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ZnO based surface acoustic wave ultraviolet photo sensor

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Abstract Ultraviolet (UV) sensor based on ZnO thin film surface acoustic wave (SAW) device is reported. ZnO films were grown using an RF magnetron sputtering technique. SAW devices were made using such ZnO films exhibiting a central frequency at ~41.2 MHz. The SAW UV sensor was fabricated by depositing a 70 nm thin photoconducting ZnO overlayer on the fabricated SAW device. The SAW UV sensor was found to exhibit interesting photoresponse behavior to UV illumination, and a downshift in frequency of ~45 kHz, and a change in insertion loss ~1.1 dB were observed under UV illumination intensity of 19 mW/cm^2. The changes in the frequency of operation and the insertion loss have been attributed to the acoustoelectric interaction between the photogenerated charge carriers and the potential associated with the acoustic waves. Results show the promise of ZnO for the fabrication of low cost wireless SAW UV sensors.

Keywords UV sensor · ZnO film · Magnetron sputtering · SAW devices

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1 Introduction

ZnO, a wide band gap semiconducting oxide material (band gap=3.3 eV) is gaining considerable attention due to its versatile properties. It exhibits excellent piezoelectric, optical, and semiconducting properties, and finds application in transparent conductor, thin film gas sensor, varistor, surface acoustic wave (SAW) devices, optical wave-guides, acousto-optic modulators/deflectors, ultraviolet (UV) LASER source, and UV detectors [1–10]. Its easy processing and tunable properties make ZnO as one of the highly researched materials in these days [10–12]. ZnO possesses a significant electromechanical coupling coefficient, and is possibly the first material of its kind, which was successfully exploited to make commercial SAW devices in thin film form [13]. The response of SAW devices is very sensitive to any external perturbation that is taking place on its surface. This behavior of SAW device can be utilized for various applications like gas sensors, chemical sensors, biological sensors, optical sensors etc., if the medium between the input and output interdigital transducers (IDTs) is covered by a sensing layer [3–9]. Probably the most interesting application of surface acoustic waves is a phenomenon known as acoustic charge transport (ACT). ACT involves the interaction between surface acoustic waves and free electrons within a piezoelectric semiconductor. Extensive theoretical [14,15] and experimental [16,17] research has been made so far, particularly in the ACT properties of a two-dimensional electron gas (2DEG), formed within a GaAs/Al$_x$Ga$_{1-x}$As heterostructures. Properties of the semiconductor result in an acoustoelectric interaction in which electric field waves corresponding to the acoustic waves interact with the 2DEG. The ACT behavior in a device can be used to design novel devices, if instead of placing a semiconducting layer on top of a SAW device, a photoconducting layer is used,

Table 1 Deposition parameters for the growth of ZnO thin films.

	Photoconducting films	Insulating films
Sputtering mode	RF magnetron	RF magnetron
Target	Zn Metal (99.99%)	Zn Metal (99.99%)
Substrates	Glass and fused quartz	Fused quartz
RF power	500–600 W	600 W
Sputtering pressure	50 mTorr	25 mTorr
Sputtering gas	100% O_2	60% O_2, 40% Ar
Substrate heating	No intentional heating	No intentional heating
Target to substrate	8.5 cm	10 cm

and the acoustoelectric interactions in these structures are induced by optical radiation, then various types of optical sensors based on SAW structures can be imagined. One of the first reports on the UV detectors based on SAW devices was published by Ciplys et. al. [5], where they reported the UV photoresponse of a GaN based SAW oscillator operating at 221.34 MHz. A downshift in the oscillator frequency (60 KHz) under UV illumination was observed. Palacious et al. [6] demonstrated the ACT behavior in a GaN based SAW device on c-plane sapphire under UV light illumination. Interestingly, exploiting the photoconducting property of ZnO and piezoelectric property of $LiNbO_3$, Sharma et al. [8] reported the UV photoresponse of ZnO/$LiNbO_3$ bilayer SAW device exhibiting a downshift in frequency of ~170 kHz under UV illumination of 35 mW/cm^2. Very recently, Emanetoglu et al. [7] reported a UV photodetector fabricated with ZnO/Mg:ZnO/ZnO multilayers on r-plane sapphire, capable of detecting UV intensity of 810 μW/cm^2 using the Sezawa mode of a SAW device (711.3 MHz). Based on these developments it can be inferred that SAW UV sensors have a promising future, and ZnO has shown a tremendous potential for the design of such sensors. ZnO is well known for its photoconducting properties especially in UV region [7–11] with an added advantage of exhibiting a good piezoelectric property [10, 13]. Therefore, combining the piezoelectric and photoconducting properties of ZnO can lead to an interesting class of promising SAW UV sensor. This can be achieved by fabricating a ZnO thin film SAW device with an overlayer of photoconducting ZnO thin film.

