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著者	SHARMA PARMANAND
journal or publication title	Journal of Materials Research
volume	18
number	3
page range	545-548
year	2003
URL	http://hdl.handle.net/10097/47403

doi: 10.1557/JMR.2003.0069

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Interaction of surface acoustic waves and ultraviolet light in ZnO films

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(Received 10 October 2002; accepted 9 December 2002)

The frequency response of a 37 MHz bulk $LiNbO_3$ surface acoustic wave (SAW) filter with a 200-nm-thick ZnO overlayer exhibited a downshift in the frequency with ultraviolet (UV) light due to acoustoelectric interactions between the photo-generated carriers in the semiconducting ZnO and the surface acoustic waves. In contrast, a 36 MHz ZnO thin film SAW delay-line with insulating ZnO films exhibited an upshift in the frequency. The response was more pronounced at higher harmonics (130–315 MHz) and was attributed to changes in the elastic/dielectric properties in the upper surface layer of ZnO. A linear change in the frequency with UV intensity shows immense applicability for wireless ultraviolet sensor applications.

Surface acoustic wave (SAW) sensors offer many attractive features. They are highly sensitive, and their frequency output allows the fabrication of wireless sensors for remote sensing applications. In a SAW device the measured response arises from perturbations in the wave propagation characteristics. Changes in the wave velocity and attenuation caused by acoustoelectric interactions and/or mass loading effects have been exploited for fabricating a variety of SAW sensors.[1–5] Acousto-electric interactions on a piezoelectric material can be utilized effectively for light-sensing applications when the near-surface region of a piezoelectric is made optically active by a suitable overlayer, so that the photo generated carriers can strongly interact with the piezoelectric fields and potentials accompanying the surface wave.

SAW interaction with light has stimulated a new application area for developing integrated devices.[6,7] Recently, Ciplys *et al.*[8] reported the effect of ultraviolet (UV) radiation on the frequency response of a GaN-based SAW oscillator operating at 221.34 MHz. A downshift in the oscillator frequency under UV illumination was observed, and this was attributed to the interaction of optically generated charge carriers in GaN with SAWs. Several authors have reported that the relative change in SAW velocity ($\Delta V/V$) due to acousto-electric interactions in a piezoelectric semiconductor depends on the coupling coefficient (K), and the change can be less then or equal to $K^2/2$.[1,9,10] Materials like $LiNbO_3$ with a high electromechanical coupling coefficient are most useful, and when combined with other materials possessing optoelectronic properties, can lead to an interesting class of light-sensing SAW devices.

In recent years optoelectronic properties of zinc oxide (ZnO) thin films have attracted a lot of attention for selective UV photodetector applications.[11,12] The piezoelectric property of ZnO allows fabrication of SAW devices,[13] and its wide band gap is an added advantage for sensing UV light. However, the UV photoconductivity in ZnO is found to depend strongly on the crystallite orientation[11,14] and the defect concentration in the film.[15] ZnO films oriented along the *c* axis that are useful for SAW device fabrication actually exhibit weak photoconductivity in comparison to films with a mixed crystallographic orientation.[11]

In the present paper, we examined the interaction of SAWs with UV light in ZnO films that are either semiconducting or insulating in the presence of ultraviolet light. Mechanisms for the change in the SAW velocity under UV illumination are shown to be different and found to generate an opposite effect in the measured frequency response of the SAW device.

Details on the deposition conditions for producing semiconducting or insulating ZnO films have been described elsewhere.[15] To study the effect of optically generated charge carriers on the SAW properties, a

