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Film Bulk Acoustic-Wave Resonator Based Relative Humidity Sensor Using ZnO Films

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This article described relative humidity (RH) sensing using a ZnO-based film bulk acoustic-wave resonator (FBAR). The resonant frequency of the FBAR decreased in a two-stage manner as the RH increased. For low RH, a frequency downshift of 2.2 kHz per 1% RH change was observed. This effect was attributed to water molecules replacing the adsorbed oxygen on the ZnO surface, thus increasing the density of the film. For high RH, a frequency downshift of 8.5 kHz per 1% RH change was obtained, which was due to the mass loading effect of the water layers formed on the ZnO surface.
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Humidity is a dynamic parameter that is essential for various fields of industry as well as human lives. There is a substantial interest in the development of relative humidity (RH) sensors for applications in monitoring moisture level at home, in clean rooms, cryogenic processes, medical and food science, and so on. Humidity sensors based on changes in the capacitance[1] or resistance[2] of the sensing element from adsorption of water vapor have been investigated extensively. Alternatively, surface acoustic wave (SAW) resonant sensors have also been developed with polymer films deposited on top of a SAW resonator as the sensing layer.[3]

Film bulk acoustic-wave resonator (FBAR) has been well developed both as filters[4] and as high sensitivity mass sensors[5] in recent years. In this study, we described an RH sensing device using a ZnO-based FBAR. The design and the testing process of the FBAR RH sensor were described, and the mechanism for the frequency response of the FBAR sensor under different RH values was discussed. UV light was applied to monitor its effects on the humidity sensing performance of the FBAR. The mechanism of the UV influence was also investigated.

The schematic structure of the FBAR RH sensor is shown in Fig. 1. A sputtered ZnO (1.2 μm) film (deposited by a Kurt J. Lesker PVD75 sputtering machine) acted both as the RH sensitive layer and the piezoelectric actuation layer for the FBAR sensor. The top and bottom electrodes were made of Au (0.2 μm) and Al (0.2 μm), respectively. The resonant frequency of the FBAR sensor was monitored with an Agilent E5071C network analyzer and recorded by a LabVIEW program. RH was measured by an HH314A humidity temperature meter. A versatile handheld UV lamp (365 nm) was used as the UV source. A UVX digital UV intensity meter was applied to calibrate the UV power received by the FBAR.

The resonant frequency of the FBAR sensor was at 1.4 GHz, suitable for integration with a wireless sensor network. The noise floor was around 0.7 ppm. The quality factor (Q) of the FBAR was about 530–550.

The RH response of the FBAR sensor at room temperature is shown in Fig. 2. A two-stage response was identified. At low RH (RH < 50%), the resonant frequency decreased with RH and a frequency downshift of 2.2 kHz per 1% RH change was observed. With the current noise floor, the detection limit was around 0.45% RH. The RH response in this range was due to the replacement of adsorbed oxygen with water molecules on the ZnO surface.[6] Therefore, the density of the ZnO film increased due to water absorption. The resonant frequency of the FBAR can be determined from the following two equations: $v = (E/\rho)^{1/2}$ and $f = v/2d$, 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.[7] As the density of the ZnO film increased with RH, the acoustic velocity inside the film decreased, resulting in a decrease in the resonant frequency. At high RH (RH > 50%), the resonant frequency decreased linearly with RH and a frequency downshift of 8.5 kHz per 1% RH change was obtained, corresponding to a detection limit of around 0.12% RH. With increasing RH, a discrete water layer began to form on the ZnO surface, which acted as a mass loading for the FBAR. Thus, the resonant frequency of the FBAR decreased linearly with the mass of the water accumulated on top of the resonator as RH increased.[5] This can also be observed from the Q response of the FBAR with increasing RH (Fig. 4a). At RH higher than 50%, Q decreased quickly with humidity, while at RH lower than 50%, Q changed by less than 10%. These results indicated that a water layer formed on the ZnO surface when RH was higher than 50%, thus attenuating the acoustic wave, resulting in a lower Q.

