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The origin of the lateral photovoltaic effect in the $SiO_2/TeO_2/Bi_2Te_3/n$-Si(111) multilayer structure

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Abstract. The paper presents the study of the lateral photovoltaic effect in the $SiO_2/TeO_2/Bi_2Te_3/n$-Si(111) multilayer structure. The spectral dependences of photosensitivity identify the localization of the photogeneration process in the space charge region of the silicon substrate at the bismuth telluride layer thickness of 5 nm or more and in the Bi_2Te_3 layer at its thickness of less than 5 nm. It is established that lateral photosensitivity can serve as an indicator of the natural oxidation process of the protective transparent covering. We defined that the studied structure demonstrates promising results as photovoltaic cell when the Bi_2Te_3 layer thickness of 5 nm and illumination parameters of λ = 730–830 nm and W = 0.8 mW.

Keywords: lateral photovoltaic effect, topological insulator, silicon, multilayer structure, optoelectronics

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Происхождение латерального фотовольтаического эффекта в многослойной структуре $SiO_2/TeO_2/Bi_2Te_3/n$-Si(111)

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Аннотация. В работе представлено исследование латерального фотовольтаического эффекта в многослойной структуре $SiO_2/TeO_2/Bi_2Te_3/n$-Si(111). Спектральные зависимости фоточувствительности идентифицируют локализацию процесса фотогенерации в области пространственного заряда кремниевой подложки при толщине слоя теллурида висмута 5 нм и более и в слое Bi_2Te_3 при его толщине менее 5 нм. Установлено, что латеральная фоточувствительность может служить индикатором процесса естественного окисления защитного прозрачного покрытия. Мы определили, что исследуемая структура демонстрирует многообещающие результаты в качестве фотовольтаической ячейки при толщине слоя Bi_2Te_3 5 нм и параметрах освещения λ = 730–830 нм и W = 0,8 мВт.

Ключевые слова: латеральный фотовольтаический эффект, топологические изоляторы, кремний, многослойные структуры, оптоэлектроника

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Introduction

The development of optoelectronics opens up new possibilities, including current control using light [1–3]. One of the promising areas of optoelectronics development is the use of topological insulators (TI), which will increase the speed of response [2–5]. TIs are materials capable of conducting spin-polarized current along their surface, while remaining an insulator in the volume. For example, in Ref. [6], a study of the Bi_2Te_3 crystal surface showed that accelerated electrons are able to move along the surface of a TI practically without scattering – unlike movement in a conventional crystal – which means that they conduct current much faster, without heating losses [6].

The lateral photovoltaic effect (LPE), in which the surface potential difference of a certain system of materials varies linearly depending on the position of the incident laser beam, is one of the popular effects found in optoelectronics [7, 8]. As a rule, in silicon-based photovoltaic cells, lateral photovoltage is generated in the space charge region of silicon. However, since in the $SiO_2/TeO_2/Bi_2Te_3/n$-Si(111) structure both Si substrate and Bi_2Te_3 layer are absorbed in the visible spectrum, it is be interest to study the origin of LPE in this structure. Moreover, due to the spin splitting in Bi_2Te_3, when absorbing light, circular photovoltaic effect (CPE) is generated in it. Therefore, if the regions of LPE and CPE generation are separate, then photovoltaic cells based on the Bi_2Te_3/Si structure will expand the functionality of optoelectronic devices.

In this work, we studied the LPE in the $SiO_2/TeO_2/Bi_2Te_3/n$-Si structure by varying the thickness of the Bi_2Te_3 topological insulator layer under continuous and pulsed illumination, as well as the wavelength and power of laser radiation to identify the origin of the photogeneration process. Since the optical characteristics of the Bi_2Te_3/n-Si(111) structure depend on oxidation, in order to increase the reliability of the LPE characteristics we formed the compound protective transparent covering of SiO_2/TeO_2. The spectral dependences of the photosensitivity made it possible to determine the localization of the generation-recombination processes at different thicknesses of the topological insulator layer. According to the obtained results, the change in the localization of the photogeneration process in the Bi_2Te_3/n-Si(111) heterostructure is due to the kinetics of the energy structure with an increase of the thickness of the single-crystal Bi_2Te_3 film.

