b)), in pursuance of getting the denser porous layer in the vicinity of metallic contact and thus improving the ohmic properties of the contact. Porosity of the 3–5 μm thick surface layer defined by the density of anodic current was estimated to be about 55% [12]. The basic layer of porous silicon PSiL2 was formed in the second phase of the etching process. Its thickness was about 5–20 μm and porosity reached 75% [1–3, 7]. The thickness of the basic PSiL2 layer was varied by choosing the etching time; thus resistance of the sample was controlled. For ohmic contacts, the surface of the plates was additionally boron-doped by ordinary boron diffusion followed by thermal evaporation of aluminium in vacuum and subsequent annealing at 450 °C temperature in nitrogen ambient. In contrast to the allover background contacts, round islands of aluminium of 100 μm in diameter were set for PSiL1. The samples of 0.5×0.6 mm^2 size were cut out of the plates. For comparison, the crystalline silicon (c-Si) sample without porous layers has been produced also following the same technological steps except the formation of porous layers (Fig. 1(a)).

Microwave measurements were carried out at 10 GHz frequency, with the samples placed in a narrowed Π-type waveguide. The microwave radiation was chopped into pulses of 2 μs duration at 40 Hz repetition rate to minimize thermal heating of the crystal lattice. The signal was taken from the bottom contact with respect to the grounded Al contact island on p$^+$-PSiL1 layer. The response signals were recorded and analysed by oscilloscope "Agilent 5464-2A".

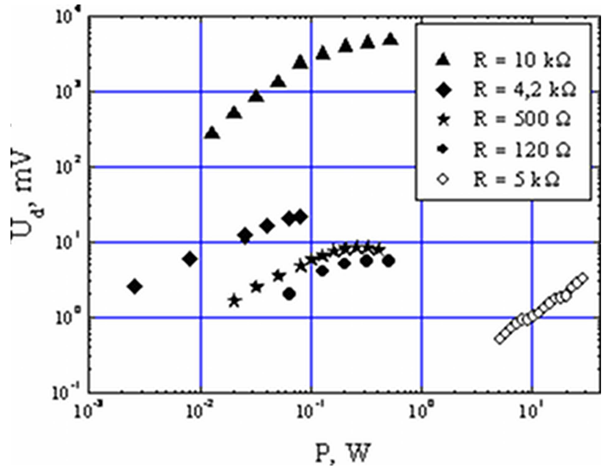

Fig. 2. Dependences of response amplitude on microwave power: open diamonds for c-Si device, other points for devices containing PSi layers.

3. Results and discussion

The structures demonstrated a rise of emf signal even at comparatively low values of applied microwave power. Experimental voltage–power dependences of μPSi containing devices with different resistance values are depicted in Fig. 2.

The emf signals increased non-monotonically with the microwave power. The highest emf value was exhibited by the sample of 10 kΩ resistance, while the lowest signal was detected across the sample of the lowest resistance (120 Ω). Characteristic pulse shape of the response followed the shape of the exciting microwave pulse, thus the time constant of the response was shorter than one microsecond.

The response of the reference crystalline sample is shown in Fig. 2 by open diamonds. It is seen that there the signal reaches the same value of amplitude as the emf across the μPSi devices at microwave power by about four orders higher in magnitude. Obviously, voltage sensitivity of the crystalline Si device to microwave radiation is much lower in comparison to that of μPSi containing device. The tendency of saturation of the response in all samples is evident at microwave pulse power near 1 W. It is caused by multiple structure of the sample, containing two different layers of porous silicon. The saturation is caused by another response signal emerging on the border of PSiL2 layer and c-Si, which is of opposite sign comparing to the response under study [8].

From the dependence of voltage sensitivity $S = U_\mathrm{d}/P$ of the samples on microwave power, shown in Fig. 3, it is seen that the sensitivity of μPSi containing

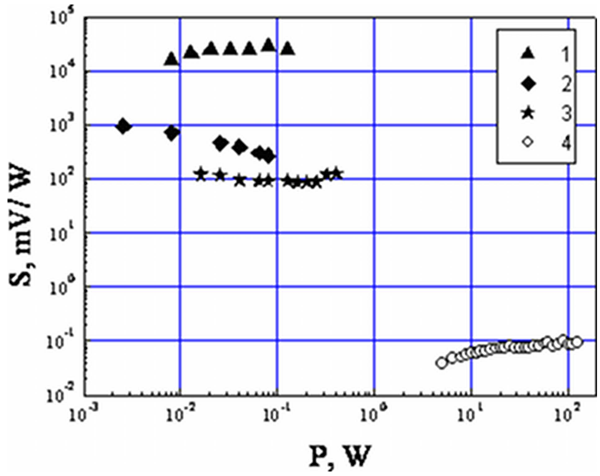

Fig. 3. Voltage sensitivity of the devices as a function of microwave power: *1*, *2*, *3* are μPSi containing samples; *4* is a reference c-Si sample. Sample resistance: *1* 10 kΩ, *2* 4.2 kΩ, *3* 500 Ω, *4* 5 kΩ.

samples is by three to five orders higher than that of the c-Si sample.

An emf signal across the c-Si sample appearing under the action of microwave radiation is a well-known phenomenon and is caused by hot carrier effect in semiconductors [10]. To explain the results, we assume similar concept of charge carrier heating effect in the samples containing μPSi layer. In addition, we consider a non-uniform architecture of the sample, which is crucial for the explanation of high values of voltage sensitivity of the devices.