A previous study showed that the adsorption of water on the ZnO surface can be enhanced with UV illumination.[8] Thus, UV may improve the RH response of the ZnO-based FBAR. The RH response of the FBAR under UV (600 μW/cm^2) is shown in Fig. 3. It was also a two-stage response. At low RH (RH < 50%), a frequency downshift of 3.4 kHz per 1% RH change was observed with a detection limit of 0.3% RH. In this region, UV can enhance the adsorption of water on the ZnO surface, resulting in a higher sensitivity. While at high RH (RH > 50%), a frequency downshift of 5.7 kHz per 1% RH change was obtained, corresponding to a detection limit of around 0.18% RH. This value was degraded compared with the detection limit in the UV absent case (around 0.12% RH). It can

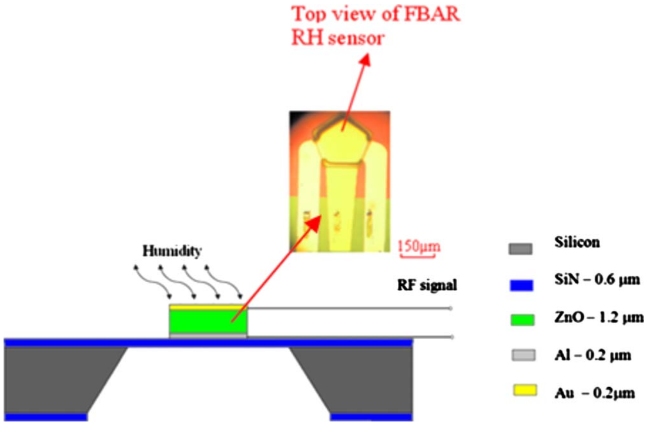

Figure 1. (Color online) Schematic cross-sectional structure of the FBAR RH sensor with a photograph of the top view of a fabricated device.

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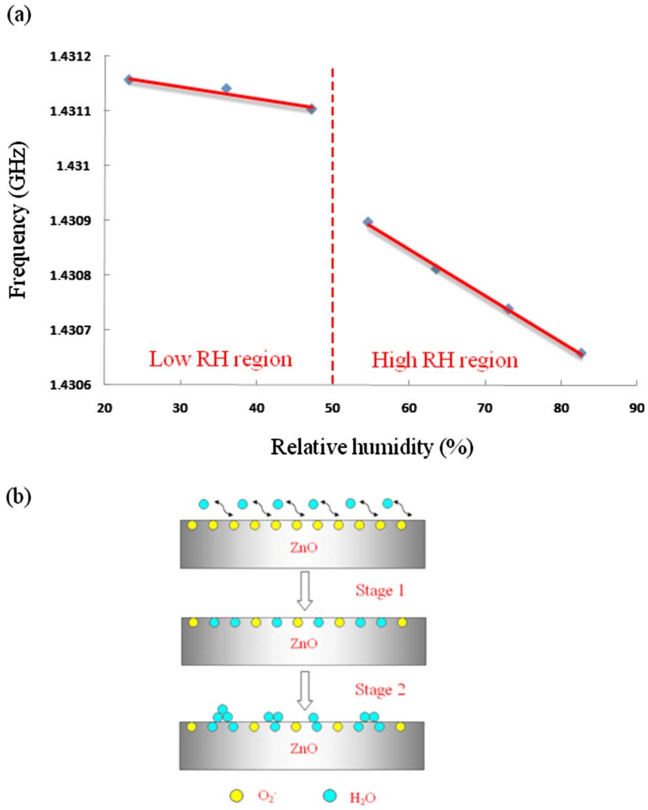

Figure 2. (Color online) (a) The RH response of the FBAR sensor at room temperature. Two stages can be identified: At low RH (RH < 50%), a frequency downshift of 2.2 kHz per 1% RH change was observed. At high RH (RH > 50%), a frequency downshift of 8.5 kHz per 1% RH change was obtained. (b) The mechanism of the two-stage response of the FBAR RH sensor. At low RH (stage 1), the response was due to the replacement of adsorbed oxygen with water molecules on the ZnO surface. At high RH (stage 2), a discrete water layer began to form on the ZnO surface, which acted as a mass loading on the FBAR.

