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Film bulk acoustic-wave resonator based ultraviolet sensor

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This letter described ultraviolet (UV) radiation sensing with ZnO based film bulk acoustic-wave resonator (FBAR). The resonant frequency upshifted when there was UV illumination on the FBAR. For 365 nm UV light, the frequency upshift was 9.8 kHz with an intensity of 600 $\mu W/cm^2$, and the detection limit of the sensor was 6.5 nW. The frequency increase in the FBAR UV sensor was proposed to be due to the density decrease in ZnO film upon UV illumination. When UV was incident on the ZnO film, it can cause oxygen desorption from the ZnO surface, resulting in density decrease in the film. This study has proven the feasibility of detection of low intensity UV using ZnO film based FBAR. © 2009 American Institute of Physics. [DOI: 10.1063/1.3122342]

Detection of ultraviolet (UV) radiation is very important in a number of areas, such as UV astronomy, resin curing of polymeric materials, combustion engineering, water purification, flame detection, and biological effects with more recent proposals, such as early missile plume detection, secure space-to-space communications, and pollution monitoring. UV detectors with metal-semiconductor-metal (MSM) structures have been reported extensively. They can be realized either by Ohmic contact photoconductive principle[1] or Schottky barrier photovoltage principle[2] using ZnO films. In these detectors, generally a change in photogenerated current was measured in the presence and absence of UV illumination. Alternatively, surface acoustic wave (SAW) resonant UV sensors have also been developed with photoconductive ZnO film deposited on top of a SAW filter as a UV sensitive layer.[3,4] The detection limits were 50 $\mu W/cm^2$ using insertion loss, as the photoresponse signal[3] and 10 $\mu W/cm^2$ by incorporating the SAW filter in an electric oscillation loop.[4]

Film bulk acoustic-wave resonators (FBARs) have been well developed both as filters[5] and as high sensitivity mass sensors[6] in recent years. In this letter, we investigated a ZnO UV sensing device using FBAR technology. The design and fabrication process of the FBAR UV sensor were described and the mechanism for the frequency increase in the FBAR sensor under UV illumination was discussed.

The schematic structure of the FBAR UV sensor is shown in Fig. 1. The FBAR was fabricated on top of a SiN diaphragm (0.6 μm thick). A sputtered ZnO film (1.2 μm thick) acted both as the UV sensitive layer and the piezoelectric actuation layer for the FBAR sensor. The top and bottom electrodes were made of Au (0.2 μm thick) and Al (0.2 μm thick), respectively. Around 45% UV can penetrate the gold electrode layer and reach the ZnO beneath it.[7] The fabrication process of the FBAR UV sensor was as follows. In the first step, a SiN layer was deposited on a Si wafer (100) with low-pressure chemical vapor deposition. Then the Si wafer was etched from the backside anisotropically in potassium hydroxide (KOH) to form the cavity. Next, the bottom Al electrode was deposited by electron-beam (e-beam) evapora-

tion and patterned on top of the SiN film. ZnO was radio-frequency sputtered and etched to form the desired pattern. The last step was the e-beam deposition and patterning of top Au electrode by lift-off.

The ZnO film was characterized by x-ray diffraction (XRD) (Fig. 1). Only the Bragg reflection corresponding to (002) planes was observed, indicating that the film had preferred orientation along the wurtzite *C* axis, which is normal to the silicon substrate. A versatile hand-held UV lamp (365 nm, Cole-Parmer, Vernon Hills, IL) was used as the UV source. A UVX digital UV intensity meter (Cole-Parmer, Vernon Hills, IL) was applied to calibrate the UV power received by the FBAR sensor. The resonant frequency of the FBAR was monitored with an Agilent E5071C network analyzer and a LABVIEW program.

The quality factor (*Q*) of the FBAR was calculated to be between 400 and 420 using the following equation:

$$Q_{s/p} = \frac{f_{s/p}}{2} \left| \frac{d\phi_{zs/p}}{df} \right|_{f=f_{s/p}}, \tag{1}$$

where $Q_{s/p}$ is the quality factor at series/parallel resonance; $f_{s/p}$ is the series/parallel resonant frequency; and $\phi_{zs/p}$ is the
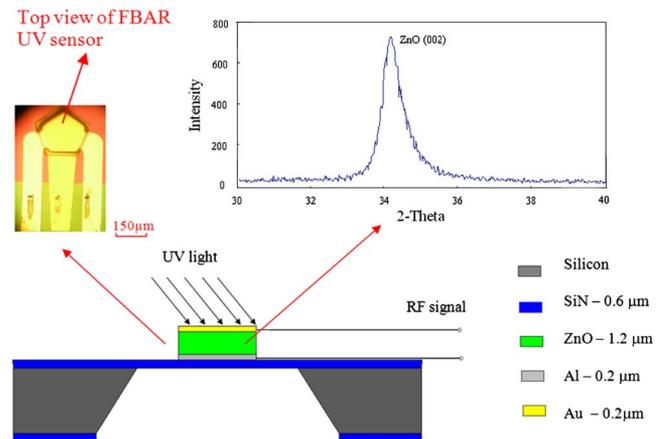
FIG. 1. (Color online) Schematic cross-sectional structure of the FBAR UV sensor with a photograph of the top view of a fabricated device on the left and an XRD trace of the ZnO film illustrating that it had ⟨002⟩ crystal orientation on the right.

