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Avalanche multiplication of charge carriers in nanostructured porous silicon

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Abstract. The phenomenon of avalanche multiplication of charge carriers in Al/PS-(c-Si) sandwich-structures based on nanostructured porous silicon (PS) is studied. Experimentally received dependences of ionization rates on intensity of an electrical field correspond to the diffusion mechanism of electron-hole pairs heating up to a threshold of ionization. The distinction of effective factors of shock ionization for electrons and holes is unsignificant. The estimation of length of free run of hot electrons is carried out at scattering of energy on the optical phonons.

Keywords: porous silicon, heterojunction, avalanche multiplication.

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1. Introduction

Obtaining of porous silicon (PS) and research of its physical properties as a new morphological form of monocrystalline silicon (c-Si) is of interest in connection with the presence of intensive electro- and photoluminescence in the visible spectral range [1–6]. The area of practical use of porous silicon in the optoelectronics constantly enlarges. Photodetectors [7], light oscillators, gas and biological sensors [8] can be created on its base.

Nanostructured porous silicon was received on bulk Si wafers by the method of anodic electrochemical etching in hydrofluoric acid solutions [9]. It has been shown, that selection of anodization times and anodic current density allows to change a peak position of the PL spectrum of porous silicon in the range from 580 to 780 nm. The variations of the specified parameters also strongly influenced PL quantum output. The specified PL properties of porous silicon are connected with quantum size effects, i.e. with change of the band diagram and widening of effective band gap [1]. In this paper, the phenomenon of avalanche multiplication of charge carriers in Al/PS-(c-Si) sandwich-structures based on nanostructured porous silicon is studied.

2. Experimental

Porous silicon samples were prepared by electrochemical etching of Si substrates with [111] orientation and 10 Ω·cm resistivity in HF-ethanol solution (HF (49 %):C_2H_5OH - 1:1). Anodization was carried out at room temperature. Anodization current density was varying from 5 to 40 mA/cm^2. The time of etching changed from several minutes to one hour. The received samples were maintained in open air during one week for stabilization of the created porous layers. The influence of anodization parameters on the PL spectra of the obtained porous samples was studied at excitation by UV nitrogen laser ($\lambda =$ $= 337$ nm, pulse duration $\tau = 10$ ns, frequency $f = 50$ Hz, average power 3 mW). After that the PS samples were installed into the vacuum chamber, and aluminum films were evaporated onto the PS layers for preparation of the Al/PS-(c-Si) sandwich-structures. The area of aluminum contacts was ~ 4 mm^2.

Measurements of the current-voltage characteristics (CVC) of dark current and photocurrent, and also spectral distributions of photocurrent and photo-EMF were carried out in the special holder at cross geometry of sample illumination (Fig. 1a).

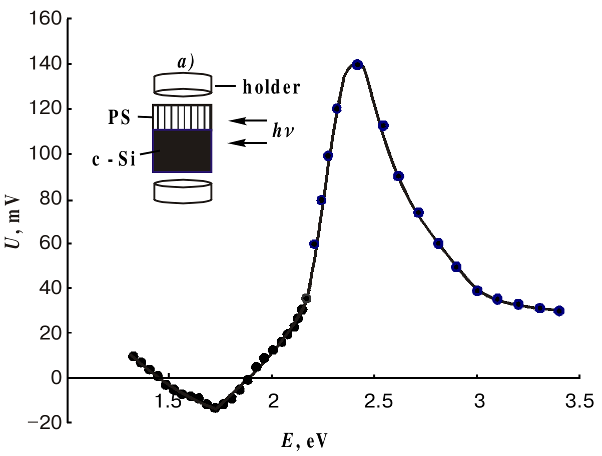

Fig. 1. The photo-EMF spectrum of the Al/PS-(c-Si)/Al sandwich-structure. a) A scheme of the sample investigated.

