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Highly sensitive ultraviolet detector based on $ZnO/LiNbO_3$ hybrid surface acoustic wave filter

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Fabrication of a highly-sensitive UV detector based on the surface-acoustic-wave (SAW) principle is reported. The output voltage of the SAW oscillator constructed with a $ZnO/LiNbO_3$ hybrid SAW filter was found to decrease linearly with increasing UV light intensity, and a very low intensity UV light of 10 $\mu W/cm^2$ was detected easily. Our results show its potential use in wireless UV measurement systems. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1622436]

In recent years, UV light detection with zinc oxide (ZnO) has generated a lot of interest for selective photodetector applications.[1–4] Until now, UV detectors based on photoconducting layers[2,3] and metal–semiconductor Schottky barriers[1,4] using ZnO films have been commonly reported. In these detectors, basically a change in photogenerated current is measured in the presence and in the absence of light. As the intensity of UV light falling on the detector decreases, the photogenerated current becomes comparable to the dark current, or noise level, and results in difficulties in the measurement. Alternatively, surface-acoustic-wave (SAW) devices are known to be sensitive to any minute changes in the physical characteristics of the surface, because in SAW devices a high density of acoustic energy propagates in the near-surface region of a piezoelectric.[5]

SAW sensors offer many attractive features. They are highly sensitive, and their frequency output allows the fabrication of wireless sensor for remote sensing applications. In a SAW device, the measured response arises from perturbations in the wave propagation characteristics. Changes in wave velocity and attenuation caused by acoustoelectric interactions and/or mass loading effects have been exploited for fabricating a variety of SAW based chemical and gas sensors.[5–9] The acoustoelectric interactions arise between electric fields generated by the SAW and the charge carriers in a conducting or a semiconducting film. The interaction between SAW and charge carriers in the semiconductor is interesting in terms of not only the characteristics of an acoustical effect, but also application of such devices as a convolver, a correlator, and a charge transferred device. Acoustoelectric 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 photogenerated carriers begin to interact strongly with the piezoelectric fields and potentials accompanying the surface wave.

SAW interaction with light has stimulated a new application area for developing integrated devices.[10–12] Recently, Ciplys *et al.*[13] reported the effect of 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 (i.e., acoustoelectric effect). The attenuation (Γ) and the change in SAW velocity (Δv) due to acoustoelectric interaction are given by[14]

$$\frac{\Delta v}{v_o}=\frac{K^2}{2}\frac{1}{1+(\sigma/\sigma_m)^2}, \tag{1}$$

$$\Gamma=K^2\frac{\pi}{\lambda}\frac{\sigma/\sigma_m}{1+(\sigma/\sigma_m)^2}. \tag{2}$$

Where, K^2, λ, v_o, σ, and σ_m are the coupling coefficient, wavelength, SAW velocity on free surface, sheet conductivity, and material constant, respectively. As the attenuation (Γ) and the velocity change (Δv) [Eqs. (1) and (2)] is proportional to the coupling coefficient (K^2), a high K^2 would be desirable in order to yield a large acoustoelectric effect. However, in common semiconductor materials the coupling coefficient is very low [i.e., GaAs (100) $K^2=0.064\%$, and GaN$=0.055\%$]. Therefore, the maximum change in SAW velocity and/or attenuation is not large enough for sensitive detector applications. Materials like $LiNbO_3$ with a high electromechanical coupling coefficient ($K^2=4.5\%$) are most useful, and when combined with photoconducting ZnO can lead to an interesting class of light-sensing SAW devices.

In the present letter, we report on the interaction of SAWs with UV light, and fabrication of a highly sensitive UV detector based on a $ZnO/LiNbO_3$ hybrid SAW filter configured in the form of an oscillator is described.

A 200-nm-thick ZnO film possessing (100), (101) mixed crystallite orientation that exhibits a large change in conductivity under UV illumination was deposited using unbalanced rf magnetron sputtering on a prefabricated bulk $LiNbO_3$-based SAW filter (center frequency$=37$ MHz). The 200-nm-thick ZnO film was found sufficient because the penetration depth of UV light was estimated to be around 183 nm.[2] The details on deposition and characterization of

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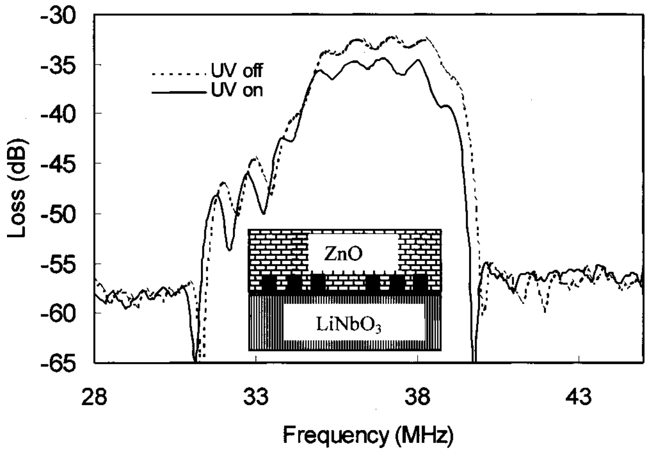

