Highly Sensitive UV Sensors Based on SMR Oscillators

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Abstract

The interest in ultraviolet (UV) light sensors have been stimulated in the fields of ozone layer and ultraviolet radiation monitoring, satellite communications and UV astronomy. Zinc oxide (ZnO) thin film is an attractive candidate for acoustic wave devices and ultraviolet optoelectronics, due to its high coupling coefficient and the direct energy band gap of approximately 3.2 eV at room temperature. In general, thin film bulk acoustic wave (TFBAW) devices, which are solidly mounted resonator (SMR) devices in this study, possess a higher operating frequency and better frequency response than those of surface acoustic wave (SAW) devices. Therefore, ZnO thin films in the SMR devices acting as both the piezoelectric layer and UV sensing layer were adopted to investigate the acoustic and UV properties in this study. The SMR-based oscillator is composed of a high frequency amplifier, the matching networks, and an SMR device. The resonance frequency of the SAW oscillator is 619.31 MHz with output power of -18.75 dBm, and the phase noise is -60.63 dBc at 100 kHz. The frequency shifts of SMR oscillators show a trend as a function of the illumination intensities of UV light. Finally, the maximum frequency shift of 552 kHz could be obtained when the illumination intensity of UV light was 212 \mu W/cm\textsuperscript{2}.

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1. Introduction

The interest in ultraviolet (UV) light sensors have been stimulated in the fields of ozone layer and ultraviolet radiation monitoring, satellite communications and UV astronomy. UV sensors based on metal-semiconductor-metal phototransistor, photoconducting layers [1, 2] and Schottky Barrier [3] have been successfully demonstrated. The sensing mechanism for these kinds of PN junction device is to monitor the variations between dark current and photocurrents that produced by the illumination of UV light. Besides, surface acoustic wave (SAW) devices were also introduced for UV sensing application because they were well-known as a good candidate for the field of various sensing applications [4-11]. Most of the acoustic waves propagate in the vicinity of the thin film surface within a depth of one wavelength, so SAW devices are very sensitive to any slight changes in the physical characteristics of the surface.

In this study, thin film bulk acoustic wave (TFBAW) devices were employed due to the fact that TFBAW devices have advantages of low insertion loss, high power handling capability, small size, and high operating frequency, compared with SAW devices. TFBAW devices operated with a short wavelength and therefore more sensitive to the changes in material properties of films so they were expected to create a UV sensor with a considerably high sensitivity and better performance.

Zinc oxide (ZnO) thin film has attracted much interest because of its excellent piezoelectric, optical, and semiconducting properties. The film has several applications, such as in SAW devices, thin-film bulk acoustic wave resonators, optoelectronic devices and sensors. ZnO is an attractive material candidate for acoustic wave device and ultraviolet optoelectronics, since it has a high coupling coefficient and a direct energy band gap of approximately 3.2 eV at room temperature. Therefore, ZnO film in this study was adopted simultaneously as the UV sensing layer and the piezoelectric layer.

2. Experimental

2.1 The fabrication of SMR-based TFBAW devices

The fundamental SMR device is composed of a piezoelectric layer which is sandwiched between two metal electrodes and then attached to a Bragg reflector which has been formed on a Si substrate. In this study, the SMR device was fabricated using dc/rf magnetron sputtering and patterned by three masks of photolithography processes.

Firstly, the Bragg reflector was formed by alternately depositing tungsten (W) and silicon dioxide (SiO₂) using a dual-gun dc/rf magnetron sputtering system, respectively, with a rotatable substrate-heating holder. For the ½ λ mode configuration, the first layer of Bragg reflector on the substrate is set as a high acoustic impedance layer, i.e. tungsten. Then, SiO₂ and W thin film layers are alternately deposited. The half-wavelength configuration of Bragg reflector is formed while the process is stopped at the layer of the SiO₂ thin film. On the contrary, the quarter-wavelength configuration of Bragg reflector is formed by reversing the sequence of fabrication flow. The thickness of each layer in the Bragg reflector is one quarter-wavelength (λ/4) at the resonance frequency. The detailed deposition parameters are listed in Table 1.
Table 1 Deposition parameters of W and SiO₂ thin films for Bragg reflector.

|                      | W                     | SiO₂                  |
|----------------------|-----------------------|-----------------------|
| Deposition system    | dc sputter            | rf sputter            |
| Target               | Tungsten (99.995%)    | Silicon dioxide (99.995%) |
| Substrate-to-target distance (mm) | 50                | 50                    |
| Base pressure (Torr) | 4×10⁻⁵               | 4×10⁻⁵               |
| dc power (W)         | 200                   | 150                   |
| Substrate temperature (°C) | 400          | 350                   |
| Sputtering pressure (mTorr) | 10          | 4                     |
| Ar flow (sccm)       | 10                    | 10                    |

Secondly, after the completion of the Bragg reflector, a piezoelectric layer sandwiched between two electrodes was deposited onto the Bragg reflector. Pt thin film was employed as the bottom electrode and patterned using photolithography and lift-off techniques. ZnO piezoelectric layer was deposited on the bottom electrode using a reactive rf magnetron sputtering system. Finally, the transparent film of the alloy of Ag and Ti was deposited and patterned as the top electrode of G-S-G type to fit Cascade Microtech’s coplanar probes. The detailed fabrication processes of an SMR device is illustrated in Fig. 1.