3. Results and discussion

Electrical and photoelectrical properties of the Al/PS-(c-Si) sandwich-structures on c-Si substrates were investigated. Experimentally received dependences of structure capacity on the enclosed constant bias and thickness of the PS layer at frequency 1 MHz well be coordinated with predicted if to take into account, that the structure capacity includes two series capacities – geometrical capacity of a PS layer and capacity of a potential barrier on PS-(c-Si) heterojunction [10]. The reason of weak change of capacity from the applied bias in thick PS layers ($d > 10$ µm) is connected with the formation of transitive ʜ-layer between PS and c-Si during anodic etching of silicon. Spectral distribution of the photocurrent looks like a wide strip in an interval of photon energy from 1.3 to 3.2 eV. Nonequilibrium charge carriers are generated in PS. The PS layer behaves as a wide-band semiconductor sensitive to the visible light (Fig. 2). Effective width of the band gap in the vicinity of heterojunction determined by the photoelectrical method [10], was 2.52 eV. The inversion of sign of photo-EMF is found out.

Fig. 1 shows the photo-EMF spectrum of a PS sample. Photo-EMF changes its sign in the area of photon energies about 2.5 eV. Hence, at the photon energies more than 2.5 eV potential of c-Si-(ν-layer) is higher than potential of PS-ʜ barrier, which is situated inside a porous layer. At the energies of incident photons less than 2.5 eV the porous layer gets a negative potential. The observable polarity of photo-EMF can be explained by the asymmetry of junctions as a result of porosity gradient of the received samples [12].

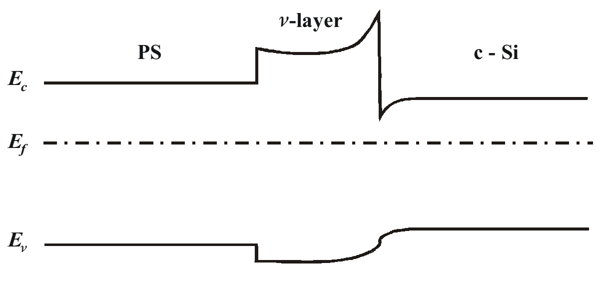

Fig. 2. The band diagram of PS–ν–(c-Si) structure.

In Al/PS-ν-(c-Si) sandwich-structures on a direct branch of current-voltage characteristics sharp increase of the current was observed (Fig. 3). The downturn of temperature results in reduction of a breakdown voltage. Avalanche multiplication of photocurrent and recombination radiation take place at the achievement of the breakdown voltage, proving the generation of nondominant charge carriers. These phenomena confirm an avalanche character of the breakdown in the given structures.

In prebreakdown regime the current-voltage characteristic (Fig. 3) look like

$$I = I_0(T)e^{\alpha U},$$

where α change a little in the interval of temperatures 77–300 K. Magnitude of I_0 also poorly depends on a temperature. Current-voltage characteristics of such sort are appropriate for the currents connected with tunneling through a potential barrier. It is possible to explain observable CVC of the structures in the prebreakdown regime taking into a count the break of C-zone between PS and ν-layer The potential barrier (0.2–0.6 eV for our structures) arising as a result of the break of zones is overcome by tunneling at 4–12 V (Fig. 3). Density of the tunnel current through a barrier

$$j = j_0 e^{\alpha/E_0},$$

where $\alpha = \dfrac{4\sqrt{m^*}}{3e\hbar}\varphi_0{}^{1/2}$, φ_0 – magnitude of break of C-zone, E_0 – average intensity of field in the area of tunneling. If the voltage applied to the highresistance layer, $U >> \varphi_0$, the field in the area of tunneling might be considered homogeneous.

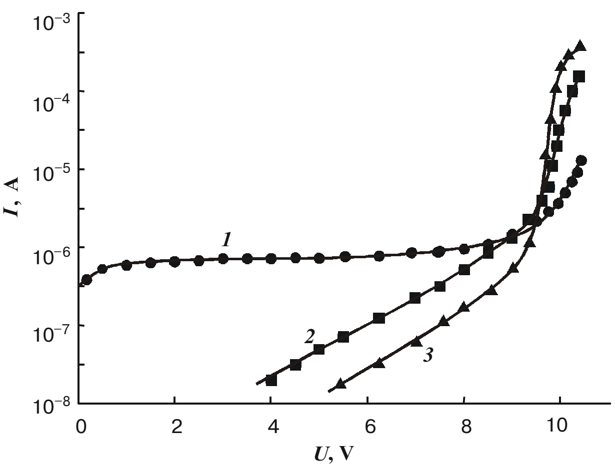

Fig. 3. Current-voltage characteristic of the porous silicon sample; *1* – photocurrent, *2,3* – dark current at temperatures: *2* – 300 K, *3* – 77 K.

