# $Zn_{0.8}Mg_{0.2}O$-based metal–semiconductor–metal photodiodes on quartz for visible-blind ultraviolet detection



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# $Zn_{0.8}Mg_{0.2}O$-based metal–semiconductor–metal photodiodes on quartz for visible-blind ultraviolet detection

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**Abstract**

$Zn_{0.8}Mg_{0.2}O$ metal–semiconductor–metal ultraviolet photodiodes were fabricated on quartz by radio frequency magnetron sputtering. Dark current, spectral responsivity and pulse response experiments were carried out for the device. The photodetectors showed a peak responsivity at 330 nm. The ultraviolet-visible rejection ratio ($R$330 nm/$R$400 nm) was more than four orders of magnitude at 3 V bias. The photodetector showed fast photoresponse with a rise time of 10 ns and a fall time of 170 ns. In addition, the thermally limited detectivity was calculated to be $3.1 \times 10^{11}$ cm $Hz^{1/2}$ $W^{-1}$ at 330 nm.

(Some figures in this article are in colour only in the electronic version)

## 1. Introduction

Visible-blind ultraviolet photodetectors are in demand for a wide range of applications such as flame detection, engine monitoring, missile plume detection, chemical sensing, and intersatellite communications [1–5]. Due to its wide direct band gap, the ZnMgO material system is an excellent choice for optoelectronic devices in the ultraviolet (UV) portion of the spectrum. $Zn_{1-x}Mg_xO$ also possesses unique figures of merit, such as the availability of lattice-matched single-crystal substrates (ZnO and MgO for hexagonal and cubic $Zn_{1-x}Mg_xO$ films, respectively) [6], tunable band-gap energy (3.3–7.8 eV) [7–9], relatively low thin-film growth temperatures (100–750 °C) [9], intrinsic visible blindness and radiation hardness [10], which are crucial for practical optoelectronic devices. However, the lack of reliable p-type ZnMgO hinders any p–n junction-based optoelectronic devices. In contrast metal–semiconductor–metal (MSM) structured UV detectors with either Schottky or Ohmic contacts have attracted great interest [6, 11, 12] due to their simple structure and their not needing reliable p-type ZnMgO. Furthermore, MSM photodiodes have several attractive features which make them ideal candidates for space applications, such as a very low dark current, high responsivity, a large bandwidth and low noise densities [14]. Solar or visible–blind $Zn_{1-x}Mg_xO$ photodetectors have been fabricated on sapphire [6, 11], glass, [6] and silicon substrates [12, 13]. Hullavarad *et al* have reported that the UV/visible rejection ratio, a quantity defined as the ratio of photoresponse at 310–800 nm, is $10^4$ for $Mg_{0.15}Zn_{0.85}O$ on $Al_2O_3$ and $10^3$ on quartz substrates [6]. Photodetectors fabricated on $Mg_{0.68}Zn_{0.32}O/SrTiO_3/Si$ show that the peak photoresponse is at 225 nm and the UV/visible rejection ratio is only one order of magnitude for the detector [13]. Prototype $Zn_{1-x}Mg_xO$ UV photodetectors with different Mg contents have been fabricated and analysed, revealing high photoresponsivities with sharp cutoffs at ∼375 nm, ∼350 nm, ∼315 nm and ∼300 nm for the $x$ values of 0, 0.10, 0.26 and 0.34, respectively [12].

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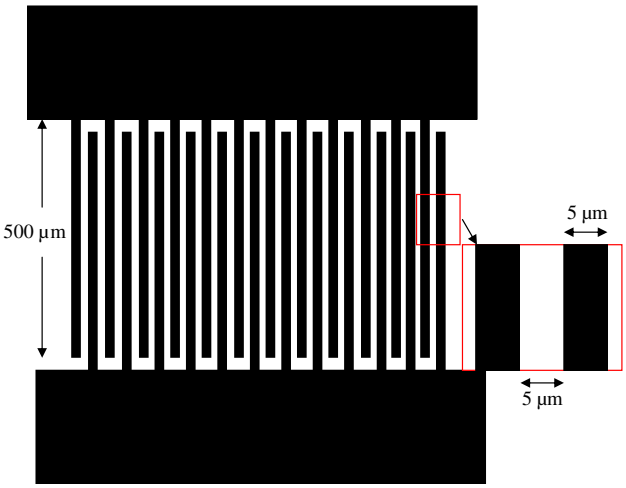


