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Original Research

# Au plasmon enhanced high performance $\beta$-$Ga_2O_3$ solar-blind photo-detector

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## Abstract

Surface plasmon polariton (SPP) is electro-magnetic wave coupled to free electron oscillations near the surface of metal, and has been used to improve the photoelectric properties in many optoelectronic devices. In the present study, the Au nanoparticles (NPs)/$\beta$-$Ga_2O_3$ composite thin film was fabricated through depositing Au ultra-thin film on the $\beta$-$Ga_2O_3$ thin film followed by post-thermal treatment. Compared to bare $\beta$-$Ga_2O_3$ thin film, a significant absorption around 510 nm, which is attributed to SPP of Au NPs, was observed in the UV–vis spectrum of Au NPs/$\beta$-$Ga_2O_3$ composite thin film. The results showed that the photoresponse of Au NPs/$Ga_2O_3$ photodetector illuminated under 254 nm + 532 nm light was much higher than that illuminated under 254 nm light, indicating an enhancement of photoelectric property for the solar-blind photodetector based on $\beta$-$Ga_2O_3$ thin film.


*Keywords:* Au/$Ga_2O_3$; Surface plasmon polariton; Enhance; Solar-blind photodetector

## 1. Introduction

Due to its wide application in many areas, such as missile launching detection, space and astronomical research, environmental monitoring, UV radiation calibration and monitoring, and optical communication, UV detectors have attracted considerable amount of research interests [1–3]. Many kinds of wide bandgap semiconductors, including GaN, SiC, ZnO and $Ga_2O_3$ etc., have been developed and applied on fabrication of UV photodetectors [4,5]. Among these wide bandgap semiconductors, $Ga_2O_3$, with a wide direct band gap of 4.9 eV, has been a potential candidate for short-wavelength optoelectronics applications such as light-emitting diodes [6], and UV photodetectors [7–9]. However, from the UV photodetectors point of view, high internal quantum efficiency does not always warrant high external efficiency. In particular, it is well known that a large amount of light is usually trapped inside the luminescent layer that results in a low external efficiency. Hence, it is important to obtain high efficiency for application in short wavelength light sources and optoelectronic devices. Several studies have been conducted to optimize the growth parameters and tune oxygen vacancy to enhance performance in $Ga_2O_3$ photodetectors [7,10], but only small progress has been achieved. It is very important to improve the responsivity of $Ga_2O_3$ based UV photodetectors. SPP is electro-magnetic wave coupled to free electron oscillations closed to the metal surface, leading to giant enhancement of the local electromagnetic field around nanoparticles, and has been used to improve the photoelectric properties of optoelectronic devices [11,12]. In this work, Au NPs/$Ga_2O_3$ thin film based UV photodetectors was fabricated, and much larger photocurrents than that in the film of $Ga_2O_3$ without Au

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nanoparticles was observed, suggesting that the introduction of SPP can improve the photoelectric properties of $Ga_2O_3$ based UV photodetectors.

## 2. Experimental

The $\beta$-$Ga_2O_3$ thin film with a thickness of 100 nm was prepared by radio frequency magnetron sputtering. Silicon (100) was used as substrates for film deposition. Before sputtering, the substrate was cleaned in the water, acetone, water, ethanol, and water under ultrasonic cleaning for 5, 10, 5, 10, and 5 min in turn to remove the impurities on the surface. The deposition chamber was evacuated to a pressure of $\sim 10^{-5}$ Pa, and then, high pure argon was admitted up to a pressure of 0.8 Pa (sputtering). The $\beta$-$Ga_2O_3$ thin films were prepared for 1.5 h at 750 °C, using a target-to-substrate distance of 50 mm. The sputtering power of is 80 W. In order to obtain Au NPs, the Au thin film was deposited (for 10 s/20 s) by DC frequency magnetron sputtering onto the $Ga_2O_3$ thin film and then post-treatment for 1 h at 750 °C in situ. After that, electrodes of Ti (20 nm)/Au (100 nm) layer in radius of 0.75 mm were deposited on the Au NPs/$\beta$-$Ga_2O_3$ composite thin film by DC sputtering using shadow mask, followed by thermally annealing at 200 °C for 10 min in Ar ambient.

The morphology and structure of detectors were characterized by a Hitachi S-4800 field emission scanning electron microscope (FE-SEM). Ultraviolet–visible (UV–vis) absorption spectrum was taken using a Hitachi U-3900 UV–visible spectrophotometer. The current–voltage (*I–V*) characteristics and time-dependent photoresponse of the photodetectors were measured by Keithely 2450. The photocurrent was measured under illumination of 254 nm and 532 nm UV lights.

