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NANOSTRUCTURE DEVICES

Study of the Photovoltage in Mn/SiO$_2$/n-Si MOS Structure at Cryogenic Temperatures

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Abstract—Lateral photovoltaic effect in metal/insulator/semiconductor hybrid structures is a significant phenomenon for spintronics, as it establishes the interplay between the optical irradiation, electronic transport and spin-dependent properties of carriers. In present work we investigated photovoltaic phenomena in Mn/SiO$_2$/n-Si MOS structure. The sample was prepared on a single-crystal n-Si (phosphorus-doped) substrate. The SiO$_2$ layer with thickness of 1.5 nm was formed on the substrate surface by a chemical method. Manganese film with thickness of 15nm was deposited by thermal evaporation in ultrahigh vacuum in the "Angara" chamber. It was observed that at $T < 45$ K the values of lateral and transversal photovoltage nonmonotonically depend on the temperature and such dependences show complex behavior. Features of the photovoltage dependence on temperature, in the region above 20 K are explained by the change of carriers' mobility and the competition between carriers' drift velocity in the electric field of the space-charge region and their diffusion rate in the transverse and lateral directions. Below 20 K, the main contribution into the photovoltage is given by hot electrons injected from surface states levels to the conduction band. A strong magnetic field influence on the photovoltage below 20 K was observed. We associate it with the Lorenz force effect on the hot electrons, although we also don't exclude the presence of mechanisms caused by spin-dependent scattering and recombination of hot electrons at occupied donor states.

Keywords: lateral photovoltage, transverse photovoltage, MOS structures, low temperature, space-charge region

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1. INTRODUCTION

Metal-insulator-semiconductor (MIS) hybrid structures have been actively studied since the discovery of giant magnetoresistance effect (GMR) in 1988 [1]. Semiconductor materials such as silicon provide compatibility with CMOS and SOI technology which allow integrating MIS based devices into the modern electronics while the magnetic metals can be used to control the electronic properties via the spin state of carriers. Such structures find various applications from magnetic field sensors to MRAM elements. In order to further unleash the potential of MIS based devices, one can consider studying the interplay between magnetic-field-dependent transport and optical irradiation. In our previous works, we reported on the optically induced magnetoresistance effect [2] and investigated the lateral photovoltaic effect (LPE) in the Fe/SiO$_2$/p-Si structure [3]. The present work will be focused on the features of LPE and transversal photovoltaic effect (TPE) in Mn/SiO$_2$/n-Si structure.

LPE was firstly discovered by Schottky [4] and expanded upon by Wallmark in floating Ge p–n junctions [5]. It is widely used in position detectors due to the sensitivity of the effect to laser spot position [6–8].

The presence of the oxide layer between magnetic and semiconductor layers can lead to a larger LPV and superb linearity with laser position [9, 10]. The presence of the Schottky barrier leads to the stronger built-in electric field at the interface and to inducing a larger number of excited carriers which results in larger LPE. As we have shown for the Fe/SiO$_2$/p-Si structure, the Schottky barrier plays a decisive role in the occurrence of LPV [11].

It was shown that LPE is sensitive to external conditions, such as magnetic field and bias voltage [12–16]. Wang et al. found that LPV is coupled to the magnetic alignment of FM layer [17]. This gives a reason to suggest that photovoltaic effect can be used to induce spin-dependent phenomena, and therefore would be useful for spintronic applications.

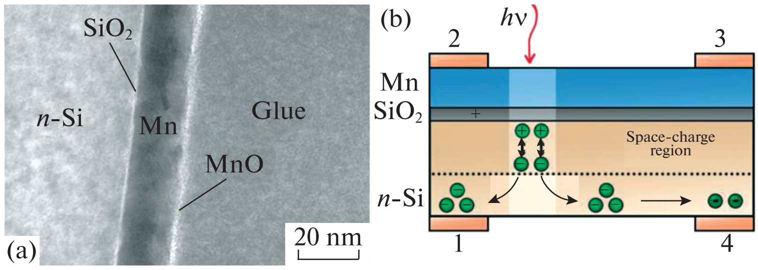

Fig. 1. (a) High resolution TEM image of the $Mn/SiO_2/n$-Si structure cross section. (b) Experimental setup for photovoltaic properties studied.

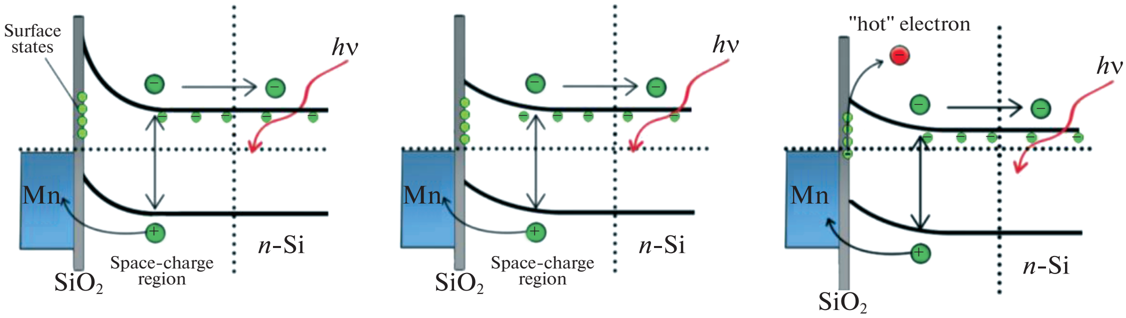

Fig. 2. Schematic energy band diagram of the MIS junction at a temperature above 45 K (left), at radiation power is high (center) and at temperature below 20 K (right).

