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Investigation of the effect of optical radiation on resistive switching of MIS-structures based on ZrO_2(Y) on Si(001) substrates with Ge nanoislands

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The effect of optical radiation in the visible and near-infrared bands on resistive switching of a MOS stack based on ZrO_2(Y) film on an n-Si(001) substrate with self-assembled Ge nanoislands on its surface has been studied. An increase in the resistive switching logical gap was observed upon the photoexcitation, in particular, when the photon energies were smaller than the Si band gap. The effect was associated with the impact of the photo-emf at the Si/Ge/ZrO_2(Y) interface. In the latter case, the effect is associated with spatially indirect interband optical transitions in Ge nanoislands.

Keywords:: memristor, photo-induced resistive switching, yttria-stabilized zirconia, MIS-structure, Ge/Si nanoislands.

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1. Introduction

The memristors are new-generation elements of the non-volatile computer memory [1] and the neuromorphic computational systems [2]. Their functioning is based on the resistive switching effect (RS). Fabricating the memristors based on the metal–insulator–semiconductor (MIS) structures opens up possibilities for controlling the RS by optical radiation. In [3], a change in the RS parameters in the MIS-structure of Zr/ZrO_2(Y)/n-Si under photoexcitation was found, which is associated with the photo-emf at the Si/ZrO_2(Y) interface during interband absorption of radiation in Si with the energy $h\nu > E_g$ (E_g is the Si band gap). This results in amplification of the electric field in the ZrO_2(Y) layer, thereby inducing RS.

In [4], the impact of the radiation with $h\nu > E_g$ on RS in the MIS-structure of Zr/ZrO_2(Y)/n-Si with the Ge/Si islands on the Si surface. It has been suggested that the GeSi islands act as concentrators of the electric field in ZrO_2(Y), thereby improving the RS parameters.

The present paper has investigated the photoexcitation (including by infrared (IR) radiation with $h\nu < E_g$) on the RS in the MIS-structure of ITO/ZrO_2(Y)/n-Si/n^+-Si(001) with the Ge nanoislands embedded at the ZrO_2(Y)/n-Si interface. The obtained results show the fundamental possibility of creating of optically controlled memristors based on the studied MIS-structures for the so-called communicative wavelength range of $\lambda = 1.3-1.55\,\mu$m, including the memory photo-detector matrices (image detectors).

2. Experimental procedure

The n-Si/n^+-Si(001) structure with the Ge nanoislands on the surface has been grown by means of the original molecular-beam epitaxy (MBE) setup described in [5]. A n-Si buffer layer of the 500 nm thickness was grown on the surface of the n^+-Si (Mn) (0.001 Ωcm) substrate grade at the temperature of 1000°C from the n-Si (P) (0.15 Ωcm) source. The Ge nanoislands were grown by the hot wire chemical vapor deposition (HW CVD). GeH_4 was puffed in the growth chamber up to the pressure of $6 \cdot 10^{-4}$ Topp [6,7]. The flux of Ge atoms to a surface of the growing layer was created by pyrolytic decomposition of GeH_4 on the Ta strip heated to 1200°C by transmitting the direct current. The substrate temperature was 500°C. During the growth, the Ge layer was doped by Sb from a sublimation source Ge : Sb, heated to 890°C. The Sb doping was carried out to reduce the density of surface states at the Ge/ZrO_2(Y) surface [3,8] (it is suggested that Sb is segregated at the surface of the growing layer of Ge).

The ZrO_2(Y) film (12 mol.% Y_2O_3) of the 30-nm thickness was deposited by the radio-frequency magnetron sputtering at the substrate temperature of 300°C by means of the Torr International vacuum system. The transparent electrically-conductive top electrodes made from a mixture of indium-tin oxides (ITO) were deposited by the electron-beam evaporation through a mask with holes of the 0.5-mm diameter, followed by further oxidation in air at 250°C. The image of the studied MIS-structure is schematically shown on Fig. 1, *a*.

