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Giant lateral photovoltaic effect in the TiO_2/SiO_2/p-Si heterostructure

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Abstract: In this work, we study the lateral photovoltaic effect in the TiO_2/SiO_2/p-Si structure. It was found the giant lateral photoeffect occurs in the TiO2/SiO2/p-Si heterostructure due to the high built-in barrier formation at the SiO_2/*p*-Si interface. The maximum LPE sensitivity ~600 mV/mm is observed in the TiO_2/SiO_2/*p*-Si structure under the TiO_2 film deposition for 45 min. However, the LPE nonlinearity in this structure is too large for practical applications. A decrease of the nonlinearity is achieved by the TiO2 film thickness control. The structure fabricated by the TiO_2 film deposition for 50 min has the LPE sensitivity and LPE nonlinearity are 477 mV/mm and 9%, respectively, which are more suitable for optoelectronic devise. The reason for the significant values of the rise time and fall time at pulsed illumination is the impedance behaviors of the TiO_2/SiO_2/*p*-Si structure in the near-contact region.

Keywords: lateral photovoltaic effect, heterostructure, silicon, titanium dioxide, interface, built-in barrier

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Гигантский латеральный фотовольтаический эффект в гетероструктуре TiO_2/SiO_2/*p*-Si

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Аннотация. В данной работе проведено исследование латерального фотовольтаического эффекта в структуре TiO_2/SiO_2/*p*-Si. Установлено, что гигантский латеральный фотоэффект наблюдался в гетероструктуре $TiO_2/SiO_2/p$-Si вследствие формирования в ней на границе раздела SiO_2/p-Si высокого встроенного барьера. Максимальная чувствительность ЛФЭ ~600 мВ/мм наблюдается в структуре $TiO_2/SiO_2/p$-Si при толщине пленки TiO_2, осажденной в течение 45 мин. Однако, нелинейность ЛФЭ в этой структуре слишком велика для практических применений. Уменьшение нелинейности достигается регулированием толщины пленки TiO_2. Обнаружено, что характеристиками пригодными для оптоэлектронных устройств обладает структура, полученная при осаждении пленки TiO_2 в течение 50 мин, в которой чувствительность и нелинейность ЛФЭ составляют 477 мВ/мм и 9%, соответственно. Причиной значительных величин времени нарастания и спада при импульсном освещении являются импедансные характеристики структуры $TiO_2/SiO_2/p$-Si в области контактов.

Ключевые слова: латеральный фотовольтаический эффект, гетероструктура, кремний, диоксид титана, граница раздела, встроенный барьер

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Introduction

Recently, the lateral photoelectric effect (LPE), which is a characteristic feature of semiconductor structures, has been identified as an indispensable and effective method for studying the properties of nanomaterials and nanostructures due to the unique mechanism of operation [1]. It is known [2, 3] that LPE occurs when a laser beam nonuniformly irradiates the surface of a *pn*-junction or heterojunction; as a result, a large number of electron-hole pairs are excited and then separated by this *pn*-junction in the illuminated region by means of the built-in field. Thus, an electric potential difference is created by the carrier concentration gradient between the illuminated and unilluminated regions, which leads to lateral diffusion of non-equilibrium photocarriers from the illuminated region to the contacts. Interest in this effect is due to the linear dependence of the lateral photovoltage on the laser spot position between the electrodes, which makes it possible to convert light signals into electrical signals, which can be used as components of photovoltaic systems in various areas of optoelectronics, for example, in position-sensitive detectors (PSD) [2, 4–6]. The main operating characteristics of these optoelectronic devices are the LPE sensitivity and LPE nonlinearity [4, 5], as well as the response times under pulsed illumination [7, 8]. Innovations in the LPE scientific research field are precisely aimed at improving these characteristics.

It is known [1, 5, 6, 8–11] that LPE sensitivity is determined by several critical factors, such as the distance between the electrodes, the power and wavelength of the light source, the choice of a material for the top layer and substrate, and the thickness of the top layer of hybrid structures. The development of nanotechnologies has offered a new direction in LPE research, attracting attention to hybrid structures such as metal-oxide-semiconductor (MOS) structures [1, 5, 12] and heterostructures [1, 13, 14]. In these cases, one of the ways to increase the LPE sensitivity is to choose a material for the top layer with high resistivity and high work function. The high work function provides a significant band bending at the interface (structures with an inversion layer are preferred [15]), and the low specific conductivity shifts the optimal film thickness to the range that guarantees the formation of a homogeneous built-in barrier at the interface [16].