## 3. Results and discussion

Fig. 1 shows the SEM micro-images of the surface of bare $\beta$-$Ga_2O_3$ thin film and Au (10 s) NPs/$\beta$-$Ga_2O_3$ composite thin films. The bare $\beta$-$Ga_2O_3$ thin film shows a dense and smooth morphology (Fig. 1a). The thickness of the thin film was estimated to be 100 nm (Fig. 1b). The uniform dispersal of Au nanoparticles in the average size of 70 nm on the $\beta$-$Ga_2O_3$ surface is quite evident from the SEM images (Fig. 1c).

The optical absorption measurements are extremely important in evaluating the optical parameters of thin films such as absorption coefficient and energy band gap etc. In order to obtain the optical properties of thin film, we deposited similar films on sapphire substrate. The UV–vis absorbance spectra of bare $\beta$-$Ga_2O_3$ thin film and Au NPs/$\beta$-$Ga_2O_3$ composite thin film on sapphire substrate are shown in Fig. 2. For the bare $\beta$-$Ga_2O_3$ thin film, a significant absorption was observed at wavelengths less than 250 nm, near the lower edge of the solar-blind region. Compared with bare $\beta$-$Ga_2O_3$ thin film, except the absorption less than 250 nm, it was found that a significant absorption of Au NPs/$\beta$-$Ga_2O_3$ composite thin film located at around 510 nm due to the resonant absorption of Au NPs.

A further analysis of the optical spectra was performed to calculate energy band gap. For $\beta$-$Ga_2O_3$ with a direct band gap, the absorption follows a power law of the form [13–15]:

$$(\alpha h\nu)^2 = B\left(h\nu - E_g\right) \qquad (1)$$

where $h\nu$ is the energy of the incident photon, $\alpha$ is the absorption coefficient, B is the absorption edge width parameter, and $E_g$ is the band gap. The optical absorption coefficient, $\alpha$, of the film is evaluated using the relation:

$$\alpha = \left[1/d\right]\ln\left(10^A\right) \qquad (2)$$

where $d$ is the film thickness, and $A$ is the absorbance. The optical band gap was determined by extrapolating the linear region of the plot $(\alpha h\nu)^2$ versus $h\nu$ and taking the intercept on the $h\nu$-axis. The obtained band gap was $\sim$5.0 eV as shown in the inset of Fig. 2, which is larger than that of $\beta$-$Ga_2O_3$, which has been reported to be 4.9 eV.

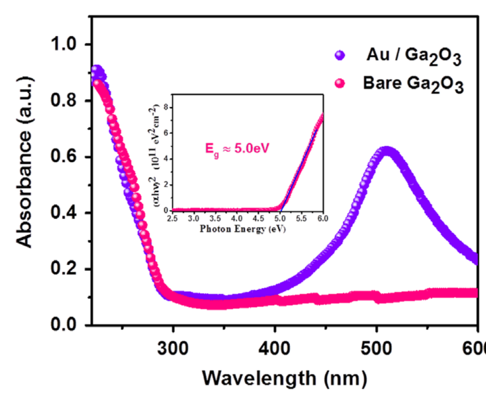


Fig. 2. UV–vis absorbance spectrum of the bare $\beta$-$Ga_2O_3$ thin film and Au NPs/$\beta$-$Ga_2O_3$ composite thin film.

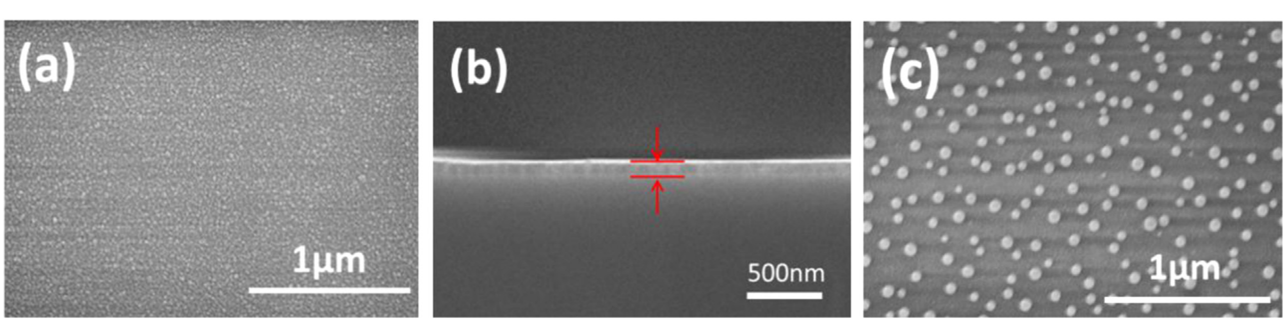


Fig. 1. SEM images of (a) bare $\beta$-$Ga_2O_3$, (b) cross-section of a $\beta$-$Ga_2O_3$ thin film and (c) Au NPs/$\beta$-$Ga_2O_3$ composite thin film.