**Figure 1.** Schematic full view of the interdigital metal electrodes of the $Zn_{0.8}Mg_{0.2}O$ UV detector.

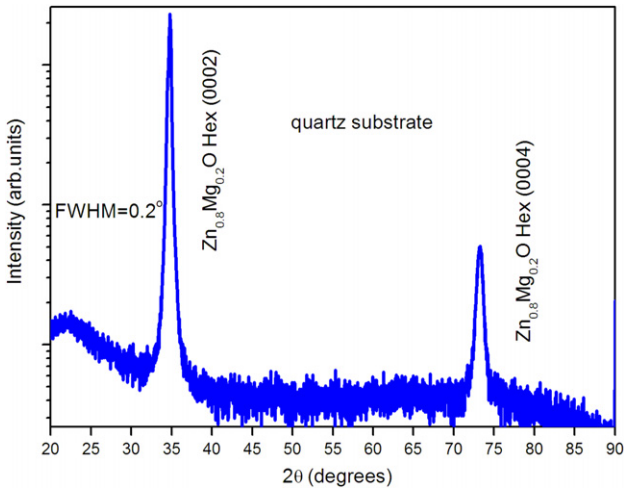


**Figure 2.** XRD spectra of the $Zn_{0.8}Mg_{0.2}O$ film prepared by rf magnetron sputtering on quartz at 500 °C.

Although the electronic and spectral responsivities of the MSM photodetectors based on pulsed laser deposition- and molecular beam epitaxy-grown ZnMgO films on deferent substrates have been achieved, there is no report on the properties of photodetectors based on ZnMgO films prepared by other methods. In this paper, the MSM photodetectors were fabricated on 1 $\mu$m-thick $Zn_{0.8}Mg_{0.2}O$ films on quartz substrates by radio frequency (rf) magnetron sputtering. Low dark current and fast photoresponse were achieved. The detectivity of the device has also been calculated.

## 2. Experiment

$Zn_{0.8}Mg_{0.2}O$ thin films were grown on quartz substrates using an rf magnetron sputtering technique. High-purity $Zn_{0.82}Mg_{0.18}O$ ceramic was selected as the target. The substrates were cleaned using acetone and ethanol for 5 min in an ultrasonic bath, followed by rinsing with de-ionized water. Quartz substrates were placed on the sample holder parallel to the $Zn_{0.82}Mg_{0.18}O$ target. The substrate to target distance was 7.5 cm. The chamber was pumped down to a high vacuum of $10^{-4}$ Pa by a turbo molecular pump. The working pressure in chamber was kept at 1.0 Pa during the film growth. The rf power was kept at 100 W. Ultrapure (5N) Ar gas was introduced into the sputtering chamber through a mass flow controller with the flow rate of 60 SCCM (standard cubic centimetre per minute). The substrates' temperature during deposition was kept at 500 °C. The rate of deposition for the $Zn_{0.8}Mg_{0.2}O$ films was 250 nm $h^{-1}$ and the thickness of the films was 1 $\mu$m.

The interdigital metal electrodes, which were defined on a 200 nm Au layer by conventional UV photolithography and lift-off procedure, are 500 $\mu$m long and 5 $\mu$m wide, with a 5 $\mu$m gap. Figure 1 shows the schematic full view of the interdigital metal electrodes of the $Zn_{0.8}Mg_{0.2}O$ UV detector, in which the black and white parts are the electrode and $Zn_{0.8}Mg_{0.2}O$, respectively. There are 24 fingers in our interdigital structure, 12 up and 12 down.