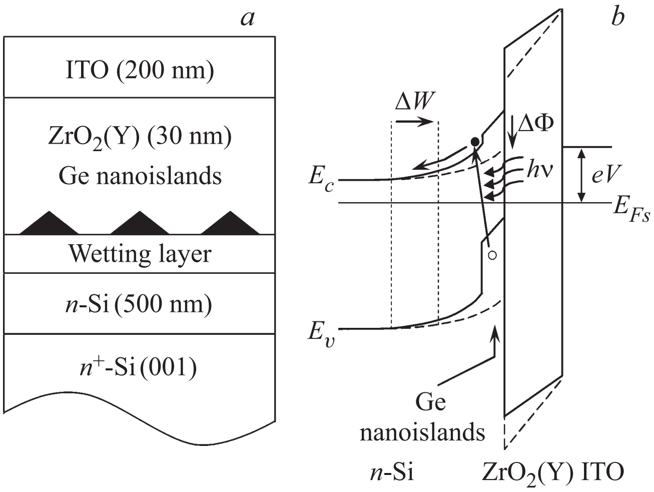

Figure 1. Schematic representation (a) and energy band diagram (b, qualitatively) of the MIS-structure of ITO/ZrO_2(Y)/Ge/n-Si/n^+-Si(001) when applying the reverse bias V in the darkness (the solid line) and during the interband photoexcitation with the quantum energy $h\nu < E_g$ (the dashed line). $\Delta\Phi$ — reduction of a potential barrier height at the semiconductor/dielectric material interface (photo-emf), ΔW — reduction of the SCR thickness during photoexcitation.

The surface morphology of the n-Si/n^+-Si(001) structure with the Ge nanoislands on the surface (before deposition of the ZrO_2(Y) layer) was investigated by the atomic-force microscopy (AFM) using the Solver Pro AFM in the atmospheric conditions in a semi-contact mode. The ETALON HA_NC AFM probes with a tip's curvature radius < 10 nm (in accordance with the passport data).

The photovoltaic properties of the fabricated MIS-structure were studied by the no-load photo-emf spectroscopy (300 K) at the modulated photoexcitation at the frequency of 130 Hz. The monochromatic radiation was sourced from the MDR-2 monochromator with a 100-W halogen lamp powered by a stabilized current source. The photo-response was recorded by means of the synchronous detector Stanford Research SR-510.

The impact of the photoexcitation on the RS of the MIS-structure was studied by measuring cyclic current-voltage characteristics ($I-V$ curves) using the Agilent B1500A semiconductor device parameter analyzer at 300 K. The visible photoexcitation was realized by radiation of semiconductor lasers ($\lambda = 660$ and 462 nm, the radiation power of ~ 1.5 W, the beam diameter of ~ 1 mm). The IR radiation was sourced from a tungsten incandescent lamp with the power of 20 W. A light filter designed as a p-Si (B) (40 Ωcm) plate was used to cut off the radiation with $h\nu > E_g$. The light filter was designed to avoid the photoeffect during the interband absorption of radiation in the Si buffer layer, thereby revealing the effect of interband absorption of IR radiation when $h\nu < E_g$ (for which the Si plate was transparent) in the Ge nanoislands. The lamp radiation was focused in a spot with the size of ~ 1 cm at the surface of the MIS-structure.

3. Experimental results and discussion

Fig. 2 shows the AFM image of the surface of the n-Si/n^+-Si(001) structure with the Ge nanoislands on the surface, as well as a scan line profile drawn through the vertices of the single nanoisland. In accordance with the AFM data, the surface mainly exhibited the islands of the height of up to 10 nm and lateral sizes of up to 100 nm. In accordance with the literature data, MBE deposition of Ge onto Si(001) at the substrate temperature of 500°C forms the pyramidal islands of the height of up to 10 nm and a typical aspect ratio of 1 : 10 (see, for example, [9]). The most of the islands of Fig. 2 had the similar sizes and aspect ratio (see the insert of Fig. 2). However, the island faceting of Fig. 2 is weakly expressed (the pyramid edges look rounded, so the apexes are blunt). It is correlated to the convolution effect [10] due to a finite curvature radius of the AFM probe tip, which is comparable with the island height. It has also noted the formation of single dome islands of the height of up to 20 nm and with the typical aspect ratio of 1 : 5. Such a bimodal height distribution of the islands in a transient area from formation of the pyramid islands to the dome ones was previously noted by many authors (see, for example, [11]). Thus, our results of the AFM investigation of the Ge/Si(001) nanoislands fabricated by the HW CVD agreed with the literature data for the islands formed by the MBE method in the similar conditions.

Fig. 3 shows the photo-emf spectrum of the MIS-structure (300 K). In addition to a band in the spectrum range $h\nu > E_g$ correlated to the interband Si photosensitivity, the spectrum has evidently the band in the range $h\nu < E_g$, which is caused by the interband optical absorption in the Ge nanoislands (Fig. 1, b).