FIG. 1. Frequency response of the $ZnO/LiNbO_3$ hybrid SAW filter showing the effect of UV light ($40\ mW/cm^2$) on the frequency response. Inset: device structure.

the photoconducting ZnO thin film have been reported elsewhere.[2,3] The $ZnO/LiNbO_3$ hybrid SAW filter was illuminated with the UV light of wavelength $(\lambda) = 365$ nm, and intensity was varied from $\sim 5\ \mu W/cm^2$ to $40\ mW/cm^2$. The effect on frequency response of the $ZnO/LiNbO_3$ hybrid SAW device was studied using an Agilent Network Analyzer (8712ES), and a Tektronix™ digital cathode ray oscilloscope.

The frequency response of the bulk $LiNbO_3$ SAW filter was studied with and without the 200-nm-thick photoconducting ZnO overlayer. The deposition of the thin ZnO layer did not show any appreciable change in the frequency response and insertion loss (IL) of the $LiNbO_3$ SAW filter. However when the $ZnO/LiNbO_3$ hybrid device was illuminated with UV light of intensity $= 40\ mW/cm^2$, the insertion loss ($\Delta IL \sim 3.23$ dB) increased, and a significant decrease in center frequency ($\Delta f = 170$ KHz) was noted (Fig. 1).

Upon illumination with UV light, there is a significant presence of photogenerated carriers in the ZnO layer. The interaction between the SAW and the charge carriers leads to the change in SAW frequency and attenuation (acoustoelectric effect). However, the increase in insertion loss is due to the SAW attenuation caused by acoustoelectric effect, and the increased conduction between the interdigital transducer

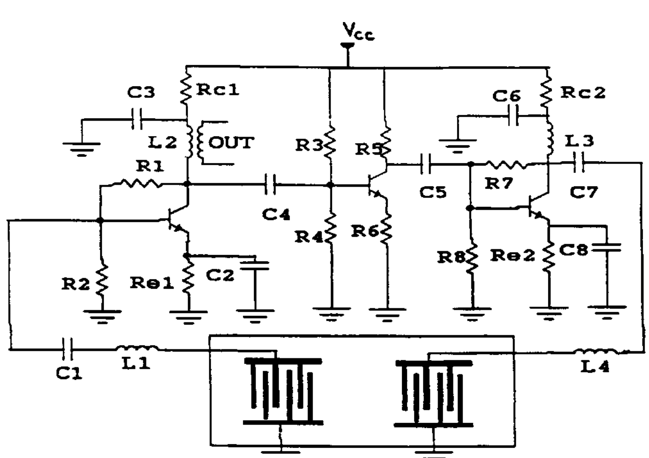

FIG. 2. $ZnO/LiNbO_3$ hybrid SAW filter configured in the form of an oscillator.

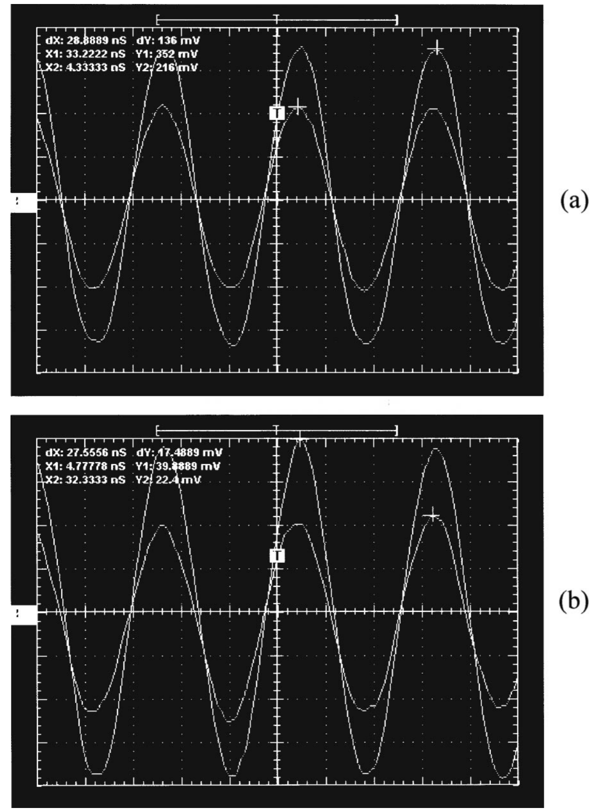

FIG. 3. Frequency output of $ZnO/LiNbO_3$ based SAW oscillator showing a decrease in amplitude in the presence of UV light. (a) At UV light intensity $4\ mW/cm^2$ and $V_{cc} = 26$ V, change in amplitude $= 136$ mV. (b) UV light intensity less than $10\ \mu W/cm^2$ and $V_{cc} = 14$ V, change in amplitude $= 17.48$ mV.

fingers of the $LiNbO_3$ SAW device. The hybrid $ZnO/LiNbO_3$ SAW device structure exhibited a relatively large shift in frequency at a much lower operating frequency of 37 MHz in comparison to the earlier reported GaN nitride-based SAW oscillator ($\Delta f = 60$ KHz) operating at 221.30 MHz.[13] The large frequency shift observed in the present case is primarily due to the high electromechanical coupling coefficient ($K^2 = 4.5\%$) of $LiNbO_3$ over that of GaN, which has $K^2 = 0.05\%$ [Eq. (1)]. These results indicate that the $ZnO/LiNbO_3$ can be utilized for the fabrication of a highly sensitive, low-cost UV detector, if configured in the form of a SAW oscillator.