Previously, we studied the $Fe/SiO_2/n$-Si [9] and $Fe_3O_4/SiO_2/n$-Si [10] structures in which LPE was observed, and an increase of the top layer resistivity led both to an increase of the LPE sensitivity by a factor of 4.7 and to a decrease of non-linearity from 6 to 5%. In both cases, there was a dependence of the LPE parameters on the top layer thickness. In this work, we chose low-conductivity TiO_2 films as the top layer satisfying the above properties [17].

Materials and Methods

TiO_2 films doped by manganese were formed on the oxidized silicon surface by the sol-gel method [17]. The film thickness dependence on the deposition time (in the selected time range) closes to linear [18]. To measure the photovoltage, aluminum contacts (2×1) mm were deposited on the film surface o with a distance of 2 mm between them. Illumination was carried out by a He-Ne laser with $\lambda = 633$ nm and a radiation power incident on the sample surface of 0.3 mW. The dependences of the photovoltage $U(x)$ and $U(t)$ were measured using a Keitly-2000 multimeter and an AKIP-4115/5A digital oscilloscope, respectively.

Results and Discussion

The band diagrams presented in Fig. 1 were plotted for the $TiO_2/SiO_2/Si$ structure. For energy calculations, we used the values of the band gap and work function for titanium dioxide, 3.1 eV and 5.87 eV, respectively [19, 20]. It follows from the analysis of these diagrams that in the $TiO_2/SiO_2/Si$ heterostructure a large built-in potential φ_i = 0.62 eV is formed at the SiO_2/*p*-Si interface, while φ_i = 0.16 eV at the SiO_2/*n*-Si interface. It is the small value of the built-in barrier in the TiO_2/SiO_2/*n*-Si structure that is the reason for the absence of the photovoltaic effect in it.

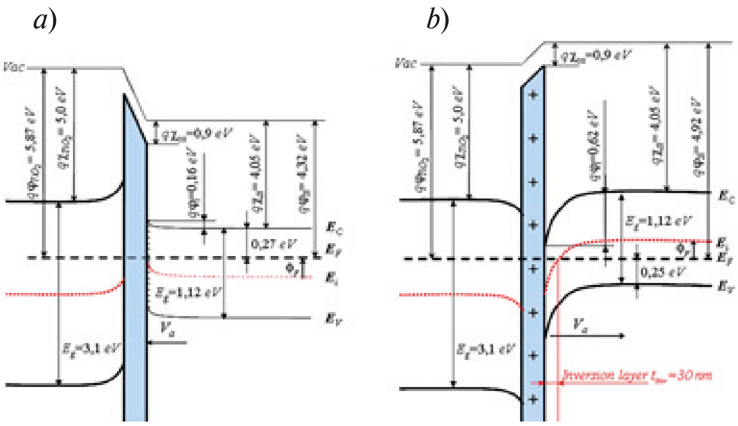

Fig. 1. Energy band diagrams of the heterostructure: TiO_2/SiO_2/*p*-Si (*a*); TiO_2/SiO_2/*n*-Si (*b*)

Fig. 2,*a* shows the dependences of the lateral photovoltage on the laser spot position at different top layer thickness for the TiO_2/SiO_2/*p*-Si structure. As can be seen in Fig. 2, *a*, there is a non-linear dependence of the lateral photovoltage on the film thickness (deposition time). Fig. 2, *b* shows the thickness dependences of the LPE sensitivity and LPE nonlinearity. It can see from Fig. 2, *b* that the LPE sensitivity dependence on the thickness is extreme, as for the structures studied earlier [1, 5, 9, 10], and the LPE nonlinearity dependence decreases exponentially with an increase of the top layer thickness. As can be seen from Fig. 2, *b*, the maximum sensitivity is achieved at the thickness of the titanium dioxide film obtained for 45 min and reaches 605 mV/mm. Unfortunately, the LPE nonlinearity at such a film thickness is 21%, which exceeds the applicability threshold, which is 15% for PSDs [4]. Based on the requirements for the performance characteristics of PSD [4], in this case, the optimal thickness should be a sample obtained for 50 min, having the sensitivity 477 mV/mm and the nonlinearity 9%.