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200 nm thick ZnO film that exhibited a strong photoconductivity under UV illumination[11] was deposited on a bulk $LiNbO_3$ SAW filter with a center frequency of 37 MHz. The 200-nm-thick ZnO film was found sufficient because the penetration depth of UV light was estimated to be around 183 nm.[15] The frequency response of the $LiNbO_3$ filter was first studied with and without the ZnO layer. The deposition of the ZnO layer did not show any appreciable change in the frequency response and the insertion loss and clearly indicated there is no mass loading effect by the ZnO layer. However, when illuminated with UV light (40 mW/cm^2) an increase in the insertion loss of the filter (ΔIL $\approx$ 3.23 dB) and a significant decrease in the center frequency ($\Delta f \approx$ 170 KHz) were observed (Fig. 1). The increase in insertion loss is due to the change in conductivity of the ZnO layer and the resulting conduction between the interdigital transducer fingers (IDT), and the decrease in the center frequency is attributed to acoustoelectric interactions. The hybrid ZnO/$LiNbO_3$ SAW structure exhibited a relatively large shift in frequency ($\Delta f \approx$ 170 KHz) at a much lower operating frequency of 37 MHz in comparison to the earlier reported GaN-based SAW oscillator (Δf = 60 KHz) operating at 221.30 MHz.[6] The large frequency shift observed in the present ZnO/$LiNbO_3$ device is primarily due to the high electromechanical coupling coefficient (=4.5%) of $LiNbO_3$ over that of GaN, for which K^2 = 0.05%. Although bulk $LiNbO_3$ offers a high coupling coefficient, we realized that the use of such bulk substrates does not allow the fabrication of integrated devices. Since the deposition techniques for fabricating $LiNbO_3$ films are not yet well established in the literature, we realized that an integrated ultraviolet SAW sensor could be fabricated using *c*-axis-oriented piezoelectric ZnO films.

Thick ZnO films (8 μm) were deposited on fused quartz substrate by radio frequency (rf) magnetron sputtering and were found to possess a preferred *c*-axis (002) orientation useful for piezoelectric applications. A pair of IDTs with split electrode geometry was fabricated. Each transducer consisted of 50 finger pairs, with a line width of 6 μm and a gap of 14 μm between each finger. The fundamental center frequency of the as-fabricated SAW delay line was 36.31 MHz, and besides the fundamental mode (or Rayleigh mode) other high frequency harmonics and modes were also observed. The high-frequency harmonics were generated either due to the low value of metallization ratio (≈0.3) or the uneven line widths generated during the photolithographic patterning process. Two distinct types of frequency response were observed. The responses that were similar in shape to the fundamental mode, or Rayleigh mode are labeled as mode-1, and the results are shown in Figs. 2(a) and 2(b). The

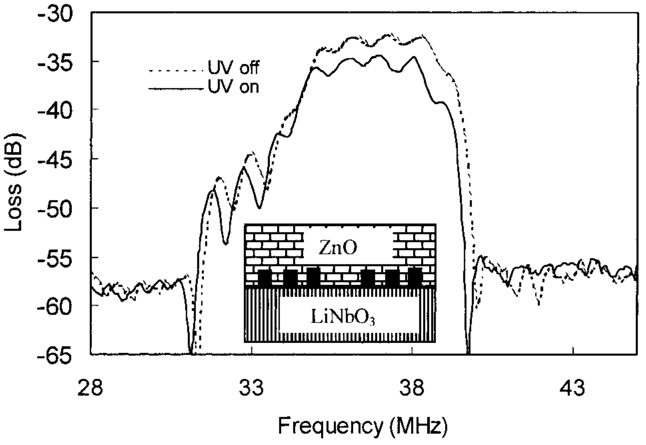

FIG. 1. Frequency response of ZnO/$LiNbO_3$ hybrid SAW filter showing the effect of UV light (40 mW/cm^2) on the frequency response. Inset: device structure.

