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Photovoltage formation across Si p-n junction exposed to laser radiation

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Photovoltage formation across Si p-n junction exposed to laser radiation is experimentally investigated. Illumination of the junction with 1.06 µm wavelength laser radiation leads to formation of classical photovoltage U_{ph} due to intense electron-hole pair generation. When the photon energy is lower than the semiconductor forbidden energy gap, the photovoltage U is found to consist of two components, $U = U_f + U_{ph}$. The first U_f is a fast one having polarity of thermoelectromotive force of hot carriers. The second U_{ph} is classical photovoltage with polarity opposite to U_f. It is found that U_f is linearly dependent on laser intensity. The classical photovoltage is established to decrease with the rise of radiation wavelength due to decrease in two-photon absorption coefficient with wavelength. Predominance of each separate component in the formation of the net photovoltage depends on both laser wavelength and intensity.

Keywords: *silicon; laser radiation; p-n junction; solar cell; hot carriers*

1. Introduction

Electric energy generated by solar cells (SC) is a most promising and environmentally friendly energy source. However, the SC generated electricity is currently significantly more expensive than the electricity acquired by traditional methods due to high price of solar cells. At present time, about 80 % of worldwide SC are made from silicon. The efficiency of a one-junction silicon solar cell produced in a scientific laboratory reaches 25.6 % and is close to the theoretical limit of 33.3 % [1]. Solar cell efficiency is limited by the efficient use of only photons having energy close to the forbidden energy gap. Photons with higher energies create electron-hole pairs, but the excess energy is transmitted to the carriers which then become hot carriers. In an ideal single junction solar cell 55 % of incident solar radiation is lost due to the thermalization of hot carriers with lattice [2]. Ross et al. [3] proposed the idea of hot carrier solar energy convertors in which photoexcited carriers should be extracted over a narrow range of energies at a rate faster than they lose energy to the lattice. Theoretical efficiency of such device can be sufficiently high, up to 66 %. Lately, large number of theoretical and experimental works have been carried out in developing hot carrier solar cells [4–6] as it was theoretically shown that maximum efficiency of such devices can reach 85 % [4]. However, no hot carrier solar cell valuable for practical applications has been built yet. Nevertheless, hot carriers must be taken into account during the study of photovoltage formation across a p-n junction under the sunlight illumination.

In this paper, we present the results of experimental investigation of hot carriers influence on the photoresponse formation across Si p-n junction illuminated by laser radiation of different wavelength.

2. Experimental

The investigated p-n junction was produced by chemical vapor deposition of epitaxial p-type Si on n-type Si substrate. Electron density was

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7×10^{15} cm^{-3}, and respective hole density was 5×10^{16} cm^{-3}. Ohmic contact to p-Si was formed by boron diffusion into a thin p^+-layer at 950 °C temperature giving hole density of 8×10^{19} cm^{-3}, and subsequent thermal deposition of aluminium at a temperature of 300 °C and annealig at 560 °C in Ar atmosphere for 1 minute. The p-n junction was illuminated from the epitaxial layer side through the square window etched in the p^+-layer (Fig. 1). In the experiments, the Nd:YAG laser with 1.06 μm wavelength and 25 ns pulse duration was used. $LiNbO_3$ nonlinear crystal was used to shift the radiation wavelength. To increase the excitation intensity, the laser beam was focused on the sample surface, and thus maximum pulse power intensity was about 1 MW/cm^2. Temporal behavior of the photovoltage and laser pulse in the nanosecond time scale was recorded by digital storage oscilloscope Instek GDS-2202. All the measurements were carried out at room temperature.

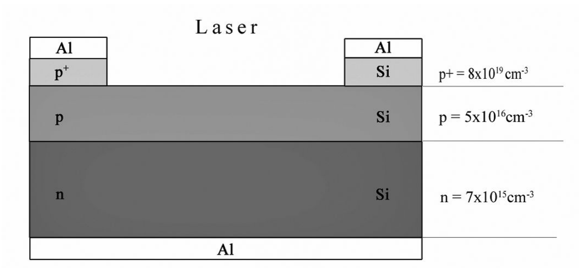

Fig. 1. Si sample structure (not to scale).

3. Results and discussion

The spectral dependence of short circuit photocurrent is depicted in Fig. 2. It is seen that the photocurrent has maximum at λ = 940 nm, and a cutoff wavelength is 1180 nm for the case of low light intensity. Illumination of Si p-n junction with 1.06 μm laser radiation leads to intense electron-hole pair generation. In this case, the classical photovoltage U_{ph} can be observed across the junction. The situation changes essentially with the wavelength increase.

Temporal profile of the photovoltage across Si p-n junction induced by 1.489 μm laser radiation

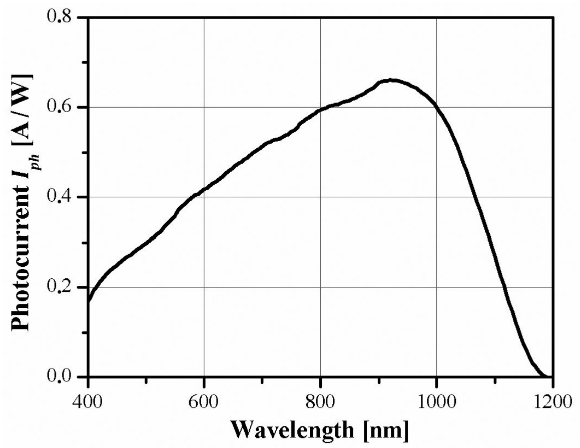

Fig. 2. Spectral dependence of short-circuit photocurrent through Si p-n junction at low light intensities.