The cyclic $I-V$ curves of the MIS-structures (Fig. 4), which are measured in the darkness and at the photoexci-

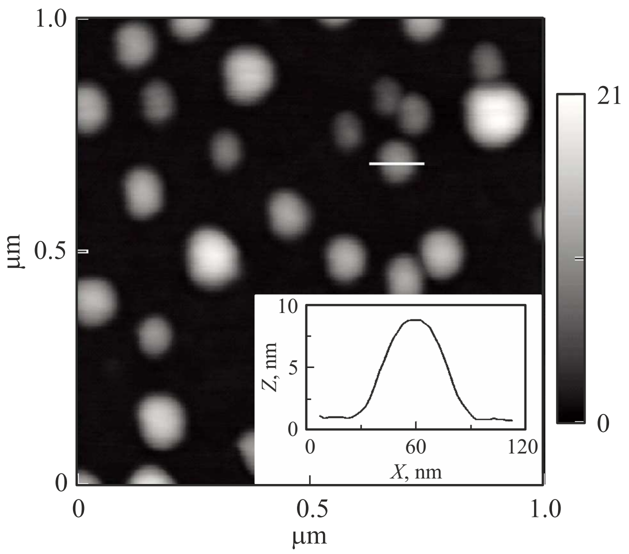

Figure 2. AFM-image of the surface of the n-Si/n^+-Si(001) structure with the Ge nanoislands on the surface. The insert shows the scan line profile drawn through the vertex of the pyramidal island.

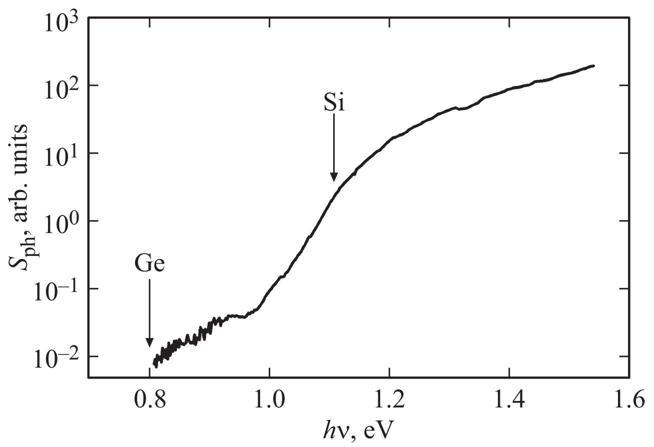

Figure 3. Photo-emf spectrum (300 K) of the MIS-structure of ITO/ZrO_2(Y)/Ge/n-Si/n^+-Si(001).

tation, had evidently a hysteresis correlated to the bipolar RS. The dark $I-V$ curves have the weak hysteresis. When illuminating by the visible and near-IR radiation, it was observed that the hysteresis loop area (the logical RS corridor) was increased.

A mechanism of the influence of the optical radiation with $h\nu > E_g$ on the RS was not different from the one described previously in [3]. In case of the photoexcitation by the IR radiation with $h\nu < E_g$, the influence of the IR radiation on the RS can be explained as follows. Fig. 1, b qualitatively shows the energy band diagram of the reversely biased MIS structure with the Ge nanoislands in the darkness and in the photoexcitation with $h\nu < E_g$. In this case, the radiation is partially absorbed by the Ge islands (indirect interband optical transitions both in a direct and reverse space). The photo-excited electrons drift to the quasi-neutral area n-Si in the field of the semiconductor (Si) — dielectric material barrier (ZrO_2(Y)). At the same time, the photo-generated holes remain localized in the Ge islands. The electric dipole resulted from separation of the photo-excited electron-hole pairs leads to formation of the photo-emf at the Si/ZrO_2(Y) $\Delta\Phi$ barrier and, correspondingly, to a reduced width of the space charge region (SCR) of the barrier W. In turn, it results in the increased electric field strength in the ZrO_2(Y) layer, thereby inducing the electroforming and the RS. The results of the photo-emf spectroscopy (Fig. 3) of the MIS-structure of ITO/ZrO_2(Y)/Ge/n-Si/n^+-Si(001) confirm the above-described mechanism of the influence of the IR radiation on the RS in these structures.

It should be noted that the hysteresis value in the photoexcitation (Fig. 4, d) is comparable with the hysteresis value in the photoexcitation with $\lambda = 472$ nm (Fig. 4, b) and is higher than that in the photoexcitation with $\lambda = 660$ nm