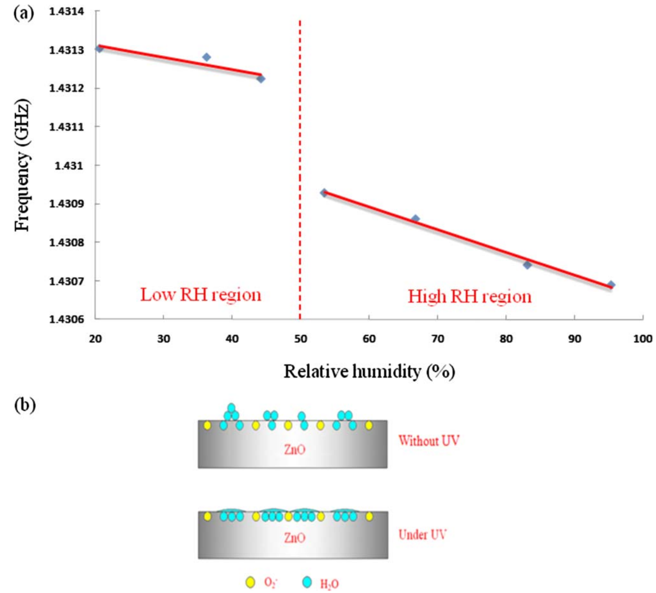

Figure 3. (Color online) (a) The RH response of the FBAR under UV (600 $\mu W/cm^2$) illumination. It was a two-stage response. At low RH (RH < 50%), a frequency downshift of 3.4 kHz per 1% RH change was observed. In this region, UV can enhance the adsorption of water on the ZnO surface, resulting in a higher sensitivity. However, at high RH (RH > 50%), a frequency downshift of 5.7 kHz per 1% RH change was obtained. This value was smaller compared with the UV absent case. (b) The response of the FBAR sensor at high RH region in the presence and in the absence of UV illumination. When there is UV illumination on the ZnO film, the wettability of the surface is enhanced, resulting in a more hydrophilic surface. Therefore, under UV illumination, due to the improved hydrophilicity, the water layer on the FBAR distributed more uniformly with a smoother surface and less mass loading effect compared with the UV absent case, where the ZnO surface was less hydrophilic.

be explained as follows: When there is UV illumination on the ZnO film, the wettability of the surface is enhanced, resulting in a more hydrophilic surface.[8-12] Therefore, under UV illumination, due to the improved hydrophilicity, the water layer on the FBAR distributed more uniformly (Fig. 3b) with a smoother surface and less mass loading effect compared with the UV absent case, where the ZnO surface was less hydrophilic. The frequency shift of the FBAR due to additional mass loading can be estimated as $\Delta f/f = \rho_1 d_1/\rho_0 d_0$, where Δf and f are the frequency shift and the resonant frequency of the FBAR, respectively.[5] ρ_1 and d_1 are the density and thickness of the added mass, respectively, while ρ_0 and d_0 are the density and thickness of the piezoelectric layer, respectively.[5] With a smoother surface, the effective thickness of the water layer on the ZnO film under UV illumination was smaller compared with the UV absent case, resulting in a reduced frequency shift. Thus, the RH response under UV illumination was smaller in this region. This was in agreement with the measured Q response of RH under UV illumination (Fig. 4b). Q decreased more slowly at high RH in this case due to the reduced attenuation of the acoustic wave with the smoother water layer.

In summary, an RH sensor was developed with a ZnO-based FBAR. The resonant frequency of the FBAR decreased in a two-stage manner as RH increased in the environment. For low RH (RH < 50%), a frequency downshift of 2.2 kHz per 1% RH change was observed, while for high RH (RH > 50%), a frequency downshift of 8.5 kHz per 1% RH change was obtained. UV light was applied to monitor its effects on the humidity sensing performance of the FBAR. UV can enhance the sensitivity at low RH (frequency downshift increased to 3.4 kHz per 1% RH change), while degrading the sensitivity at high RH (frequency downshift decreased to 5.7 kHz per 1% RH change). The mechanisms of both the RH response

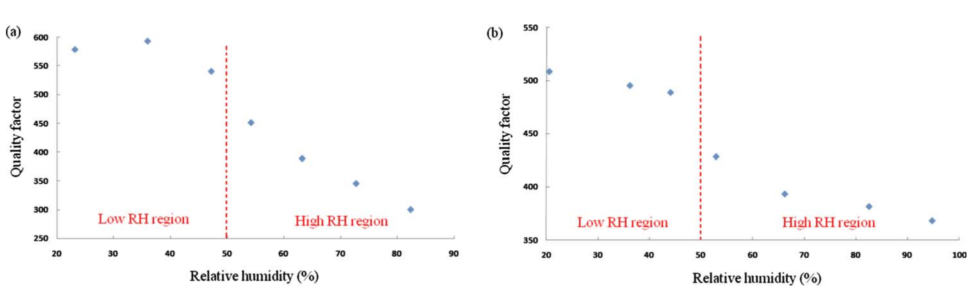

Figure 4. (Color online) (a) The response of FBAR's Q vs RH. Two stages can be identified. At RH lower than 50%, Q changed by less than 10%. However, at RH higher than 50%, Q decreased quickly with humidity. (b) The response of FBAR's Q vs RH under UV (600 $\mu W/cm^2$) illumination. At RH higher than 50%, Q decreased more slowly compared with the UV absent case.

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and the influence of UV illumination were investigated. This study has proven the feasibility of measuring RH using a ZnO-film-based FBAR.

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