Flexible surface acoustic wave broadband strain sensors based on ultra-thin flexible glass substrate

Jinkai Chen[1], Wenbo Wang[1], Weipeng Xuan[1], Xiaozhi Wang[1*], Shurong Dong[1], Sean Garner[2], Pat Cimo[2] and Jikui Luo[3,1*]

[1]Coll. of Info. Sci. & Electron. Eng., Zhejiang University, 38 Zheda Road, Hangzhou 310027, China.

[2]Corning Incorporated, One River Front Plaza, Corning, NY 14831, USA

[3]Inst. of Renew. Energy & Environ. Technol., Bolton University, Deane Road, Bolton BL3 5AB, UK

Corresponding authors email: xw224@zju.edu.cn, jl2@bolton.ac.uk

ABSTRACT:

Flexible SAW devices based on ZnO piezoelectric thin film deposited on ultra-thin flexible glass were fabricated and their performances as a strain sensor have been investigated. The XRD and AFM characterizations showed that the ZnO layers have good crystal quality and smooth surface. The flexible SAW devices show excellent strain sensitivity which increases from ~87 to ~137 Hz/με with the increasing ZnO thickness, and the sensors can withstand strains up to ~3000 με, 4~6 times larger than those of SAW strain sensors on rigid substrates. The sensors exhibited remarkable stability up to hundreds of times bending under large strains. The effects of environmental variables (temperature, humidity, UV light) on the sensor performance have been investigated. The temperature has a significant effect on the performance of the SAW strain sensor, while humidity and light have limited effect.

INTRODUCTION

Flexible electronics is an emerging technology with rapid progress and wide penetration into various technologies and application areas. Various flexible electronic devices and microsystems have been developed and their applications have been explored [1-3]. The most common substrates so far being explored for flexible electronics are polymers such as PET, PI and PMMA *etc*. They can endure extremely large strains owing to the nature of their flexibility, but suffer from many shortages such as poor mechanical strength, poor wear resistance, low thermal stability and low processing and operating temperatures *etc*. The recently developed ultrathin Willow Glass has the combined merits of good flexibility, high transparency, excellent corrosion and wear resistance, mechanical reliability and thermal stability, and thus has raised great interests for the fabrication of flexible electronic devices[4-7]. Surface acoustic wave (SAW) devices are essential devices for communication and sensors, and recently we have successfully demonstrated flexible SAW devices on various polymer substrates with good performance, and demonstrated the excellent performance and applications of these SAW for sensors and microfluidics [8-10]. The paper reports a new type of flexible SAW devices that are made on the ultrathin glass substrate, and shows that the SAW devices have excellent performance as a strain sensor with ultra-broad strain ranges and remarkable stability and reliability.

EXPERIMENT

The flexible SAW devices were fabricated on the ultrathin glass (~100 µm, Corning® Willow Glass®) with a ZnO piezoelectric (PE) layer of 2.0-3.5 µm deposited by DC magnetron sputtering. Aluminum (Al, ~100 nm) interdigitated transducers (IDTs) were formed by photolithography and lift-off process. Al was deposited by the magnetron sputtering as well. The detailed fabrication conditions can be found in our previous work[4, 5]. Fig. 1(a) is a photo of the fabricated SAW devices on a Willow Glass, showing good flexibility and transparency. Fig. 1(b) shows the X-ray diffraction (XRD) spectrum of the ZnO piezoelectric layer with a single strong peak at 34.3°, which corresponds to the ZnO (0002) crystal orientation which allows the fabrication of piezoelectric effect based SAW devices. The inset shows the typical surface roughness of a 2.0 µm ZnO layer measured using atomic force microscope (AFM). The surface roughness is about 9.1 nm for this layer and increases slowly to ~10 nm when the ZnO thickness increases from 2.0 to 3.5 µm. These are smooth enough for the fabrication of high performance SAW devices. Annealing of the ZnO layer at temperatures between 150 to 300 °C before fabrication of IDTs was found to be very effective to improve the performance of the SAW devices[5]. All the devices used here were annealed. The wavelength, λ, of the SAW devices is in the range from 12 to 24 µm.