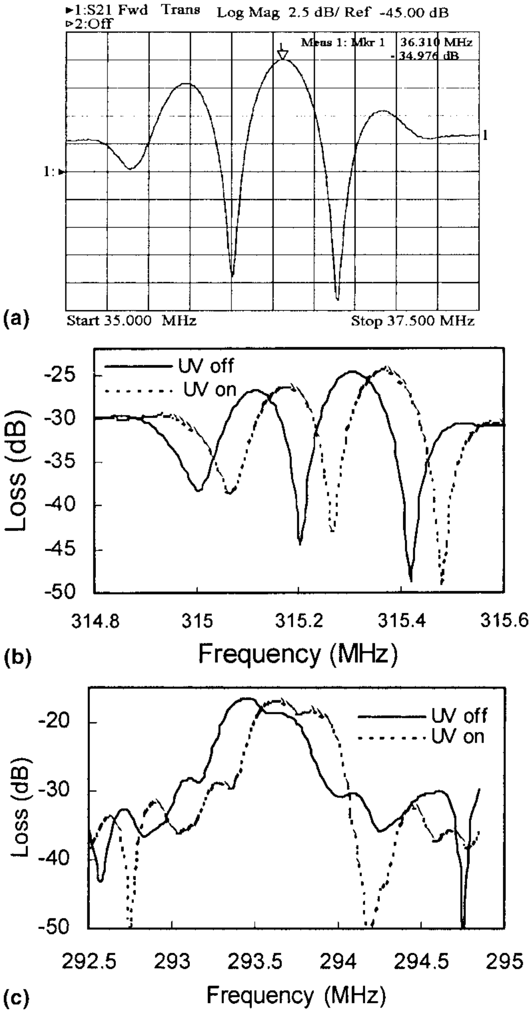

FIG. 2. Frequency response of ZnO/Fuse quartz SAW delay line: (a) typical shape of the fundamental SAW mode at 36.31 MHz (mode-1); (b) high-frequency harmonic similar in shape with mode-1 and the dashed curve (---) represents the upshift in the frequency response under UV light (12 mW/cm^2); and (c) typical shape of the SAW modes observed only above 240 MHz (mode-2) and the effect of UV light (38 mW/cm^2).

other responses that were observed only above 240 MHz are labeled as mode-2 [Fig. 2(c)]. The presence of mode-2 is probably due to the excitation of high velocity pseudo-SAW in ZnO/SiO_2 (fused quartz) layered structure.[16,17] The effect of UV light ($\lambda = 365$ nm) of varying intensity (5 to 40 mW/cm^2) on the frequency response of the SAW delay line was studied using an Agilent network analyzer (Model 8712ES, 300 KHz to 1.3 GHz).

When illuminated with UV light, the ZnO thin film SAW device did not show any appreciable change in the frequency response at the fundamental mode (36.31 MHz) and at other harmonics (<100 MHz). However, at a higher frequency (>130 MHz) both modes (1 and 2), shown in Figs. 2(b) and 2(c), respectively, were influenced by UV light, and a significant shift in the frequency to a higher value was observed without any appreciable change in the insertion loss. The shift in the frequency at a fixed UV light intensity (35 mW/cm^2) was found to increase markedly at higher harmonic and tends to saturate above 270 MHz as shown in Fig. 3. Figure 4 shows the variation in the frequency shift when the device was operated under the different modes at different harmonic frequencies. The shift in the frequency is found to be nearly linear with UV light intensity when tested at different UV illumination levels in the range 5–40 mW/cm^2.

A prominent feature in the response of the two devices to UV light was a frequency upshift in the case of ZnO SAW delay line and a downshift for the $ZnO/LiNbO_3$ hybrid structure. In the present work, the observed downshift could be easily understood in terms of acousto-electric interactions due to the semiconducting nature of the ZnO films in the $ZnO/LiNbO_3$ hybrid device, but an explanation for the strange upshift in frequency for the ZnO thin film device demanded attention for possible influence from other material parameters because the films used in this device were relatively more insulating and not photoconducting, as in the case of the $ZnO/LiNbO_3$ hybrid device.

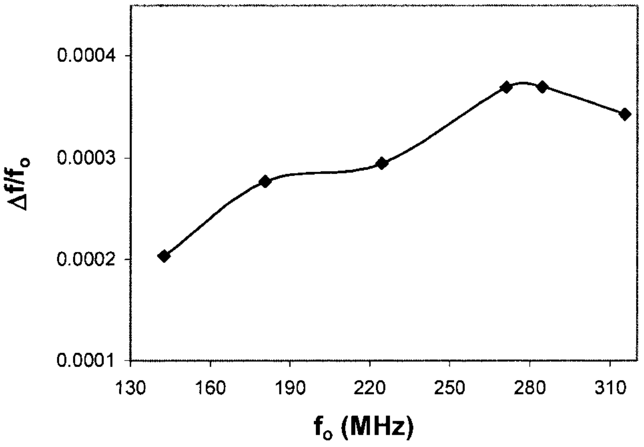

FIG. 3. Shift in frequency ($\Delta f/f_o$; f_o is center frequency) of mode-1 for different high-frequency harmonics under constant UV illumination (35 mW/cm^2).