In the present work, we report the fabrication and characterization of UV sensor based on ZnO thin film SAW device. The UV sensor is designed by depositing photoconducting ZnO thin layer on the surface of a ZnO thin film based SAW device, and the response characteristics of the bilayer SAW structure is investigated under UV illumination.

2 Experimental

For the fabrication of ZnO thin film SAW devices, ZnO films were deposited on 3 in. fused quartz wafers using an RF magnetron sputtering technique. The unit is equipped with a 6-in. diameter metallic zinc target (Cerac Inc., 99.99%). The sputtering conditions are listed in Table 1. For the fabrication of low frequency SAW devices, ZnO films of thickness ~14 μm were deposited. The magnetic configuration of the magnetron electrode was changed to slightly unbalanced mode (high rate), and a growth rate of 1.2–1.5 μm/h was achieved. The wafers could be coated with ZnO film with thickness ~14 μm within 10–12 h. The growth of photoconducting ZnO film was done under the unbalanced mode of sputtering, which is known to produce highly photoconducting ZnO films, and has been reported elsewhere [9]. Table 1 lists the deposition condition used for the growth of photoconducting ZnO thin films.

The ZnO thin films were characterized using atomic force microscopy (AFM) and X-ray diffraction (XRD). The UV photoconductivity transient study was carried out using

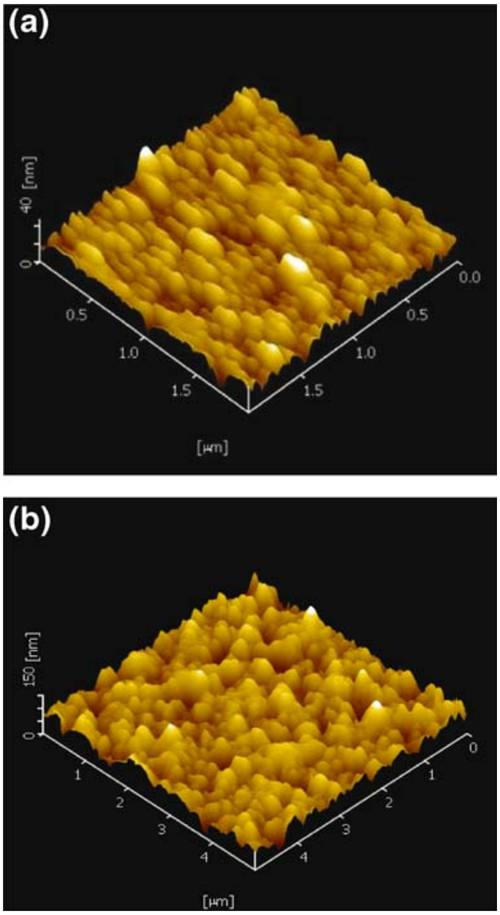

Fig. 1 Atomic force microscopy images of ZnO thin films (**a**) photoconducting ZnO film (70 nm): showing the elongated grains of average size ~74 nm; (**b**) insulating ZnO films (14 μm) showing the round shaped grains of average size ~365 nm