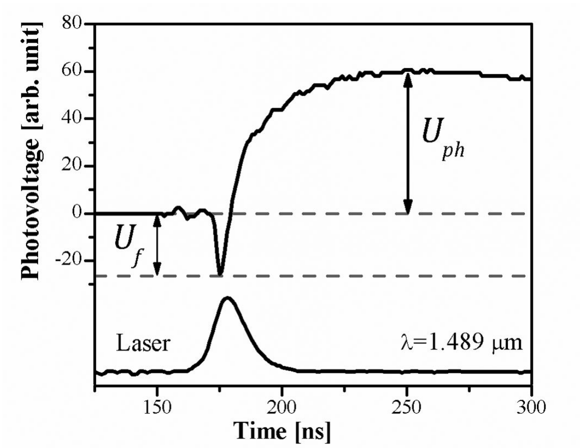

Fig. 3. Oscilloscope traces of laser pulse (bottom) and photovoltage (top) consisting of two components.

is presented in Fig. 3. The observed photovoltage U now consists of two components:

$$U = U_f + U_{ph} \quad (1)$$

where U_f is the fast component with polarity corresponding to that of thermoelectromotive force of hot carriers [7], and U_{ph} is the slow component of opposite polarity, which is classical photovoltage caused by electron-hole pair generation. It is necessary to note that, similar to the GaAs case [8], the thermoelectromotive force of hot carriers across Si p-n junction is a dominant component of the photovoltage at low excitation level, and at higher laser intensities U_{ph} prevails in the formation of the photovoltage. Moreover, investigations revealed that U_{ph} increases with the intensity of laser radiation following the square law (see Fig. 4). This fact indicates that the electron-hole pair generation is determined by the two-photon absorption since the single laser photon energy is lower than the forbidden energy gap of silicon.

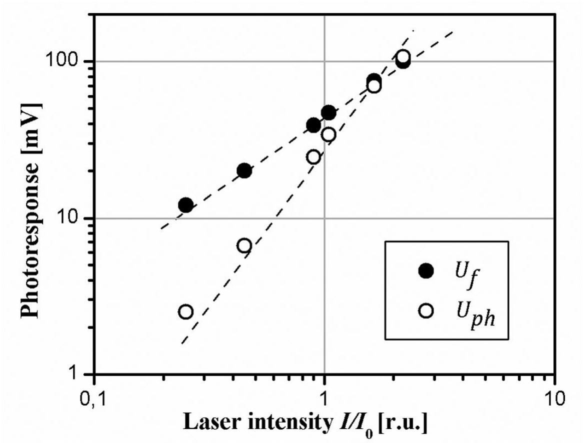

Fig. 4. The dependence of the classical photovoltage U_{ph} and the hot carrier thermoelectromotive force U_f across Si p-n junction on 1.489 μm laser intensity.

In turn, U_f is linearly dependent on the laser intensity. Such linear dependence is an inherent feature of the hot carrier thermoelectromotive force [7]. Thus, the formation of hot carrier thermoelectromotive force reduces the efficiency of a solar cell as far as its polarity is opposite to that of the classical photovoltage.

The dependencies U_f and U_{ph} on laser radiation wavelength are depicted in Fig. 5. It is seen that U_{ph} decreases as the wavelength gets longer, and at $\lambda > 2.5$ μm, the slow component of the photovoltage vanishes. This behavior is associated with the decrease in two-photon absorption coefficient with wavelength [9]: at $\lambda > 2.5$ μm the energy of two photons is lower than the forbidden energy gap of Si, and no generation of electron-hole pairs is observed.

The hot carrier thermoelectromotive force U_f also drops down when λ increases from 1.489 μm

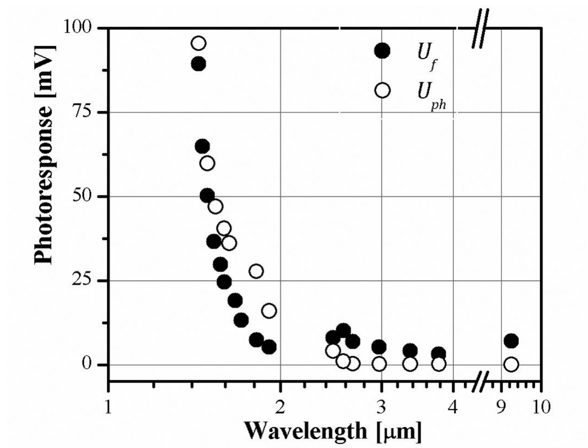

Fig. 5. The spectral dependence of the hot carrier thermoelectromotive force U_f and the classical photovoltage U_{ph} under intense laser illumination.

to 1.9 μm. However, in contrast to U_{ph}, U_f does not tend to zero but even slightly increases at longer laser wavelengths, $\lambda > 1.9$ μm. In this spectral range, the hot carrier thermoelectromotive force is determined by the optical absorption coefficients of free electrons and free holes [10, 11].

4. Summary

Peculiarities of photovoltage formation across Si p-n junction under illumination of laser radiation was investigated. When the laser radiation wavelength is longer than semiconductor cutoff wavelength, the observed photoresponse consists of two components. The fast component is caused by the laser-induced carrier heating, and the slow one is a classical photovoltage caused by electron-hole pair generation. The classical photovoltage was found to increase with laser intensity according to the square law. This fact indicates that the carrier generation is determined by two-photon absorption. At low excitation levels, the photoresponse is mainly dominated by the thermoelectromotive force of hot carriers, and at high intensities, the generation of electron-hole pairs prevails. As a result, the carrier heating reduces the efficiency of a solar cell as far as the polarity of the thermoelectromotive force of hot carriers is opposite to that of the classical photovoltage.

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