Below we will compare the sensitivities to microwave radiation of both types of devices using the model of hot-carrier point-contact semiconductor detector. Quantum confinement effect is absent in PSiL1 layer due to its lower porosity, i. e. higher cross-sectional dimensions of the silicon stem, compared to those of the PSiL2. As photoluminescence investigations have shown, the forbidden energy gap of PSiL2 layer lies in the range of 1.6–1.9 eV, i. e. is wider than that of c-Si because of quantum confinement effect [6–9]. The quantum confinement effect which is present in a stem of the PSiL2 layer indicates that the cross-section of the stem should be in the range of few nanometres [1, 2]. Consequently, we have the dimensionally non-uniform junction on the border of PSiL2 and bulk silicon layers and thus the point-contact-like area in the interface between PSiL2 and c-Si layers is of nanometre value. Moreover, since the cross-section dimensions of a single PSiL1 stem are also much larger than the stem cross-section dimensions of a microporous PSiL2 layer, we have the non-uniform heterojunction on the border of PSiL1 and PSiL2 layer as well. The high sensitivity response of the detector to the microwave radiation originates just from this last junction, as follows from analyses of the sign of the response [8]. The spatial non-uniformities cause non-uniform distribution of the microwave electric field across the sample, and, as a result, lead to non-uniform absorption of microwave energy and therefore to non-uniform heating of charge carriers within the sample. On the other hand, the top Al contact island on the reference crystal Si is of 50 μm in radius (see Fig. 1(a)), so it causes much lower response to microwave radiation.

The following expression holds for the sensitivity of hot-carrier point-contact semiconductor detector [11]:

$$S \sim F(s,p)\,\frac{\tau_\varepsilon}{3\pi n_0 r^3}\,, \tag{1}$$

where $F(s,p)$ is a function of scattering parameters s and p, τ_ε, and n_0 are energy relaxation time and density of charge carriers, respectively, r is a radius of a point contact [11]. Assumption that the contact radius is changed from tens of micrometres to few nanometres results in billion-time enhancement of sensitivity of the point-contact detector. Obviously, the expression (1) gives an overestimated increase of sensitivity according to this model since it contradicts the experimental results. However, due to statistical scattering in the dimensions of the point contacts in the border of PSiL1 and PSiL2 layers, we rate the above estimation to be only of a qualitative character. Another model that makes it possible to evaluate and to compare the sensitivities of the μPSi containing sample and that of c-Si reference is a model of planar non-uniformly narrowed semiconductor microwave detector [13]. According to this model, the voltage sensitivity is

$$S = \frac{U_\mathrm{d}}{P} = \frac{F'(\rho,\mu_0,\ldots)}{d^2\,\ln(1+a/d)}\,, \tag{2}$$

where $F'(\rho,\mu_0,\ldots)$ is a function of resistivity ρ, mobility of charge carriers μ_0, and other semiconductor and layer parameters, a and d are dimensions of the widest and the narrowest parts of the non-uniformity. Considering such a non-uniformily narrowed structure, there is only a square dependence of the sensitivity on the dimensions of a non-homogeneity. According to Eq. (2), we estimate only about a million-fold increase of the sensitivity of the μPSi containing device with respect to the reference c-Si sample. This quantity is closer to the maximum difference experimentally found in our investigations.

The difference in the response values between the different μPSi containing samples may be attributed to the result of statistical scattering in etching conditions as well. Both above-considered models are qualitatively supported by the dependence of the response magnitude of different samples on their resistance (see Fig. 2): higher values of emf are detected across the samples of higher resistance, i. e. the lower dimensions of the PSiL2 stem cause higher level non-uniformity what in turn causes higher sensitivity of the device. In addition, the saturation of the response values is attributed to the decrease of carrier mobility and energy relaxation time in silicon at high values of microwave electric field [14]. As for conclusion, we have shown that implementation of microporous silicon in the architecture of a microwave detector device can raise its sensitivity by several orders of magnitude.

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JAUTRIO GERINIMAS AKYTOJO SILICIO MIKROBANGŲ DETEKTORIUJE

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Santrauka

Tirtos mikrobangų spinduliuotės detektavimo galimybės naudojant mikroakytojo silicio (μASi) darinius. Gamybai naudotos p tipo 0,4 Ω cm specifinės varžos (100) plokštumos kristalinio silicio plokštelės. μASi sluoksniai pagaminti elektrocheminio ėsdinimo būdu naudojant HF ir etanolio (1:2) elektrolito tirpalą. Garinant vakuume, pagaminti aliuminio kontaktai, papildomai prieš tai difuzijos būdu į paviršines sritis įterpiant boro priemaišų. Atlikti bandinių, veikiant juos 10 GHz dažnio ir 2 μs trukmės mikrobangų spinduliuotės impulsais, eksperimentiniai tyrimai.

Eksperimentai parodė, kad μASi dariniuose elektrovara atsiranda esant nuo dviejų iki trijų eilių mažesnėms spinduliuotės galioms, palyginti su kristalinio silicio dariniais. Nustatyta, kad nanodarinių su mikroakytuoju siliciu voltvatinis jautris yra nuo 10^3 iki 10^5 kartų didesnis už tokios pat sandaros kristalinio silicio darinių jautrį. Kokybiniam rezultatų aiškinimui pasitelkti karštųjų krūvininkų reiškinių pagrindu veikiančių detektorių modeliai: taškinio kontakto modelis ir nevienalytiškai susiaurinto darinio modelis. Gauti rezultatai rodo mikroakytojo silicio darinių perspektyvumą mikrobangų jutikliuose.