The change in the thickness dependence of the LPE sensitivity is usually explained as follows. In the range of small thicknesses, a decrease in the LPE sensitivity is concerned with a film discontinuity and, accordingly, a decrease of the built-in barrier height [16, 21]. With an increase of the built-in potential, the number of excess photocarriers increases, and diffusion scattering decreases which results in an increase of the lateral photovoltage [16]. The LPE maximum is reached when the film becomes continuous and the height of the built-in barrier becomes homogeneous [9, 10, 21]. The decrease of the LPE sensitivity after passing the maximum is

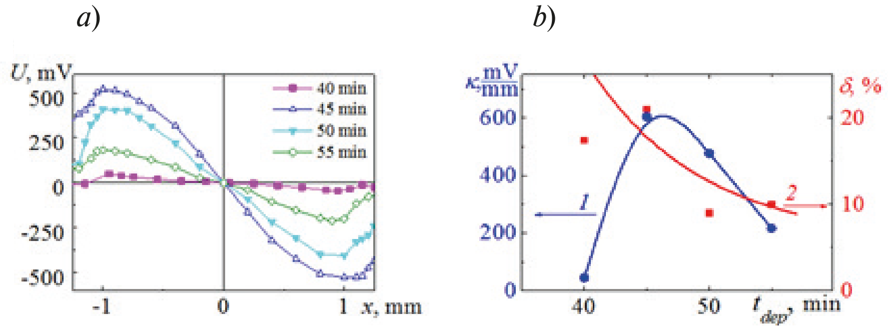

Fig. 2. LPE dependences for the $TiO_2/SiO_2/p$-Si heterostructure: lateral photovoltage dependence on the light spot position (*a*); TiO_2 thickness dependences (*b*), where *1* corresponds to LPE sensitivity and *2* to LPE nonlinearity

due to the shorting of the measuring electrodes because of a decrease of the film resistance with an increase of its thickness. However, in the $TiO_2/SiO_2/p$-Si structure, the resistance of a titanium oxide film is orders of magnitude higher than the resistance of transition metal films [3, 5, 6]; therefore, a decrease in LPE sensitivity with an increase of the TiO_2 film thickness, in our opinion, is due not to a decrease of its resistance, but rather to voltage losses at the contacts because of high film resistance in the transverse direction.

The high value of the LPE nonlinearity in the $TiO_2/SiO_2/p$-Si heterostructure, in our opinion, is due to the strong morphological roughness of the film, which may reach 30–50% of the film thickness [17, 22]. It was shown in Ref. [22] that the roughness in TiO_2 films deposited on a glass substrate reaches ~90 nm at a grain size of ~150 nm.

The time dependences of LPV at a pulsed illumination were also investigated. In this work, the rise time is defined as the time required to increase the photovoltage from 10% to 90% of the peak photovoltage (Umax), and the fall time is defined as the time required to reduce the photovoltage from 90% to 10% Umax. As can be seen from Fig. 3, *a*, the photovoltage signal in the $TiO_2/SiO_2/p$-Si heterostructure with a change of the top film thickness is characterized by both different pulse amplitude and different shape. The amplitude of the photoresponse signal varies proportionally to the change of LPE sensitivity, although it is ~3 times less. The change of the signal shape is related to the difference in the rates of excitation and quenching of photoconductivity in the $TiO_2/SiO_2/p$-Si heterostructure at different thicknesses of the titanium dioxide film. The dependences of the rise time and fall time on the TiO_2 film thickness are shown in Fig. 3, *b*.