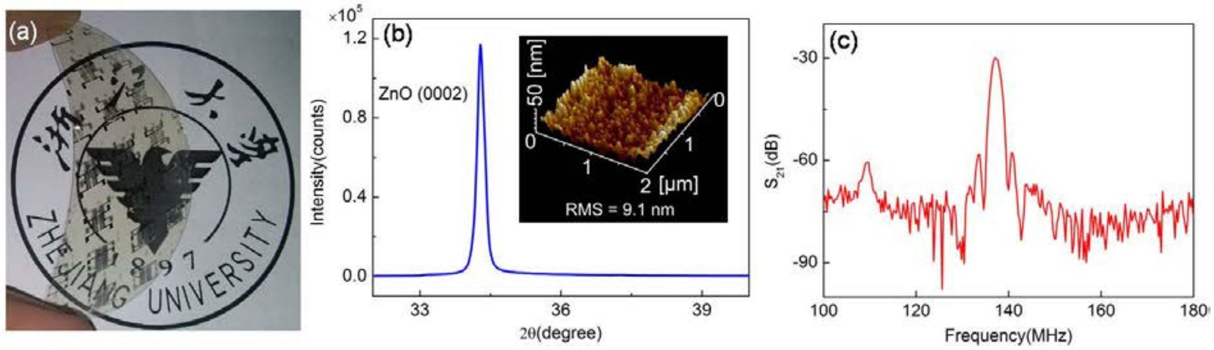

Fig. 1. (a) The transparent and flexible SAW device with excellent bendability and transparency. (b) The XRD spectrum and AFM result (inset) of the ZnO layer, showing strong (0002) crystal orientation and smooth surface. (c) The transmission spectrum of the SAW device with λ=20 µm and ZnO=2.0 µm, which has a resonant amplitude peak more than 40 dB.

For the transmission and strain sensing measurements, the SAW devices were bonded to a flexible PCB using Cu wires, and they together were glued to a flexible steel bar for bending test and strain sensing. A standard full-bridge strain gauge was placed next to the SAW device to measure the strain as the reference. A vector network analyzer (Agilent E5071C) was connected to the PCB through the SMA connectors to measure the transmission spectra. A Labview program was used to control the measurement and track the frequency shift under different measurement conditions. Fig. 1(c) shows a typical transmission spectrum of the SAW device on a 2.0 µm ZnO layer. The resonant frequency is ~138.0 MHz for the SAW with λ=20 µm, corresponding to an acoustic velocity of ~2760 m/s, in agreement with that of ZnO material. The amplitude of the resonant peak is more than 40 dB which is comparable to or better than those of SAW devices on rigid glass and silicon substrates, demonstrating its potential applications in electronics and sensors. Details for the characterizations under various temperatures and humidity can be found in our previous publications[4, 5].

RESULTS AND DISCUSSION

Sensing performance of the SAW sensors

Bending a SAW device leads to frequency shift, and is the principle of SAW strain sensor. The frequency shift under stress mainly results from two factors [4]: (1) deformation of the IDTs, hence the wavelength change of the SAW device, (2) change of material parameters, which leads to change of acoustic velocity. Fig. 2(a) shows the real-time frequency response of the SAW sensor (2.0 μm ZnO, λ=20 μm) when the applied strain increases incrementally. The resonant frequency increases from 138.09 MHz to 138.25 MHz when the strain increases from 0 to 1805 με, and the resonant frequency under different strains shows good stability. Fig. 2(b) shows the good linearity of the frequency shift with the strain applied. The sensitivity of this SAW device is 87.4 Hz/με calculated from the gradient. It was found that the sensitivity increases with the thickness of ZnO layer as shown in Fig. 2(c). For this type of strain sensors, the applicable strain ranges is up to 3000 με[5], 4~6 times larger than those of the SAW devices made on rigid glass substrates[11], showing its great potential as ultra-broad range strain sensor.

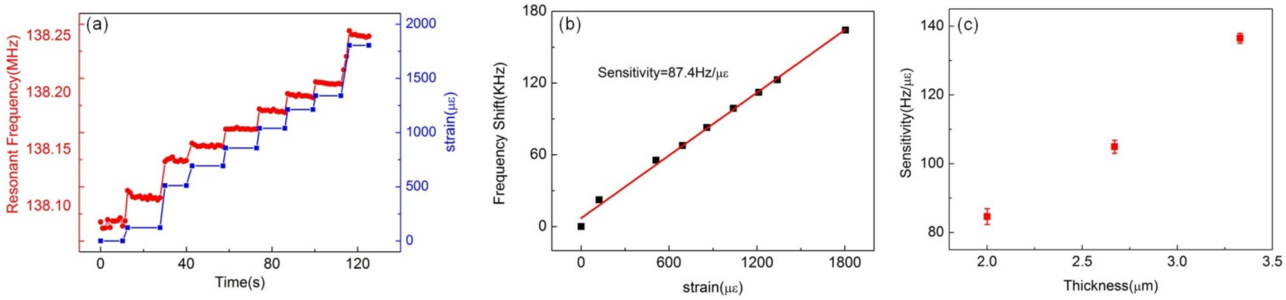

Fig. 2. (a) Real-time frequency response to different strains applied, showing good stability; (b) Frequency shift as a function of the applied strain; (c) Strain sensitivity as a function of ZnO thickness.

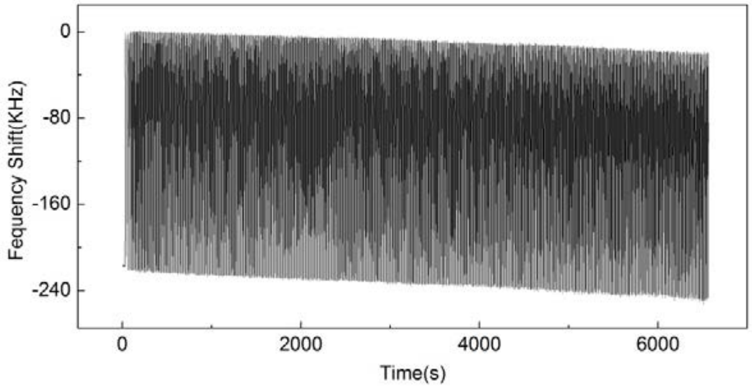

Fig. 3 Frequency under cyclic bending for 938 cycles (6568 s), showing good stability for each period.