2. SAMPLE SYNTHESIS AND EXPERIMENTAL METHODS

The sample was prepared on a single-crystal *n*-Si (phosphorus-doped) substrate. The substrate surface was pre-cleaned by the Shiraki method (chemical etching and long-term annealing at temperatures of 400–650°C) [18].

The SiO_2 layer with thickness of 1.5nm was formed on the substrate surface by a chemical method (the substrate was exposed to an aqueous solution of H_2O_2 and NH_4OH in a ratio of 1:1:1 for 30 min at 60°C). Manganese film with thickness of 15 nm was deposited by thermal evaporation under ultrahigh vacuum conditions at a sputtering rate of 0.25 nm/min.

The base pressure in the Angara chamber [19] was 8.6×10^{-6} Pa. The fabricated structures were characterized by cross-sectional transmission electron microscopy (TEM) (Fig. 1a).

Photovoltaic properties were studied using experimental setup, equipped with helium cryostat (4.2 K < T < 300 K), an electromagnet (–1 T < H < 1 T) and Keithley 2182a Nanovoltmeter [20, 21]. The top contacts to the Mn film were formed from silver epoxy and the bottom contacts to the substrate were formed by alloying indium. The optical irradiation was focused in a narrow (0.5 mm) strip on the Mn film (Fig. 1b). The narrow light beam position was fixed on the surface asymmetrically relative to the contacts for the entire measurement period. The lasers wavelength was 809 nm. The magnetic field was applied in the plane of Mn film.

3. RESULTS AND DISCUSSION

Before discussing experimental results, we will consider mechanisms responsible for the occurrence of transverse photovoltage (TPV) and lateral photovoltage (LPV). The Mn film with a thickness of 15 nm is transparent for optical radiation with a wavelength of 809 nm. Photons pass through Mn into a silicon substrate, and become absorbed in a space-charge region (left in Fig. 2).

It leads to generation of electron-hole pairs which drift in a built-in electric field of space-charge region (SCR), electrons move into the bulk of semiconductor and holes move into the Mn film. Separation of the electron-hole pairs causes the TPV. Furthermore, electrons in the semiconductor bulk uniformly diffuse in the lateral direction. If electrical contacts are arranged asymmetrically relative to the illuminated area, then the concentration of electrons under the contacts will be different and the LPV will occur.

Figure 3a shows the temperature dependences of TPV and LPV in the low-temperature region, measured at different optical radiation powers. With further increase in temperature, the value of TPV and

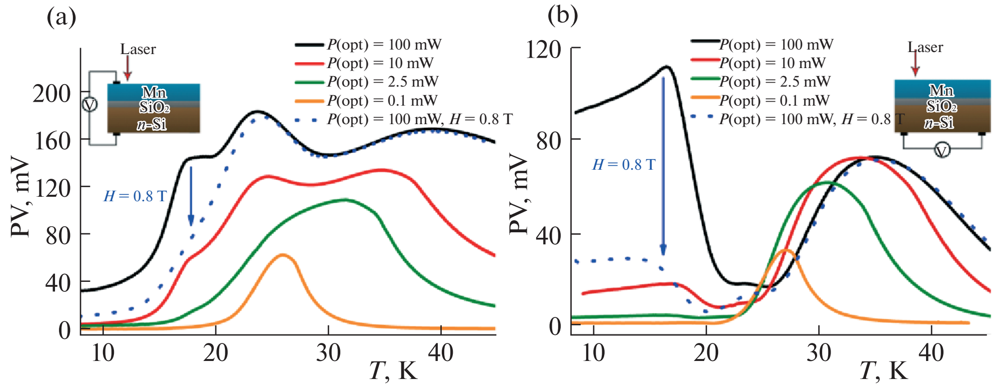

Fig. 3. Temperature dependences of transverse (a) and lateral (b) photovoltage at different light power. Dashed lines show the influence of magnetic field of 0.8 T on photovoltage.

LPV decreases monotonically and present no interest in the framework of the work. One can see that at low irradiation power, temperature dependence demonstrates a pronounced peak. Irregular shape of the peak suggests that this maximum is a superposition of several peaks. At higher power, a single maximum splits into three clearly distinguishable peaks. With further increase of power, the high temperature peak shifts towards even higher temperature and its amplitude rises. However, two low temperature peaks remain nearly unchanged and only their intensity increases.