Materials and Methods

Thin-film growth using molecular beam epitaxy was conducted in a ultrahigh vacuum (UHV) chamber with a base pressure less than 5.0×10^{-10} Torr. We used *n*-type Si(111) wafers (40–70 Ω·cm) with dimensions 3×5×0.5 mm as substrates. Atomically clean Si(111)7×7 surface was prepared in situ by flashing to 1280 °C after the wafer was first outgassed at 600 °C for 6 h. Bismuth and tellur were evaporated from effusion cells with integrated shutters. The Bi_2Te_3 layers were grown at a higher temperature of about 240 °C, at which the film grew in step-flow mode. To reduce the amount of Te vacancies, the Bi-to-Te flux ratio was chosen close to 1:14 with the growth rate of about 0.3 QL/min [4]. One quintuple layer (QL) has a thickness of 1 nm. A series of samples with Bi_2Te_3 layer thicknesses of 3, 5 and 10 nm were formed.

The Bi_2Te_3 films were covered by 2 nm of tellurium and then 1 nm of amorphous silicon to prevent oxidation of the functional Bi_2Te_3 layer, after cooling to the room temperature. The samples were exposed to air, the top silicon and tellurium layers were native oxidized. We got the formation of top optical transparent layers of paratellurid and silicon dioxise, so-called window layers [9]. As result the lateral photovoltaic effect was studied for the $SiO_2/TeO_2/Bi_2Te_3/n$-Si structure.

Lateral photovoltaic effect was investigated by using a Ti:sapphire laser (max power 0.6W) in continuous mode in wavelenght between 700–900 nm and He-Ne laser (ML101J25 with 633 nm). The wavelenght 385 nm was get on BBO (Beta Barium Borate) crystal by using a Ti:sapphire laser in femtosecond mode. Power radiation 0.25 mW for incident beam on asurface as well as a spot diameter after diaphragm 50 μm take place for both lasers. Lateral photovoltage (LPV) was measured with Keithley 2000 multimeter. The distance between the probes was 1 mm.The response time was investigated by a digital oscilloscope (Tektronix TDS 2012B) of 150 MHz.

Results and Discussion

It is known [4, 9–11] that in order to optimize the efficiency of multilayer thin-film photovoltaic cells, it is necessary to observe the criteria for selecting materials taking into account their energy parameters, loss mechanisms and recombination processes.

One of the loss mechanisms reducing the quantum efficiency of photovoltaic cells is reflection. This can be caused by light reflection at the interfaces and/or the outer surface. Another loss mechanism is the absorption of light near the surface. This problem is addressed by introducing the concept of a window/buffer/absorber heterojunction.

In addition, the generation of carriers is counteracted by the carriers' recombination [9, 10]. The recombination regions that affect the efficiency of a solar cell are the quasi-neutral recombination in the absorber layer, the recombination at space charge region, and recombination at the absorber/buffer interface. Recombination at the interface can be reduced by forming an epitaxial buffer layer [2, 3, 9].

In this work, photovoltaic cells are made on the basis of the Bi_2Te_3/n-Si(111) heterojunction covered with protective transparent layers of TeO_2 and SiO_2, which are usually called window layers. To increase efficiency, we used the same elements in subsequent layers [9]. The differences are in window materials and them properties. The absorption in transparent window layer is typically low due to the sufficiently high-energy band gap of the materials used for this layer. Unfortunately, the absorption by the Bi_2Te_3 buffer layer is a significant losses source in the studied structures. Here one has to choose between performance and losses.

In Fig. 1 we can see the lateral photovoltage dependence for photovoltaic cells with different thickness of Bi_2Te_3 buffer layer under continuous and pulse illumination. The dependence of the lateral photovoltage on the laser spot position is parameterized by the sensitivity (κ). In the top left insert of Fig. 1 the photoresponse dependences are presented in the LPV(t) graphical presentation format, since in this case the value of the photoresponse signal corresponds to the photosensitivity value. According to this parameter, the structure with a 5 nm-Bi_2Te_3 buffer layer is more promising for photosensitive detector.