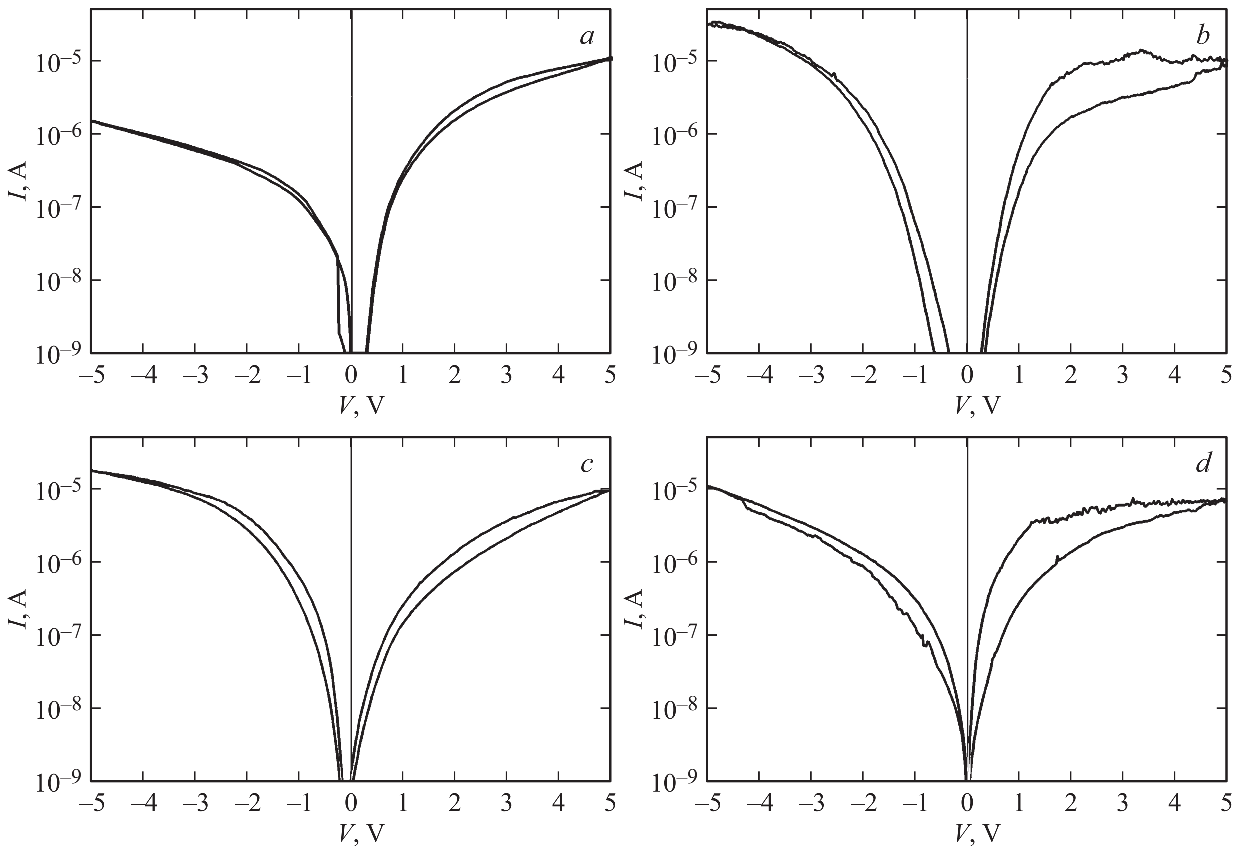

Figure 4. Cyclic $I-V$ curves of the MIS-structure ITO/ZrO_2(Y)/Ge/n-Si/n^+-Si(001) in the darkness (a) and in the photoexcitation with the various wavelengths ($b-d$): 472 nm (b), 660 nm (c), IR (d).

(Fig. 4, c). At the same time, as it follows from the photo-emf spectrum (Fig. 3), the factor of the interband optical absorption in the layer of the Ge nanoislands is significantly less than that in the bulk Si in the spectrum area of the interband absorption. It can be explained by the fact that the investigation of the photoexcitation influence on the RS included the IR photoexcitation by the wideband radiation source. As it is known, the radiation spectrum of the tungsten incandescent lamp is close to the radiation spectrum of the black body, and the wavelength of its maximum is usually close to $1\,\mu$m, i.e. it is within the band of the interband optical absorption of the Ge nanoislands. Thus, the IR photoexcitation was in the other conditions as compared to the visible excitation, thereby providing comparable resulting levels of the photoexcitation in both cases (taking into account the spectral characteristics of the sources of the photoexcitation and the object of study).

4. Conclusion

The present paper has demonstrated the increase in the logical RS corridor in the MIS-structures of ITO/ZrO_2(Y)/n-Si/n^+-Si(001) with the Ge nanoislands in the photoexcitation by the IR radiation with the quantum energy below Si band gap. The obtained results show the fundamental possibility of future creation of the optically controlled memristors based on the indicated MIS-structures, for the so-called communicative wavelength range ($1.3-1.55\,\mu$m), including the memory photo-detector matrices (image detectors).

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Conflict of interest

The authors declare that they have no conflict of interest.

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