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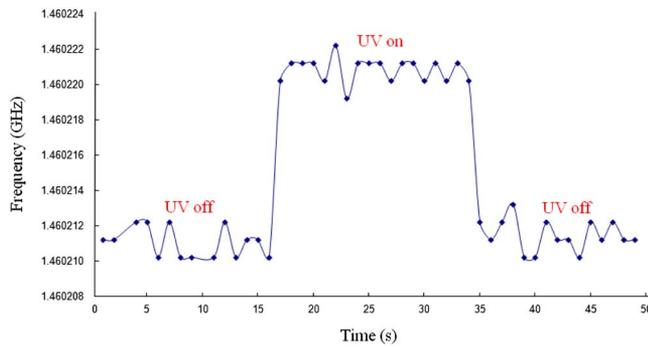
FIG. 2. (Color online) UV light sensing result with frequency upshift: when there was UV illumination (600 μW/cm^2), a frequency upshift of 9.8 kHz was observed.

impedance phase near series/parallel resonance.[8] The frequency noise floor of the FBAR sensor was 1.5 ppm at 1.4–1.5 GHz. Figure 2 shows the frequency response of the FBAR sensor with a UV intensity of 600 μW/cm^2. An upshift of 9.8 kHz was observed. This frequency upshift cannot be attributed to the temperature increase at the ZnO surface under UV illumination. For ZnO FBARs without compensation layer, the temperature coefficient of frequency (TCF) was negative, indicating a frequency downshift with increasing temperature.[9] Since a frequency upshift was observed in the UV response, the influence of temperature increase can be excluded. The measured TCF for the FBAR UV sensor was −31 ppm/°C. Different intensities of UV light were applied to monitor the photoresponse of the FBAR sensor. The results were shown in Fig. 3(a). As the intensity increased, the frequency upshift also increased. At low inten-
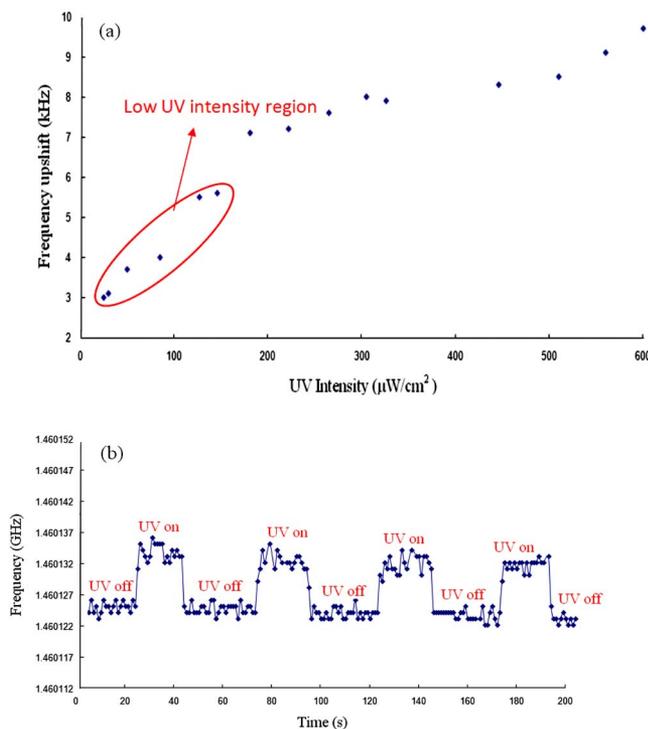
FIG. 3. (Color online) (a) The resonant frequency upshift of FBAR vs UV light intensity, which showed frequency upshift increased with increasing UV light intensity. In the low intensity region, the relationship was almost linear; (b) four cycles (one cycle lasted 40 s) of response of the FBAR sensor with a UV intensity of 290 μW/cm^2. A frequency upshift of 7.7 kHz was observed.

sity region [as shown in Fig. 3(a)], the relationship was almost linear, which made FBAR UV sensor suitable to detect low intensity UV. The lowest detectable intensity was around 25 μW/cm^2, which was comparable to the SAW UV sensor mentioned above without incorporating an oscillator unit. With the current sensing area of 0.026 mm^2 (measured from the active area of the fabricated device), the minimum UV power detectable was calculated to be 6.5 nW. Figure 3(b) shows four cycles (one cycle lasted 40 s) of response of the FBAR sensor with a UV intensity of 290 μW/cm^2. The results demonstrated good repeatability and stability of the sensor. The slight decay of the frequency pedestal in Fig. 3(b) may be attributed to the temperature rise due to the residual heating from the UV lamp.

