DOI 10.5162/SMSI2021/B9.1

Optoelectronic nociceptive sensors based on heterostructured semiconductor films

Mohammad Karbalaei Akbari[1], *Serge Zhuiykov*[1],
[1] *Gent University Global Campus, 119 Songdomunhwa-ro, Yeonsu-gu,*
Incheon 21985, South Korea
serge.zhuiykov@ugent.be

Summary:

A visible light optical nociceptive sensor was developed based on the heterostructured plasmonic $Au/G_2O_3/TiO_2$ semiconductor films. The incorporation of nitrogen atoms and the following phase transformation of G_2O_3 ultra-thin film during rapid thermal annealing enabled the nociceptive characteristics in heterostructured G_2O_3/TiO_2 plasmonic visible light sensor. The fabricated nociceptor showed the post-synaptic current, nociceptive threshold and non-adaption modes in normal states.

Keywords: Heterostructured Semiconductors, Nociceptors, Optical Sensing, Atomic Layer Deposition

Introduction

Bio-inspired nano-electronic technology is the fundamental knowledge toward the development of advanced artificial intelligence systems. The visual light reception and nociception are among the main functionalities of human eye sensory system where the accurate detection, processing and realization of optical signals lead to the visual cognition. The human eye is composed of thousands of visible light sensors and receptors which receives the environmental visible light signals, turn them into chemical pulses and send them to brain via optic nerve. Nociceptors are one of the key sensory receptors in human body with the capability of smart sensing of harmful stimuli. The human cornea has the highest number of nociceptors which generate warning signals through the neural system to brain to eventually trigger the human sensorimotor responses and then to minimize the potential sensitization (Fig. 1) [1]. The main component of such a sensory system is natural synapses, where the ultra-fast and ultra-low energy transfer of presynaptic pulses via ionic neurotransmitters through synaptic gaps enables the functionalities of human nervous system. A developed analogous artificial synaptic device composed of a nano-scaled semiconductor film sandwiched between conductive layers. Here, the ionic transfer in sandwiched semiconductor film changes the resistive switching (RS) mechanisms in the film, which resembles the transfer of ionic pulses in natural synaptic gaps. In the same concept, a heterostructured G_2O_3/TiO_2 synaptic film was deposited on the Au substrate. The heterostructured semiconductor film acts as the synaptic junction, where the Au substrate acts as plasmonic antenna which receives the visible light and transfer optically generated pulses to semiconductor body (TiO_2). The heterointerface engineering is the main strategy here to manipulate the heterointerfaces and to control the charge transfer between semiconductors and Au film of nociceptors.

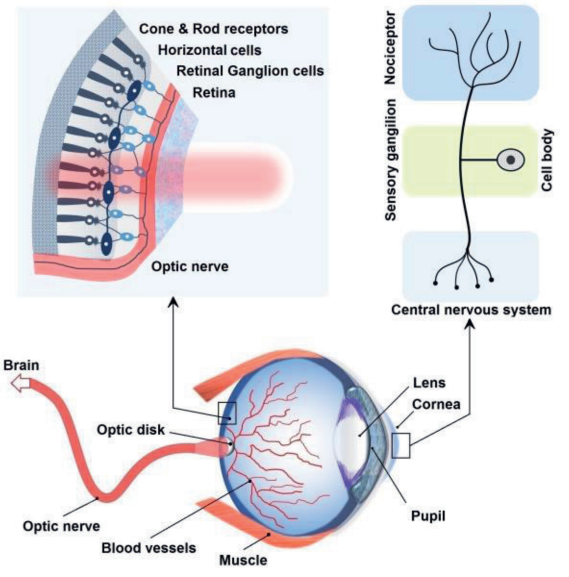

Fig. 1.The graphical scheme shows the structure of natural light receptors and nociceptors in human eye.

Results

Atomic layer deposition was used to deposit 4.0 nm thick Ga_2O_3 film on the Au substrate. The following rapid thermal annealing of Ga_2O_3 film in nitrogen at 450°C was accompanied by the phase transformation of film. In the Raman spectra, the characteristic peak of Ga-N bonding (E_2) was detected at binding energy of 515 cm^{-1}. XPS results demonstrated that the N_2 incorporation into gallium oxide film was

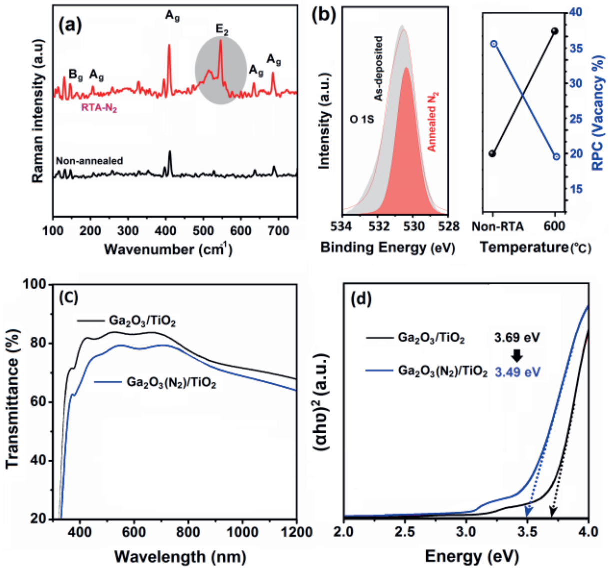

Fig. 2. (a) The Raman Spectra of as-deposited and N_2 annealed Ga_2O_3 films. (b) The XPS spectra of the similar samples including their Vacancy percentage. (c) The transmittance spectra and (d) bandgap of heterostructured Ga_2O_3/TiO_2 films.