Moreover, we defined the photoresponse performances of cover/Bi_2Te_3/n-Si(111) structures, top left insets in Fig. 1, although the photosensitivity of these structures were lower than those in metal-semiconductor or metal-oxide-semiconductor structures [5, 11], the response time of these structures were be faster.

The extreme dependence of photosensitivity on the Bi_2Te_3 layer thickness is typical for hybrid structures on silicon. However, note should be taken to the change in the sequence of the LPV(x) and $I(U)$ dependences with increasing Bi_2Te_3 buffer layer thickness. This fact indicates that in the Bi_2Te_3/n-Si(111) heterostructure, not only the change in the resistance of this system, but also the change in the energy structure of the Bi_2Te_3 buffer layer plays a role in the generation of lateral photovoltage. To understand this result, we conducted studies with varying laser illumination parameters such as wavelength and power.

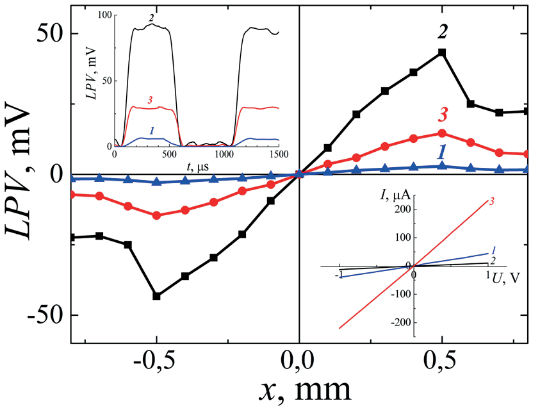

Fig. 1. Dependence of lateral photovoltage on the laser spot position in the $SiO_2/TeO_2/Bi_2Te_3/n\text{-}Si(111)$ structure with the Bi_2Te_3 layer thickness: *1* – 3 nm, *2* – 5 nm, *3* – 10 nm. Inserts: *LPV*(*t*) photoresponse (top left); dark *I*-*V* characteristics (bottom right). Ti:sapphire laser (λ = 730 nm)

Figure 2 shows the spectral dependences of photosensitivity parameterized by the TI layer thickness, and the inset shows the dependences of the photovoltage near the contact on the laser illumination power.

As can be seen in Fig. 2, the dependence of the photosensitivity of heterostructures with a Bi_2Te_3 layer of thickness 5 QL or more correlates with the well-known absorption spectrum of silicon [12, 13], which clearly indicates the generation of nonequilibrium photocarriers in the near-surface silicon layer. Whereas with a Bi_2Te_3 layer thickness of 3 QL, the spectral dependence of the photosensitivity rather agrees with the absorption spectrum of thin bismuth telluride layers presented in the work, which have a hybridization gap in the ARPES (Angle-resolved photoemission spectroscopy) [14]. This transition is explained by the kinetics of the dispersion relations of bismuth telluride [14], according to which the electronic structure develops up to a film thickness of 5 QL, that is accompanied by an increase in conductivity [15]. It is known [16] that films at 5 QL have dispersion relations of the bulk structure of Bi_2Te_3. Whereas films with a thickness of 1-3 QL are characterized by the presence of surface states in the band gap [15, 16].

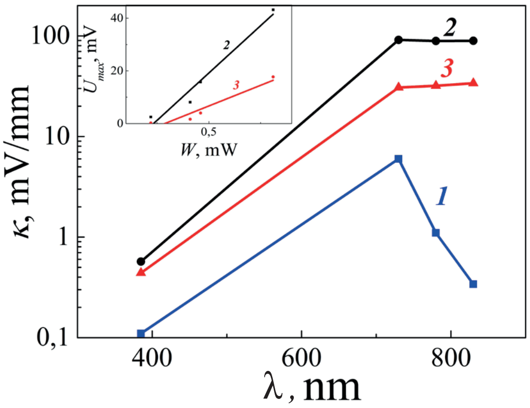

Fig. 2. Dependence of lateral photovoltage in the $SiO_2/TeO_2/Bi_2Te_3/n\text{-}Si(111)$ structure on the laser illumination wavelength (Ti:sapphire laser). The insert shows the photosensitivity dependence on the laser illumination power incidenting on a surface. *1* – 3 nm Bi_2Te_3, *2* – 5 nm Bi_2Te_3, *3* – 10 nm Bi_2Te_3

Thus, in the $SiO_2/TeO_2/Bi_2Te_3/n\text{-}Si(111)$ structure with a bismuth telluride thickness of 5 QL or more, the absorbing layer is the silicon space charge region, the bismuth telluride layer is the buffer layer, and the tellurium dioxide and silicon dioxide layers are protective transparent coatings, the so-called window layers. With the bismuth telluride thickness of 3 QL, the absorbing layer is the bismuth telluride layer, which significantly damages the photovoltaic properties.