Fig. 1 The fabrication processes of an SMR device.
2.2 The fabrication of TFBAW oscillator circuit

After the TFBAW devices were fabricated, oscillator circuits consisting of the matching networks and a high-frequency amplifier were formed. The impedance mismatch between two devices will lead to the attenuation and reflection of the input signal. Hence, the function of the matching networks is to match the impedances between TFBAW devices and the high-frequency amplifier. The designed and practical oscillator circuits were illustrated in Figs. 2 and 3.

Fig. 2 The designed oscillator circuit of an SMR device.

Fig. 3 The practical oscillator circuit of an SMR device.
2.3 UV light illumination and measurement systems

The systems for UV light illumination and measurement are set up on an optical anti-vibration table to detect ultraviolet light, as shown in Fig. 4. The ultraviolet light emission diodes (UV LEDs) are used as sources of UV light illumination and the intensities of UV light are directly proportional to the applied current, as shown in Fig. 5, which indicates that the emission wavelength of the UV LED is almost fixed at 385 nm. The various UV light intensities are adjusted by changing the arrangement of the neutral density (ND) filter to investigate the influence on the frequency shifts of TFBAW oscillators. The ultraviolet light is focused on the active area of TFBAW device using a series of lenses. Consequently, accurate experimental data on ultraviolet light detection can be obtained using these UV light illumination and measurement systems.

Fig. 4 The configuration of UV light illumination and measurement systems.

Fig. 5 UV intensities with variously supplied currents.
3. Results and Discussion

3.1 The sensing mechanisms of TFBAR-based UV sensors

The sensing mechanism for the shifts in the operating frequency of acoustic devices can be attributed to the acoustoelectric effect. When UV light was illuminated on the surface of ZnO thin film, the excess carriers in the ZnO layer would be produced. Then, the photogenerated carriers will increase the sheet conductivity in the ZnO thin film and interact with the electric field generated by acoustic wave devices, i.e. acoustoelectric effect. The photogenerated carriers will decrease the piezoelectric properties and reduce the phase velocity of piezoelectric thin films. The interaction between the acoustic waves and the charge carriers leads to the changes in phase velocity \( \Delta v \) is given by [12]:

\[
\frac{\Delta v}{v_o} = \frac{K^2}{2} \frac{\sigma^2}{\sigma^2 + (v_C C)^2}
\]

where \( v_o \) is the phase velocity on a free surface, \( K^2 \) is the electromechanical coupling coefficient of the substrate, \( \sigma \) is the sheet conductivity, \( C_s = \epsilon_s + \epsilon_o \) and \( \epsilon_s \) and \( \epsilon_o \) are the dielectric constants of the substrate and vacuum, respectively. The relationship between the sheet conductivity and the change of phase velocity was illustrated in Fig. 6. The influence of UV light illumination on SAW velocity can be monitored by measuring the frequency shifts of TFBAR oscillators.

\[ Fig. 6 \text{ The velocity shifts as a function of sheet conductivity.} \]

3.2 Frequency characteristics of an SMR device

Figure 7 shows the frequency response of an SMR device, in which, a large returning loss of 30 dB at 1.09 GHz can be observed. The discrepancy between designed and practical resonance frequencies can be attributed to the inaccuracy in the thickness of piezoelectric layer. The transistor of PHILIPs BFR 505 is adopted to construct the high frequency amplifier.
3.3 Frequency shifts of an SMR oscillator as a function of various UV light intensities

As illustrated in Fig. 8, an increase in the oscillator frequency shift corresponds to the increased intensity of UV light illumination. A relatively large frequency shift of 552 kHz based on the SMR oscillator can be obtained as the UV light intensity reached 212 μW/cm². The frequency shift of SMR oscillator reveals a similar upward trend to that based on SAW devices while illuminating various UV light intensities on the sensors.

Figure 8 shows that the UV light sensitivity of SMR-based devices is 20.66 ppm/(μW/cm²). As can be seen in Table 2, it reveals a considerable sensitivity based on an SMR device compared with those based on SAW devices. Due to the fact that the resonance wavelength for SMR devices is about 2 μm, UV light illuminated on these devices with the certain incident amount and penetrate depth has a relatively large influence on the acoustic waves in SMR devices. In other words, an acoustic wave device with a shorter wavelength is earlier disturbed than the devices with a longer wavelength. Therefore, SMR-based sensor results in a relatively large sensitivity while UV light is illuminated on the surface of ZnO sensing layer.
4. Conclusions

Comparing with SAW devices, TFBAW devices have advantages of low insertion loss, high power handling capability, small size, and high operating frequency. TFBAW devices were expected to create a UV sensor with higher sensitivity and better performance. The SMR-based TFBAW with $\frac{1}{2} \lambda$ configuration was used to construct the UV sensor owing to its better performance. As can be seen from the results, SMR-based UV sensor presented better UV sensing properties compared with SAW-based UV sensors. The reasons for the considerable frequency shifts and sensitivities can be attributed to that SMR-based sensor possessing a shorter resonance wavelength and a larger electromechanical coefficient than those of SAW-based devices. Finally, the maximum frequency shift of 552 kHz can be obtained when the illumination intensity of UV light was 212 $\mu$W/cm$^2$.

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