Let us consider the temperature dependence of TPV at irradiation power of 100 mW more thoroughly. As the temperature decreases, the mobility of charge carriers increases, as a result, the rate of transverse drift of electron-hole pairs rises, which leads to a decrease in their recombination rate and to an increase of TPV. In turn, a decrease in the recombination rate of photoinduced carriers increases electron concentration in the bulk of the semiconductor, and an increase of mobility results in higher rate of electrons lateral drift, which leads to larger LPV (Fig. 3b).

This growth of LPV continues until the freeze-out of donors in the semiconductor leads to a significant decrease of the majority carriers' concentration. It causes the increase of the space-charge region width, and the electric field gradient decreases in space-charge region. As a result, the drift velocity decreases, and the probability of recombination of the photoinduced electron-hole pairs increases. In addition, the occupied donor states act as additional recombination and scattering centers. Therefore, LPV and TPV values decrease and the high temperature maximum can be observed on *PV*(*T*) curves.

In a framework of the suggested model it is simple to explain the cause of shifting of high temperature LPV(T) and TPV(T) peaks with an increase of irradiation power. Absorption of optical radiation causes an effect similar to that of surface photovoltage [22], due to which the bending of zones decreases in the space charge region. The higher irradiation power is, the stronger is the energy band straightening (center in Fig. 2). Thus, it leads to a decrease in the electric field gradient in the SCR and a decrease in the drift velocity of electron-hole pairs. As you can see, this effect is similar to one that occurs with temperature decrease, described earlier. Complementing each other, these two effects are the reason that with an increase of the irradiation power, the decrease of the electric field gradient in SCR falls below a certain critical value at higher temperatures.

As the temperature decreases further, the electric field gradient drops so much that the carriers' diffusion rate becomes higher than the its drift velocity. As a result, an increasing number of electrons manage to diffuse in the lateral direction, and the concentration of electrons under the contact no. 4 increases. At the same time, electrons concentration under the contact #1 tends to saturate, because the high concentration of carriers causes the decrease of mobility and increase of recombination speed. It explains the minimum on LPV(T) curve.

Considering the discussion above, the concentration of electrons under contact no. 1 changes only slightly. Consequently, the second maximum on TPV(T) should be due to an increase of concentration of holes under the contact no. 2. On the one hand, due to the reduction of the electric field gradient in the SCR, we should observe a decrease of holes concentration in Mn. However, it should be taken into account that the concentration of the majority carriers (electrons) decreases exponentially with decreasing temperature and the recombination rate of photoinduced holes on the majority carriers decreases. Apparently, the competition between photoinduced holes recombination on the photoinduced electrons and on the majority carriers is responsible for the occurrence of a second TPV(T) maximum.

The third (low-temperature) maximum on LPV(T) and TPV(T) curves can be explained if one assumes the presence of surface states lying close to the conduction band of Si. The presence of such levels was confirmed by the method of impedance spectroscopy [23–25]. As the temperature decreases, the Fermi level crosses these surface states and they capture an electron from the conduction band. The absorption of light by these surface states leads to the transfer of the captured electron to the conduction band (right in Fig. 2). This electron fundamentally differs from electrons formed by the interband transition, by having higher kinetic energy and, therefore, drift velocity. Conventionally, we will call these electrons "hot".

Hot electrons do not manage to laterally diffuse due to the higher drift velocity. As a result, the concentration of electrons under the contact no. 1 (closer to the illumination zone) becomes significantly higher than under contact no. 4. This leads to a significant increase in LPV. In turn, the maximum on TPV is not so pronounced. Apparently there should be a mechanism for reducing the concentration of holes under the contact no. 2. Possibly, such a mechanism is recombination of holes on electrons captured by the surface states.

An unexpected result was obtained by measuring the temperature dependences of LPV and TPV in a magnetic field (Fig. 3). The magnetic field greatly suppresses the low-temperature LPV(T) and TPV(T) maximums. Most likely, at $T < 20$ K, the main contribution to the photovoltage is made by the hot electrons exited from already occupied surface states. Since these electrons have high kinetic energy and considering experimental geometry, it is logical to assume that the main mechanism of a magnetic field influence on a photovoltage is the Lorentz force. It will bend the paths of the carriers, reducing the photocurrent, regardless of whether they move due to drift or diffusion. Furthermore, this process will lead to increase of recombination probability and, therefore, the photovoltage will decrease, which we observe in the experiment. At the same time, a possible contribution from spin-dependent recombination cannot be excluded [26] as well as from spin-dependent scattering [27] of hot electrons at occupied donor levels, which will at the end, cause the increase of recombination probability.

4. CONCLUSIONS

In present paper we suggested a qualitative explanation of TPV(T) and LPV(T) behavior in $Mn/SiO_2/n$-Si MOS structure at the cryogenic temperatures. The non-monotonic behavior of TPV and LPV is observed due to the change of carrier mobility with changing temperature, and due to competition between the drift and diffusion contributions to the photovoltage. We associate the observed low-temperature TPV and LPV maximums (below 20 K) with hot electrons, which are generated during absorption of light by electrons localized on surface states. The main mechanism of the magnetic field effect on the low-temperature photovoltage maximum is the Lorenz force. However we do not exclude the possible influence of spin-dependent scattering and recombination of hot electrons at occupied donor states.

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