Taking into account that the multiplication begins by electrons the factor of multiplication looks like[13]

$$M = \frac{1}{1 - \alpha_m L_{eff}},$$

where α_m – maximal magnitude of ionization rates in the given structure. L_{eff} is equal to thickness ν-layer at homogeneous distribution of the field.

Factor of multiplication by electrons M_n is determined as the ratio of dark current at the given bias to the magnitude of tunnel current by extrapolation of the exponential site at a low voltage to the voltage area with avalanche multiplication.

Fig. 4 shows the dependences of factors of shock ionization of charge carriers on the intensity of an electrical field received by the analysis CVC of the dark current (curve 1) and photocurrent (curve 2) are submitted. The given dependences were received at the rate of $\alpha(E)$ and comparison of the theories of shock ionization in semiconductors [13]. The lining of the appropriate curve in the given semiconductor and in the given area of intensity of fields testifies to the applicability of the diffusion and drift theory in the dark condition unlike in *p-n* junction only the electrons are injected into the area of multiplication. At illumination by quantums from the area of own absorption of porous silicon the multiplication is initiated by the electrons, born in the high-resistance ν-layer with thickness L and holes, generated in a layer $L + L_p$, where L_p – diffusion length of holes in porous silicon, and $L_p > L$. Therefore it is possible to investigate separately dependences of ionization rates of electrons and holes on intensity of a field, temperature and other external conditions in the same structures at small magnitudes of multiplication factor. As it is seen from Fig. 4, the distinction of magnitude of the effective multiplication factors is insignificant, and $\alpha_n > \alpha_p$.

The multiplication of charge carriers begins when the accelerated carrier gets energy in the field of junction on the way, which length depends on a kind of the energy dispersion. In the Al/PS-ν-(c-Si) structures with various width of high-resistance ν-layer, the certain threshold energy of formation of hole-electron pairs hot electrons was E_i = (2.4±0.1 eV).

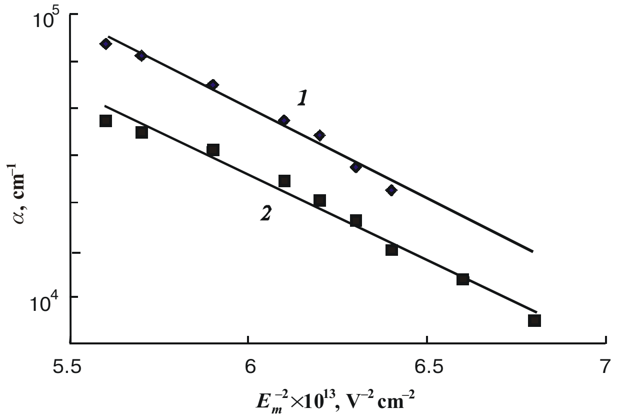

Fig. 4. Dependences of ionization rate on intensity of an electrical field: *1* – for electrons, *2* – for holes.

Kind of the equation $\alpha(E)$ submitted on Fig. 4 testifies to the diffusion mechanism of hole-electron pairs heating up to the threshold of ionization, which allows to determine the length of hot electrons free run at the dispersion on the optical phonons under the formula [14]

$$\alpha(E) = C\frac{E_0}{E}\exp\left[-\left(\frac{E_0}{E}\right)^2\right],$$

where C – constant, E_0 – characteristic field, which is equal to

$$E_0 = \left(\frac{3E_p E_i}{4e^2 C_T l_i^2}\right)^{1/2},$$

where l_i – length of free run, $C_T = cth\left(\frac{E_p}{2kT}\right)$ and E_p – energy of optical phonon. Hence, having accepted E_p = 0.063 eV and E_i = 2.4 eV we have obtained l_i = 50 Å.

In the investigated structures the experimental magnitudes of the breakdown voltage grew at the increase of ν-layer thickness. However, in samples with the large break of C-zone avalanche multiplication begins at the magnitudes of current some orders smaller than in the samples with small magnitude of φ_0.

4. Conclusions

The Al/PS-ν-(c-Si) structures are an interesting object for experimental and theoretical research of the processes of shock ionization in PS. In the dark condition unlike in p-n junction in the area of multiplication only electrons are injected. At the illumination by quantums of light from the area of own absorption of porous silicon the multiplication is initiated by electrons and holes. Therefore it is possible to investigate separately the influence of various factors on the magnitudes of ionization rates of electrons and holes in the given structures.

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