A Ringaku O/max-RA x-ray diffractometer with Cu K$\alpha$ radiation ($\lambda = 0.154\,178$ nm) was used to make $\theta$–$2\theta$ scans to evaluate the crystalline property of $Zn_{0.8}Mg_{0.2}O$. Both optical transmission and absorption spectra were recorded using a Shimadzu UV-3101PC scanning spectrophotometer. The dark current was measured by a semiconductor parameter analyser with a sensitivity of 0.1 pA. A standard lock-in amplifier technique was employed for the spectral response measurements, where a 150 W Xe lamp was used. The time-resolved response was obtained using a YAG : Nd laser with a wavelength of 266 nm and a pulse width of 10 ns. The transient signal was recorded by a boxcar with a 50 Ω impedance.

## 3. Results and discussion

Figure 2 shows the XRD $\theta$–$2\theta$ scans for the $Zn_{0.8}Mg_{0.2}O$ film grown on the quartz substrate. The appearance of only (0 0 0 1) peaks indicates that the film is highly *c*-axis oriented and corresponds to the hexagonal wurtzite structure of ZnMgO. The peaks around $2\theta = 34°$ correspond to the (0 0 0 2) orientation of the $Zn_{1-x}Mg_xO$ hexagonal structure. The $Zn_{0.8}Mg_{0.2}O$ films show strong (0 0 0 2) and (0 0 0 4) reflections, and no other phase can be found. It should be noted that the full-width-half-maximum (FWHM) of our $Zn_{0.8}Mg_{0.2}O$ XRD peak is 0.2°, which is similar to those observed from the $Mg_{0.15}Zn_{0.85}O$ film grown on the sapphire substrate [6]. Such small XRD FWHM suggests that the crystal quality of our $Zn_{0.8}Mg_{0.2}O$ film was reasonably good. Figure 3 shows the transmittance and absorption spectra of the film. The substrate contribution is excluded. There is a steep absorption edge at 350 nm. The $Zn_{0.8}Mg_{0.2}O$ optical band gap obtained from the absorption spectrum is about 3.54 eV at room temperature. The transmittance in the visible region is more than 85%.

Figure 4 shows the $I$–$V$ curve of the detector. The dark current was lower than 7 nA for $|V_{bias}| < 5$ V in the detector and it was dominated by thermionic carrier transport. Furthermore, it does not break down even up to 100 V bias voltages (inset of figure 4). The low dark current and high breakdown voltage show the high quality $Zn_{0.8}Mg_{0.2}O$ layer and good Schottky contacts.

Figure 5 displays the spectral response of the $Zn_{0.8}Mg_{0.2}O$ MSM photodetector for a bias of 3 V. The peak response is