accompanied by the decrease of intensity of O 1s peak and following shift of peak to lower binding energies. It confirms the replacement of oxygen vacancies with atomic nitrogen (Fig. 2b). The investigation of transmittance spectra of Ga_2O_3 (4.0 nm) / TiO_2 (19.0 nm) samples showed a high level of transparency in both samples in visible light region, with a slight decrease of transparency after nitrogen incorporation in Ga_2O_3 film. The measurement of bandgap energy via transmittance spectra of heterostructured samples showed the decease of bandgap from 3.69 eV to 3.49 eV. Considering the bandgap values of heterostructured Ga_2O_3/TiO_2 and Ga_2O_3 $(N_2)/TiO_2$ films, the UV source is required to excite the electrons from valence band to conduction bands of semiconductors. However, by using an Au antenna as plasmonic substrate it is possible to use the visible light to generate plasmonic hot electrons at the heterointerfaces between Au and Ga_2O_3. These hot electrons can be later transmitted to the main semiconductor body (TiO_2). This plasmonic heterostructured semiconductor acts as a resistive switching layer where the transfer of photogenerated charges between two conductive electrodes through semiconductor film enables the resistive switching characteristics. In this case, a tunable visible light (λ=650 nm) was used to excite the photoelectrons in Au/Ga_2O_3 $(N_2)/TiO_2$ heterostructured films. The following optoelectronic measurements confirmed that the Au/Ga_2O_3 $(N_2)/TiO_2/$ ITO (indium tin oxide) optoelectronic sensor showed the relaxation phenomenon which is a nociceptive characteristic. (Fig. 3a). It was also found that the higher light frequency resulted in the longer relaxation time (larger post-synaptic current) of nociceptors (Fig. 3b). The ignition (t_0) and saturation (t_s) time are two other main properties of optical nociceptors which show the light-intensity dependence performance of Au/Ga_2O_3 $(N_2)/TiO_2$ nociceptor (Fig. 3c). It was observed that the ignition time of nociceptive sensor was the factor of light intensity where the higher light intensity evoked the nociceptor response in the shorter ignition time. Fig. 3d also shows the difference between abnormal and normal performance of a nociceptor sensor, where the ignition time of a damaged nociceptor shifted to the initiation point of experiment.

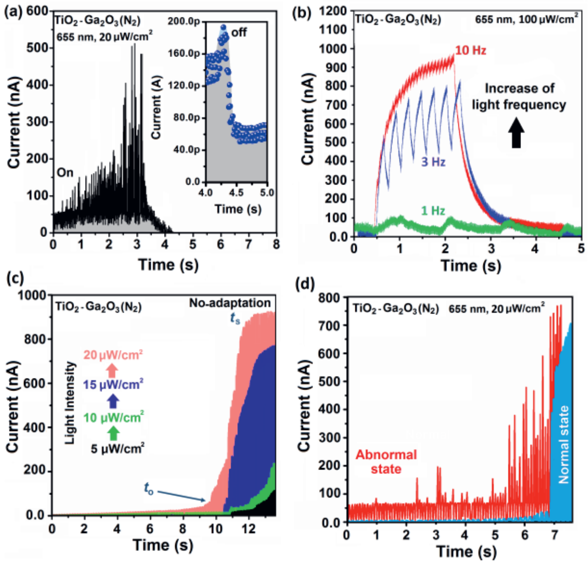

Fig. 3. (a) The relaxation time of Au/Ga_2O_3 $(N_2)/TiO_2$ (b) the light frequency dependence of post-synaptic photocurrent. (c) The dependence of ignition and saturation time to the light intensity. (d) The normal vs. abnormal photoresponse of nociceptors.

Conclusions

Heterointerface engineering enabled the fabrication of a visible light nociceptor device based on heterostructured Au/Ga_2O_3 $(N_2)/TiO_2$ ITO films. The incorporation of N_2 atoms in interlayer Ga_2O_3 assisted the control of photogenerated charge carriers at $Au/G_2O_3/TiO_2$ heterointerfaces. This sensor showed the fundamental characteristics of a visible light nociceptor including the relaxation, Ignition and saturation times.

References:

[1] M. Karbalaei Akbari, S. Zhuiykov, A bioinspired optoelectronically engineered artificial neurorobotics device with sensorimotor functionalities, *Nature Communications* 10 (2019) 3873.