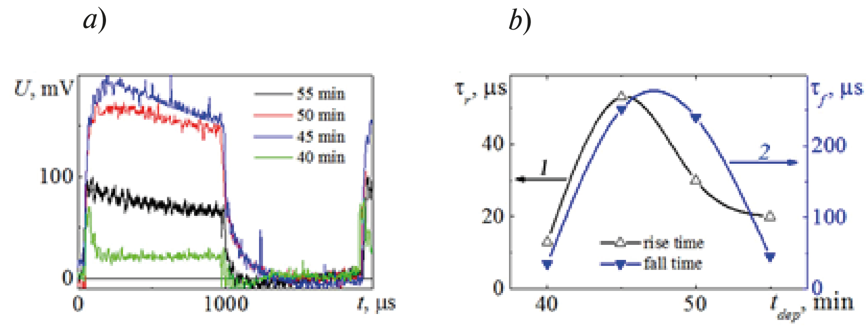

Fig. 3. Transient LPE characteristics of the $TiO_2/SiO_2/p$-Si heterostructure: time dependences of the lateral photovoltage (*a*); thickness dependences (*b*) of rise time (*1*) and fall time (*2*)

In the case of an open measurement scheme in the $TiO_2/SiO_2/p$-Si heterostructure at the optimal film thickness, the rise time is 30 μs and the fall time is 240 μs. It is easy to see that from the point of view of the transient LPE, this structure is also optimal.

Large value of time parameters in the $TiO_2/SiO_2/p$-Si heterostructure, in comparison with the previously studied structures [9, 23, 24], can be explained based on the equivalent circuit, Fig. 4. The equivalent circuit for the $TiO_2/SiO_2/p$-Si heterostructure at 300 K contains the following elements (Fig. 4): C_{pn} and R_{pn} are the capacitance and resistance in the separation region of non-equilibrium photocarriers at the SiO_2/p-Si interface, characterizing the process of photocarrier generation, R_{inv} and R_{film} are the lateral resistances of the inversion layer and TiO_2 film, characterizing the lateral diffusion of photocarriers, as well as capacitances and resistances arising in the heterostructure near the contact region in transverse direction: C_{ss}, C_{dep}, C_{ox}, C_{TiO_2} are, respectively, the capacitances of surface states, space charge region, silicon oxide layer, TiO_2 film and R_{ss}, R_{dep}, R_{TiO_2} are the resistances of surface states, depletion layer, TiO_2 film. The substrate parameters of R_{sub}, Z_{SC} are not considered in our case since these play a role only for measuring LPE from the substrate side.

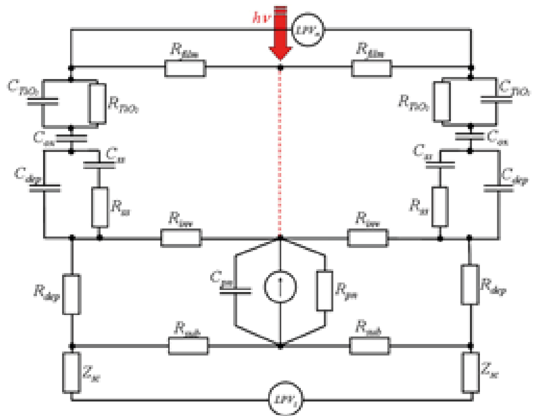

Fig. 4. Equivalent circuit of lateral photoconductivity at pulsed illumination

Since the top layer in the $TiO_2/SiO_2/p$-Si heterostructure is a semi-insulator, current transfer through it does not occur, and this conduction channel is shunted by the inversion layer and the transverse conductivity in the near-contact region. Moreover, as can be seen from Fig. 4, in contrast to conventional MOS structures, in this case, in the transverse direction considering film impedance characteristics a complementary RC-filter for the TiO_2 film is added to the RC-filter of the SiO_2/p-Si interface, which slows down the photoresponse. The decrease of the signal amplitude $U(t)$, from the standpoint of the equivalent circuit, can also be explained by the reactance losses in the transverse direction of the structure in the contact region.

Conclusion

In our opinion, the presented results conclusively prove that the giant lateral photoconductivity in the $TiO_2/SiO_2/p$-Si heterostructure, in which the semi-insulator is used as the top layer, occurs along the inversion layer and near-contact regions, bypassing the top film because of its high resistance. Meanwhile the titanium dioxide film serves only to generate the built-in potential at the SiO_2/p-Si interface.

The LPE characteristics obtained during the study of the $TiO_2/SiO_2/p$-Si heterostructure make it possible to consider this structure as a promising candidate for optoelectronics.

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