The linear increase of lateral photovoltage with increasing laser power is due to the increase in the number of photogenerated carriers. At thicknesses of 5 QL and more, such a significant increase in photovoltage is possible only when it is generated in the region of the space charge of silicon. In this case, the decrease in the slope of the $U_{max}(W)$ dependence for a thickness of 10 QL reflects both a decrease in resistance and an increase in absorption in the Bi_2Te_3 layer.

The most striking evidence of lateral photovoltage generation in silicon can be observed in the dependence of photosensitivity on the illumination wavelength. As can be seen in the inset in Fig. 2, the dependence inherits the nature of the absorption spectrum of silicon at both thicknesses of the buffer layer, which clearly indicates the generation of nonequilibrium photocarriers in the near-surface silicon layer. Thus, in the $SiO_2/TeO_2/Bi_2Te_3/n$-Si(111) structure, the absorbing layer is the silicon space charge region, the bismuth telluride layer is the buffer layer, and the tellurium dioxide and silicon dioxide layers are protective transparent coverings, the so-called window layers.

In addition, the kinetics of photovoltaic characteristics allows us to analyze the native oxidation processes of top protective layers. In order to increase the resistance and transparency of the window layer, it was proposed to form a combined transparent covering SiO_2/TeO_2. It is natural to assume that in this case, the amorphous silicon layer formed on the surface of the thinned tellurium layer is oxidized first. Due to the high electronegativity of tellurium, the oxidation process continues until the tellurium layer is completely oxidized, which follows from the current-voltage characteristics (CCV), bottom right insert Fig. 3. Such a covering improves the transport properties of the system, since its resistance increases by an order of magnitude, top left insert Fig. 3, but, unfortunately, requires a long formation time (120–150 days).

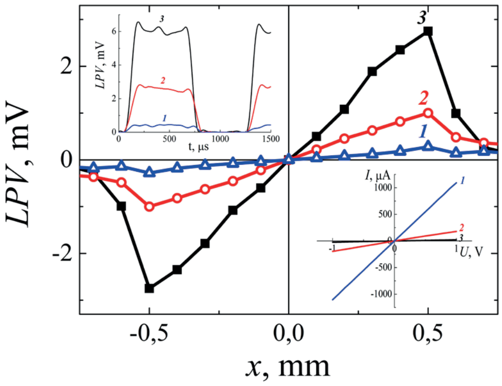

Fig. 3. Lateral photovoltage of the $SiO_2/TeO_2/Bi_2Te_3/Si$ structure during native oxidation: *1* – 10 days, *2* – 70 days, *3* – 150 days. Inserts: *LPV*(*t*) photoresponse (top left); dark *I-V* characteristics (bottom right). He-Ne laser (λ = 633 nm)

Since at the 5nm-Bi_2Te_3/n-Si(111) interface the absorber is the silicon substrate, and photogeneration occurs, where the energy parameters of the structures are identical, the reasons for the significant improvement of photovoltaic properties during oxidation of the $SiO_2/TeO_2/Bi_2Te_3/n$-Si(111) multilayer structure are an increase in the resistance and in the transparency of the covering layers, and a decrease of losses in a RC circuit, according to basic scheme of the LPE, proposed by us earlier [11].

Conclusion

This study revealed the role in a generation of lateral photovoltage of bismuth telluride layer and silicon space charge region, which absorb in the visible spectrum. It was shown that a bismuth telluride buffer layer no less than 5 nm thickness is optimal for position-sensitive detectors. It was found the $SiO_2/TeO_2/Bi_2Te_3/n$-Si(111) photovoltaic cells with a buffer layer made of a topological insulator and with protective transparent covering may have potential applications as high-speed optoelectronic devices.

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