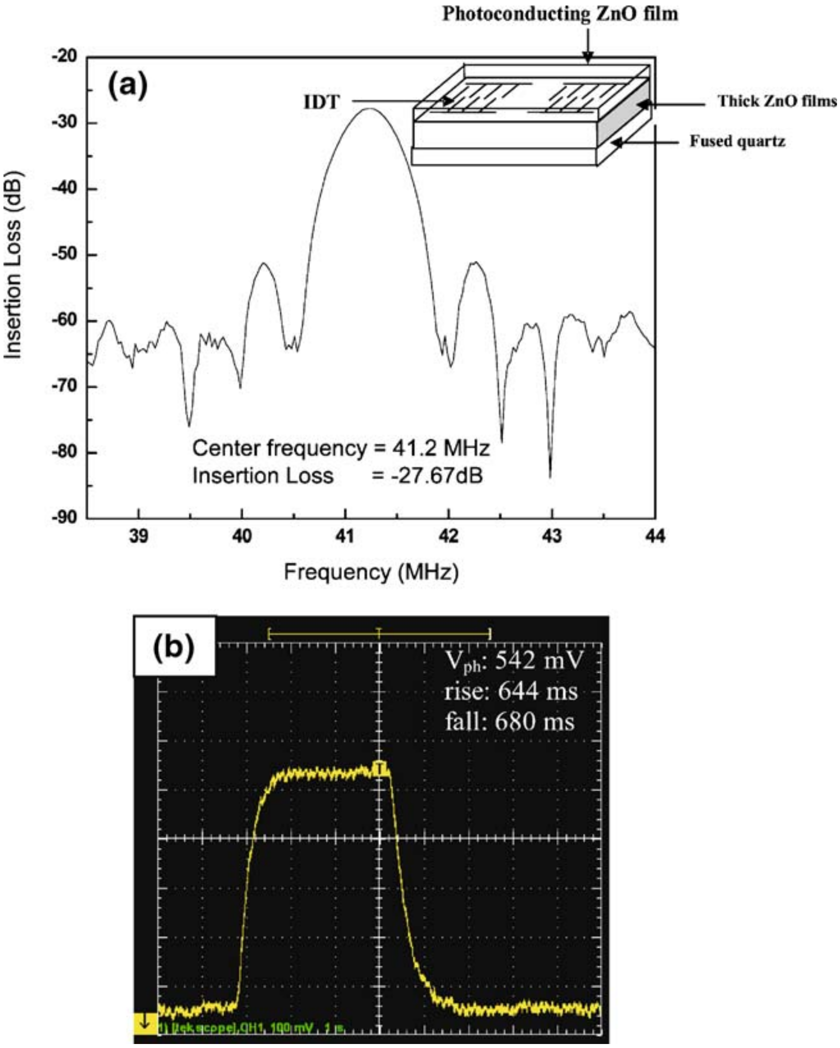

Fig. 2 (**a**) Frequency response of the fabricated ZnO thin film SAW device. *Inset* shows the structure of fabricated bilayer ZnO based SAW UV sensor. (**b**) Ultraviolet photoresponse of 70 nm thin photoconducting ZnO film under UV illumination intensity of 19 mW/cm^2. Scale: *x* axis=1 s/div; *y* axis=100 mV/div

a setup consists of a UV lamp (λ=365 nm) as a source of UV radiation and a Keithley microvolt ammeter (model 150B) interfaced to a Tektronix digital phosphorous oscilloscope (TDS 3320B) to record the observed photo-response. Network Analyzer (Agilent) was used to record the frequency spectrum of the SAW device.

3 Results and discussion

When examined by XRD, ZnO thin films (insulating and photoconducting type) grown by RF magnetron sputtering technique were found to exhibit polycrystalline nature, with preferred orientation along the c-axis (not shown). Surface

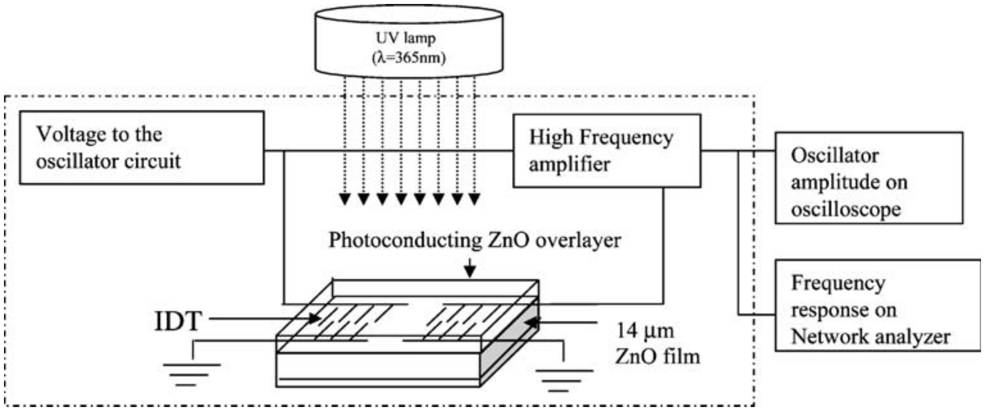

Fig. 3 Experimental set-up used for the characterization of ZnO thin film based SAW UV sensor