Frequency upshift was observed by Sharma *et al.*[10] in their SAW UV sensor which utilized a ZnO/fused quartz SAW delay line. They proposed that the change in elastic constant of the ZnO film due to UV stiffening was the main reason for the frequency upshift. However, there was no experimental evidence for their explanation. For our FBAR UV sensor, an alternative explanation for the frequency upshift was suggested as follows.

The frequency of the FBAR can be determined from the following two equations:

$$v = \sqrt{\frac{E}{\rho}}, \tag{2}$$

$$f = \frac{v}{2d}, \tag{3}$$

where E, ρ, and d are the elastic constant, density, and thickness of the ZnO film, respectively. v is the acoustic velocity inside the film and f is the resonant frequency of the FBAR. So the frequency upshift may be due to the density decrease in the ZnO film upon UV illumination. It is well established that when UV light is incident, electron-hole pairs are generated inside the ZnO film. The holes produced by light absorption migrate to the surface and discharge the negatively charged absorbed oxygen ions and surface lattice oxygen ions. When an oxygen ion is discharged by the capture of a hole, it will be thermally desorbed.[11–13] In this way, the density of the ZnO film will decrease, resulting in the increase in acoustic velocity inside the film. Therefore, the resonant frequency of the FBAR sensor will increase. When UV light is absent, oxygen reabsorption will occur. Consequently, the density of the ZnO film will increase and the resonant frequency of FBAR will decrease accordingly.

In order to support the above assumption, acetone vapor was applied to the sensor to monitor its response. It is known that oxygen is absorbed on the ZnO film through capturing electrons from the film. When ZnO is exposed to acetone, the reducing gas molecules will react with the oxygen ions on the film, and release the absorbed oxygen.[14] So the density of the ZnO film will decrease and a frequency upshift of the FBAR can be expected. Figure 4 shows the response of the FBAR sensor for 100 ppm acetone. A frequency upshift of 10.3 kHz was observed. UV light with intensity of 600 μW/cm^2 was applied subsequently and caused a 6.0 kHz frequency upshift (Fig. 4). This response was smaller than the frequency upshift without acetone (Fig. 2). It can be interpreted as following: acetone had already reacted with some surface oxygen ions in the ZnO film. Therefore, when
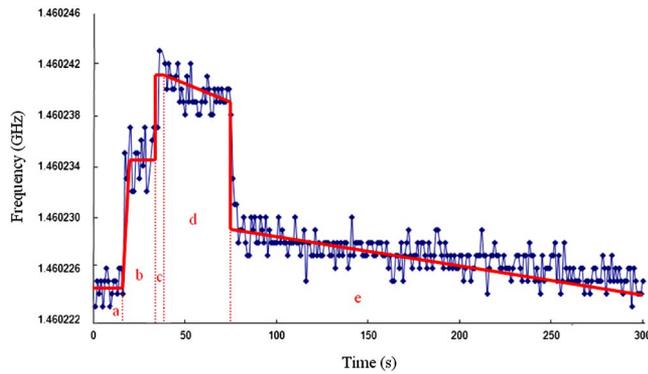
FIG. 4. (Color online) Acetone and UV exposure to the FBAR sensor. Frequency upshifted (10.3 kHz) upon acetone (100 ppm) exposure (stage b). It was followed by a subsequent upshift (6.0 kHz) due to UV (600 μW/cm^2) illumination (stage c). When acetone was cut off, frequency began to decrease (stage d). After turning off UV light, there was a fast decay of frequency followed by a slow one (stage e). It took as long as 250 s for the resonant frequency to drop back to the original value.

UV light was incident, there was less oxygen ions left on the film surface to be desorbed by UV. In this way, the frequency upshift became smaller with the same UV intensity. These results illustrated that UV light and acetone shared a similar mechanism to upshift the frequency of the FBAR sensor. Both of them can cause the density of the ZnO film to decrease and result in a frequency upshift. In Fig. 4, it was obvious that acetone possessed a much longer frequency decay time compared to UV light. UV can penetrate only around 40 nm into the ZnO film.[15] So the UV response of the sensor is a surface phenomenon with a short response time. However, acetone can react with the bulk of the ZnO film by diffusion. Therefore, the acetone response is a bulk process, which is characterized by a long response time. It took as

long as 250 s for the resonant frequency to drop back to the original value with 100 ppm acetone and an exposure time of 25 s.

In conclusion, a low intensity UV sensor was developed based on a ZnO film bulk acoustic-wave resonator. A frequency upshift was observed upon UV illumination on the ZnO film. The output of the sensor was a frequency change, which was suitable for integration with a wireless sensor network. The working principle of the FBAR UV sensor was attributed to the density decrease in ZnO with incident UV light. Moreover, experiment results with acetone supported this mechanism and demonstrated the capability of this sensor to be applied to detect reducing gases as a potential gas sensor.

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