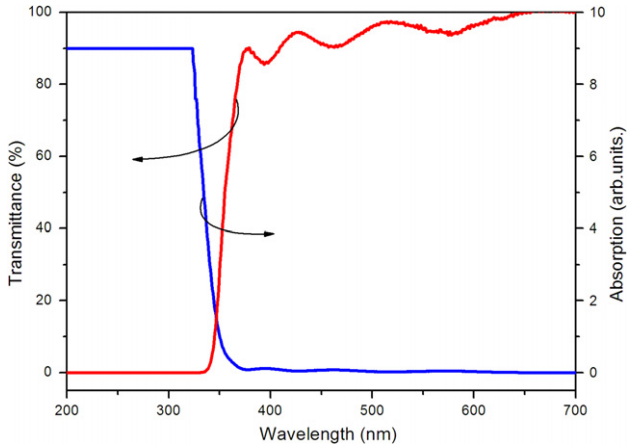


**Figure 3.** UV-visible transmission and absorption spectrum of $Zn_{0.8}Mg_{0.2}O$ on the quartz substrate.

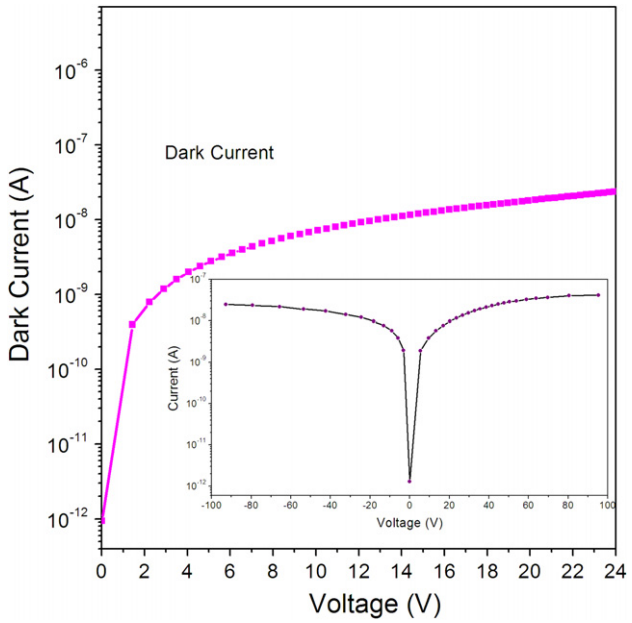


**Figure 4.** Dark current of $Zn_{0.8}Mg_{0.2}O$ MSM photodiodes.

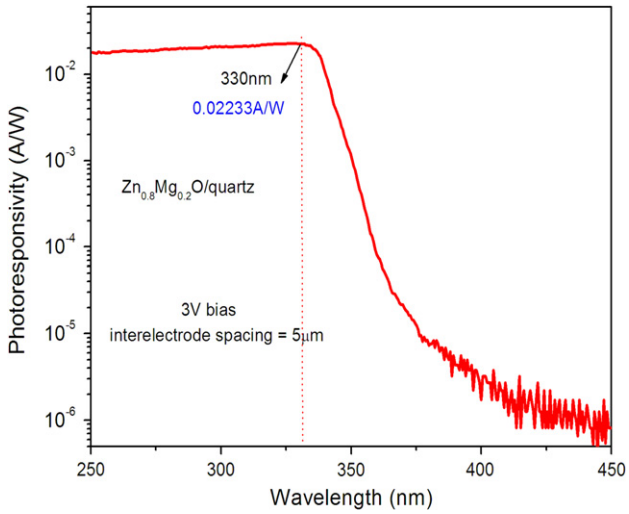


**Figure 5.** Spectral response of the $Zn_{0.8}Mg_{0.2}O$ UV detector with 5 $\mu$m finger pitch biased at 3 V.

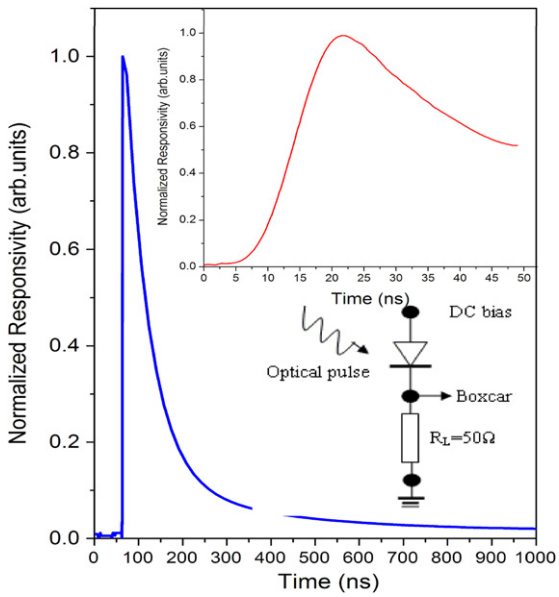


**Figure 6.** Normalized pulse response measurement of the $Zn_{0.8}Mg_{0.2}O$ UV detector excited by Nd-YAG laser pulses (266 nm, ~10 ns).

found at 330 nm with a responsivity of 0.02233 A $W^{-1}$ and the cutoff occurring at around 350 nm (the absorption edge of $Zn_{0.8}Mg_{0.2}O$). Meanwhile, it should be noted that the visible rejection ($R330\,\text{nm}/R400\,\text{nm}$) is more than four orders of magnitude, indicating a high degree of visible blindness. A flat short-wavelength spectral response was also observed in this figure.