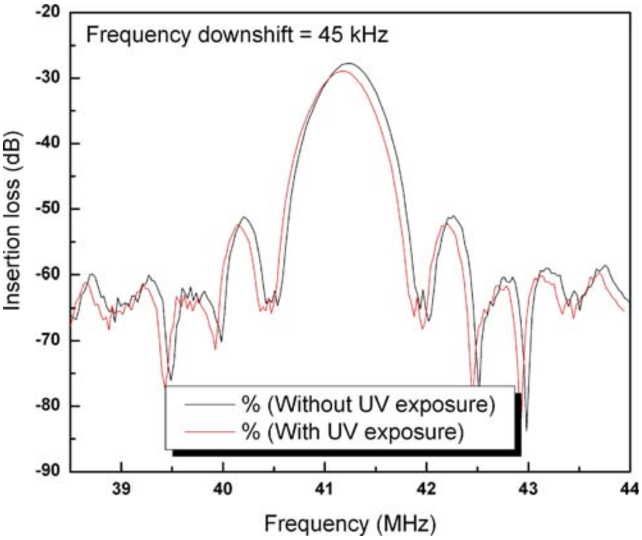

Fig. 4 Frequency response of ZnO thin film SAW device structure with photoconducting ZnO overlayer under UV illumination intensity of 19 mW/cm^2

morphology of the films was examined by AFM technique, and it was found that thicker films (14 μm) possessed average grain size value of 365 nm that were round in shape, in comparison to thin films (photoconducting type) that exhibited elongated grains [Fig. 1(a) and (b)]. The average size of these elongated grains along the short direction was estimated to be ~74 nm. The exact origin of the elongation of the grains is still not well understood, however, it may be attributed to the bombardment of ionic species during the growth of film, and such bombardments are intense in case of highly unbalanced magnetron sputtering. The smaller grain size value results in large surface to volume ratio, which is useful for exhibiting large photoconductance characteristics [9, 11].

3.1 ZnO thin film SAW device

The design and fabrication of a SAW device is a sophisticated process and assumes key significance because it is one of the critical components of the end product i.e. sensor. Thickness of the ZnO film required for the fabrication of a low frequency SAW filter has been theoretically calculated using the velocity dispersion data as a function of normalized thickness of ZnO film, and a thickness of ~14 μm of ZnO film was found sufficient to obtain SAW devices in the frequency range of 38–41 MHz. The Al IDTs were photo lithographically patterned on the ZnO film surface. The specifications of the fabricated IDTs are: the distance between the input and output IDTs electrodes—1.6 mm, the total number of fingers—200, the acoustic wavelength (λ)—44.32 μm, line width—9.79 μm, and the number of finger pairs—50. The typical response of the fabricated ZnO thin film SAW device operating at a central frequency of 41.2 MHz is shown in Fig. 2(a).

3.2 Photoresponse transient of ZnO thin layer

For the design of SAW UV sensor, photoconducting ZnO was employed as the UV sensing material. A thin layer of ZnO (~70 nm) was initially deposited separately on glass substrate to study its UV photoresponse transient. A pair of aluminum electrodes with a separation of 5 mm was vacuum evaporated on the surface of ZnO thin film. Figure 2(b) shows the UV photoresponse transient of ZnO film when illuminated by UV radiation (365 nm; Intensity=19 mW/cm^2). A fast rise (644 ms) in photoresponse characteristics was observed when UV was illuminating the film. It was interesting to note that decay in response was also fast (680 ms), when UV illumination was chopped and the film conductivity coincided with the dark conductivity value. It can be seen that such photoresponse characteristic is dominated by bulk related process, as there is no signature of shallow effect (shallow trapping) which is responsible for slow response in photoresponse behavior [11, 18]. Such photoresponse characteristic reveals that ZnO film (70 nm) exhibits excellent photoconductivity behavior and can be interfaced with ZnO based SAW device to make ZnO bilayer SAW UV sensor. Therefore, such thin layer of ZnO was sputtered deposited on the surface of fabricated ZnO thin film SAW device as shown in the inset of Fig. 2(a).