The basic system for the SAW UV sensor is a generator in which a $ZnO/LiNbO_3$ hybrid SAW filter works in the positive feedback loop of a high frequency amplifier (Fig. 2). When the amplifier gain (G_a) is set to overcome the losses in the feedback loop (L_{dB}), the device oscillates at a frequency (f_o) that is determined by the center frequency of the $ZnO/LiNbO_3$ hybrid SAW filter, and the phase conditions are given as[5]

$$2\pi f_o L_a / V + \phi = 2m\pi, \tag{3}$$

$$G_a \geq L_{dB}, \tag{4}$$

where L_a is the acoustic path length, V is the SAW velocity, m is an integer, and ϕ is the phase shift due to the electronic circuitry of the oscillator. On illumination with UV light, a change in SAW velocity of the $ZnO/LiNbO_3$ hybrid device

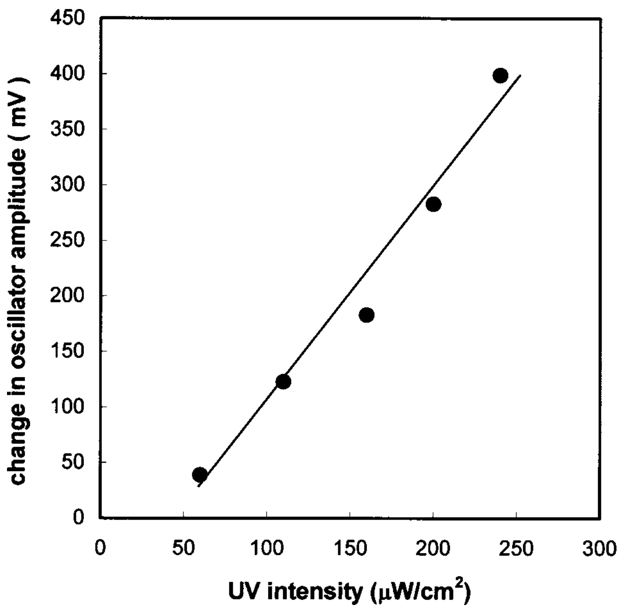

FIG. 4. Change in output amplitude of SAW oscillator with varying UV light intensity (V_{cc}=17 V).

leads to a change in the frequency, and an increase in the insertion loss results in the decrease in the oscillator output voltage [Eq. (4)].

A variable gain SAW oscillator was designed with $ZnO/LiNbO_3$ hybrid device (Fig. 2). Gain of the high frequency amplifier was controlled by power supply (V_{cc}) to the electronic circuitry (Fig. 2), and increases with increasing V_{cc}. The SAW oscillator was found to oscillate at 36.3 MHz, which lies well in the center frequency range of $ZnO/LiNbO_3$ hybrid device. When the device was exposed to varying intensity of UV light, a decrease in the output amplitude of the oscillator was observed (Fig. 3), and was found to die away at a higher UV intensity. The amplitude of the oscillator output was found to decrease linearly (Fig. 4) with increasing UV light intensity. The sensitivity (change in output amplitude) to UV light was dependent on the gain of the amplifier. Maximum sensitivity was obtained when the gain of the amplifier was set slightly greater than the insertion loss of the filter [Fig. 3(b)] because a slight increase in the insertion loss of the device can cause oscillations to die off by violating the condition of Eq. (4). UV light intensity of $\sim 10\ \mu W/cm^2$ could be detected easily, and the lower limit to the UV detector in present work was set by the commercial UV detector used for the measurement of UV light intensity. The present detector was also exposed to visible light (UV light was blocked by the UV filter), and we did not observe any changes in the oscillator output, which proves that the detector is visible-blind. These results indicate that this device can be used for the measurement of very low as well as high intensity of UV light depending upon the gain of the high frequency amplifier. The output of the device is in the form of a rf signal, which makes it interesting for the fabrication of wireless UV sensor. The present device can also be interesting for satellite applications because ZnO is a radiation hard material in comparison to other common semiconductors such as Si, GaAs, CdS, and GaN that are being investigated for the fabrication of UV detectors.[15]

In summary, a highly sensitive UV detector based on $ZnO/LiNbO_3$ hybrid SAW filter configured in the form of an oscillator has been demonstrated. Results show its potential use in the measurement of very low ($\sim 10\ \mu W/cm^2$) and high intensity of UV light, with the possibility of wireless operation.

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