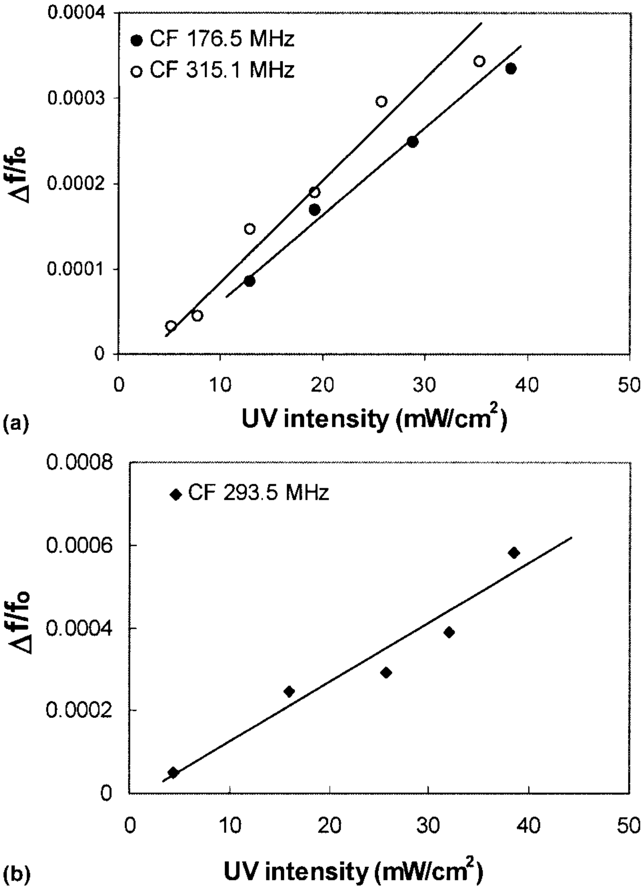

FIG. 4. Effect of UV light intensity on SAW modes of ZnO SAW delay line: (a) shift in frequency ($\Delta f/f_o$) for the mode-1 operating at center frequency 176.5 and 315.25 MHz and (b) for mode-2 at 293.5 MHz.

SAW properties are known to depend on the piezoelectric, dielectric, and elastic constants of the ZnO film. In the present case, the lack of appreciable change in the insertion loss under UV illumination indicated that the piezoelectric property of the ZnO film was unaffected by UV light and suggested that the influence of elastic/dielectric properties of the film was more dominant. Theoretical calculations on the SAW propagation characteristics in a ZnO/SiO_2 bilayer structure revealed that the SAW velocity was more sensitive to changes in the elastic constants of the ZnO film in comparison to the dielectric constant. Preliminary calculations indicate that the elastic constant c_{11} is the most sensitive. A slight increase in c_{11} by 0.5% could cause a frequency shift of 0.126 MHz at the center frequency ≈ 315 MHz. In literature the increase in SAW frequency for polymide-coated SAW devices in the presence of nitrous gas (N_2O) has been observed and attributed to the stiffening of polymer layer.[18] However, identifying the exact origin of increase in SAW frequency under UV illumination in the present work will require further study.

Changes in the ZnO film properties with UV illumination seem to occur mainly in the top surface layer of the film and decrease exponentially within the film thickness because UV light intensity decays exponentially inside the film. For a SAW delay line at a lower operating frequency, the acoustic energy is distributed throughout the thickness of the film,[5] and if the film thickness is insufficient it can even penetrate up to a certain thickness into the substrate. Therefore, in the present observations, at lower operating frequencies (<100 MHz), the absence of any appreciable shift in the center frequency indicates a weak interaction with the SAW in the upper surface layer of ZnO modified by UV. However, at a higher operating frequency (>130 MHz), as the acoustic energy begins to concentrate more in the upper layer of the ZnO film,[19] a strong interaction is observed between the SAW and the upper layer of the ZnO, which is modified by UV. Ultimately saturation is observed at very high frequencies.

In summary, the changes in the frequency response due to SAW interaction with UV light were found to depend on the nature of the film that absorbs the UV light. A frequency downshift was found to depend on the conductivity, and an upshift was related to the changes in the elastic properties of the film. The results obtained with both device structures can lead toward the potential fabrication of a wireless UV sensor.

ACKNOWLEDGMENTS

The authors are thankful to Prof. Abhai Mansingh for fruitful discussions and the Department of Science and technology, Government of India, for funding the project.

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