The expression of the responsivity can be given by the following equation(2): $R = q\lambda\eta/hc$, where $\lambda$ is the incident photon wavelength, $\eta$ is the external quantum efficiency, $h$ is Planck's constant and $c$ is the light velocity. In theory maximum responsivity is 0.266 A $W^{-1}$ at 330 nm, without surface reflection. When the surface reflection is not taken into account, the experimental values of the peak responsivity in our devices yield a $\eta$ product of 8.5%. The value of the quantum efficiency for photoenergies above the band gap depends on the finger pitch, the material quality and the bias. The spectral density of the noise current source $\langle i_{\text{rms}}^2 \rangle$ can be defined as[2] $\langle i_{\text{rms}}^2 \rangle = (4k_B T/R_{\text{dark}} + 2qI_{\text{dark}})\Delta f$, where $R_{\text{dark}}$ refers to the equivalent resistance obtained from the slope of the dark current $I$–$V$ curve at the bias point, $I_{\text{dark}}$ is the dark current at the bias point, $T$ is the temperature and $\Delta f$ is the bandwidth of the measurement. The noise equivalent power (NEP) can be calculated from the noise current: NEP $= i_{\text{rms}}/R$, where $R$ is the measured responsivity. Further, NEP can be used to define the detectivity ($D^*$): $D^* = (A\Delta f)^{1/2}/\text{NEP}$, where $A$ is the device area. The NEP of our device was found to be $1.2 \times 10^{-13}$ W $\text{Hz}^{-1/2}$ at room temperature, which corresponds to a detectivity of $3.1 \times 10^{11}$ cm $\text{Hz}^{1/2}$ $\text{W}^{-1}$ at 330 nm. This value is comparable to that of GaN-based MSM photodiodes [15].

Figure 6 shows the measured pulse response data of the devices. The detector was connected in series with a load

resistor ($R_L = 50\,\Omega$) and biased (as shown in figure 6). The measured pulse response of the $Zn_{0.8}Mg_{0.2}O$ MSM photodetector had a short rise time and an exponentially decaying fall time. The devices had rise times of 10 ns which are limited by the excitation laser (nominal pulse duration FWHM 10 ns). The 90–10% fall time is 170 ns and the slower trailing transient may be determined by two mechanisms: the *RC* time constant and the carrier transit across the finger gap. Usually, the photovoltaic detector response time was significantly dominated by the *RC* time constant of the device due to the large capacitance of the pn junction and the Schottky contact. However, the *RC* time constant limit could often be neglected for the MSM photodetector due to small capacitance. Therefore, the transit time limit should be responsible for the slow decay component. The electron velocity for the device with 5 $\mu$m gap was estimated from the ratio of the half distance between the electrodes (2.5 $\mu$m) to the measured FWHM of the response time (50 ns). Based on this result, it can be calculated that the electron velocity is $5 \times 10^3\,\mathrm{cm\,s^{-1}}$ at the average electric field of $6\,\mathrm{kV\,cm^{-1}}$.

## 4. Conclusions

We fabricated the MSM photodetectors based on the highly *c*-axis preferred oriented $Zn_{0.8}Mg_{0.2}O$ films by rf magnetron sputtering on quartz. The detector showed a low dark current (below 7 nA for $|V_{bias}| < 5$ V) due to high crystal quality and good Schottky contacts. A sharp long-wavelength cutoff was experimentally observed at 350 nm. The transient response measurement revealed fast photoresponse with a rise time of 10 ns which is limited by the excitation laser and a fall time of 170 ns which is determined by the transit time. Meanwhile, the NEP of our device was found to be $1.2 \times 10^{-13}\,\mathrm{W\,Hz^{-1/2}}$ at room temperature, which corresponds to a detectivity of $3.1 \times 10^{11}\,\mathrm{cm\,Hz^{1/2}\,W^{-1}}$ at 330 nm.

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