3.3 Characterization of SAW UV sensor

The fabricated ZnO thin film SAW UV sensor (Inset, Fig. 2(a)), was further characterized using a setup shown in Fig. 3. A high frequency amplifier was connected across the device so that a phase difference of 360° could be achieved across the loop. The frequency response of the ZnO bilayer SAW device was observed on a network analyzer.

To confirm that the photoresponse is originating only from the overlayer photoconducting ZnO layer, the fabricated ZnO thin film SAW device (without photoconducting ZnO overlayer) was examined under UV illumination, and no appreciable change in the frequency response of the SAW device was observed. This shows that the underneath insulating ZnO has no role in the photoresponse characteristics of ZnO SAW UV sensor, and the photoresponse is expected to originate only from photoconducting ZnO overlayer.

It is important to mention that the thickness of overlayer photoconducting ZnO film (~70 nm) was sufficient enough to produce no mass loading effect on the frequency response of the ZnO thin film SAW device. The SAW UV sensor was illuminated with UV intensity of 19 mW/cm^2, and a significant downshift in frequency response ~45 kHz was observed, and insertion loss was recorded to be 1.1 dB [Fig. 4]. The mechanism for the shift in frequency of operation of SAW device can be accounted by acousto-electric effect. Acoustoelectric effects are the interactions between the electric field generated by the SAW and photogenerated charge carriers in ZnO overlayer. The effect of wave/charge-carrier coupling on SAW propagation can be determined from a model that accounts for wave generated conduction currents in the film and the displacement current in the adjacent media [19]. The acoustic wave and the electric charge interaction i.e. acoustoelectric interaction results in a change in SAW velocity (Δv) and attenuation ($\Delta \Gamma$) and are given by [3]:

$$\frac{\Delta v}{v_\mathrm{o}} = \frac{K^2}{2}\frac{1}{1+(\sigma/\sigma_\mathrm{m})^2} \tag{1}$$

$$\Gamma = \frac{K^2}{2}\frac{2\pi}{\lambda}\frac{\sigma/\sigma_\mathrm{m}}{1+(\sigma/\sigma_\mathrm{m})^2} \tag{2}$$

Where σ is the sheet conductivity of the conducting film, and σ_m denotes a critical conductivity at which maximum attenuation occurs [$\sigma_\mathrm{m} = v_\mathrm{o}c_\mathrm{s}$, where $c_\mathrm{s} = \varepsilon_\mathrm{s} + \varepsilon_{\mathrm{o},}\varepsilon_\mathrm{s}$ and $\boldsymbol{\varepsilon}_\mathrm{o}$ are the dielectric constants of the substrate and vacuum, respectively]. K^2 is the electromechanical coupling coefficient of the substrate, and λ is the SAW wavelength.

Under UV illumination the photogenerated charge carriers interact with SAW potential due to acoustoelectric interactions (Eqs. 1 and 2), and result in (1) a change in SAW velocity, and hence a change in SAW operating frequency [$\Delta f\sim 45$ kHz]; (2) Under UV illumination the overlayer ZnO film produces photogenerated charge carriers, and provides a conducting path to the SAW, and results in attenuation or increase in insertion loss of the device [ΔIL ~ 1.1 dB].

Figure 4 shows the photoresponse of ZnO thin film UV sensor with and without UV illumination. It is important to note that no persistent effect in the photoresponse behavior was observed, and this can be considered entirely due to saturating behavior in photoresponse of overlayer ZnO thin film (Fig. 2(b)). In a previous report a continuous decrease in SAW frequency and increase in insertion loss was observed due to non-saturating photoconducting behavior of overlayer ZnO film when deposited on $LiNbO_3$ SAW device [9]. In the present case, the photoresponse of the ZnO SAW UV sensor was examined by chopping UV illumination at regular interval, and reproducible results were observed and show the promise of ZnO bilayer SAW based UV sensor for commercial applications. The SAW based UV detector is still in its infancy, but the encouraging results of SAW structure integrated with photoconducting ZnO overlayer show the promise for future wireless UV sensors.

4 Conclusions

ZnO thin film SAW device has been configured in the form of UV sensor by integrating with a thin layer of photoconducting ZnO overlayer. The fabricated SAW UV sensor was found to operate at a central frequency of 41.2 MHz, and exhibited a significant response to UV illumination. A downshift in frequency (~45 kHz) and a change in insertion loss (~1.1 dB) of the device show the promise of ZnO for the fabrication of low cost SAW UV sensor.

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