The SAW strain sensors are very stable and reliable when it is subjected to cyclic bending tests under large strains. Fig. 3 shows the cyclic bending test result for a SAW sensor (λ = 20 μm, 2.7 μm ZnO, sensitivity ~110.8 Hz/$\mu\varepsilon$) up to 938 times (6568 s) with the strain varied cyclically from 0 to 2000 $\mu\varepsilon$. Although there is a drift in the base line, the frequency shift induced by the applied strain, hence the sensitivity, remains the same after hundreds of times bending, demonstrating its excellent stability and reliability.

Environmental effects on sensing performance

It is well known that SAW devices are very sensitive to environmental variables such as temperature, humidity and light, and these affect the performance of the SAW devices as electronic devices as well as the sensitivity as sensors. Here, we try to clarify the effects of these environmental variables. Temperature variation induces changes in material properties, hence the frequency shift of the SAW devices and the sensitivity of the strain sensor. Fig. 4(a) shows the resonant frequency shift as a function of temperature for the SAW device (2.0 μm ZnO, λ=20 μm). It decreases by 150 kHz when the temperature increases from 12.5 °C to 79.6 °C. The temperature coefficient of frequency (TCF =$\Delta f/\Delta T f_0$, Δf, ΔT and f_0 are frequency shift, temperature change and resonant frequency, respectively) is -13.7 ppm/K, similar to those with different wavelengths[4]. The TCF is smaller than most values of the SAW devices on rigid substrate such as rigid glass, Si and $LiNbO_3$ *etc* [12], and much smaller compared with those of flexible SAW devices on polymer substrates[10]. The TCF differences for the SAWs are due to the different thermal expansion coefficients and temperature coefficients of acoustic velocity of the substrates [13]. The small TCF for the SAW sensors obtained here is attributed to the small thermal expansion coefficient of the Willow glass used, which is ~4 ppm/K. It is clear that the temperature influence to the sensitivity of the strain sensors is significant, and must be carefully considered for precision measurement of the strains. This can be done either by using a temperature reference or another SAW device as temperature sensor. Fig. 4(b) shows the frequency change with temperature under different strains for another SAW device (2.0 μm ZnO, λ=12 μm). The TCF remains constant at -15.7 ± 3 ppm K^{-1} when the strain changes from 0 to 3000 $\mu\varepsilon$, indicating little influence by strain. This is an excellent property for this type of SAW to be used as flexible temperature sensors.

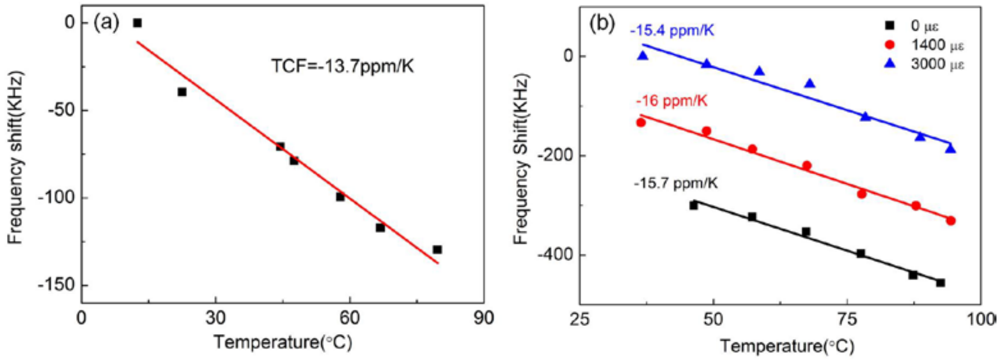

Fig. 4. The frequency shift as a function of temperature for the SAW device (2.0 μm ZnO, λ=20 μm) (a); and temperature dependence of frequency under different strains, showing good linearity with the gradients remained almost unchanged (2.0 μm ZnO and λ=12 μm) (b).

Humidity affects the performance of the ZnO SAW devices as the hydrophilic ZnO will absorb moisture from air [9]. We have investigated the humidity effect on the strain sensitivity. As shown in Fig. 5(a), the frequency decreases slowly with increase in humidity up to 40%RH and then the variation rate becomes larger with further increasing the humidity. The total frequency shift is about -10.4 kHz when the humidity increases from 10%RH to 85%RH. The humidity induced frequency shift is rather small as there is no sensing layer such as graphene oxide [9, 10], and is very small compared with that induced by strains and temperature. Fig. 5(b) is the comparison of the frequency shift before and after 15 cyclic humidity changes from

30%RH to 90%RH (for ~2 hr), at a fixed temperature of 40 °C. It is clear that the strain sensing performance remains unchanged after cyclic humidity change, showing its excellent stability. Generally the humidity change would be minor during strain measurements for a device even not encapsulated properly, therefore, the humidity effect for the SAW strain sensors is very small.

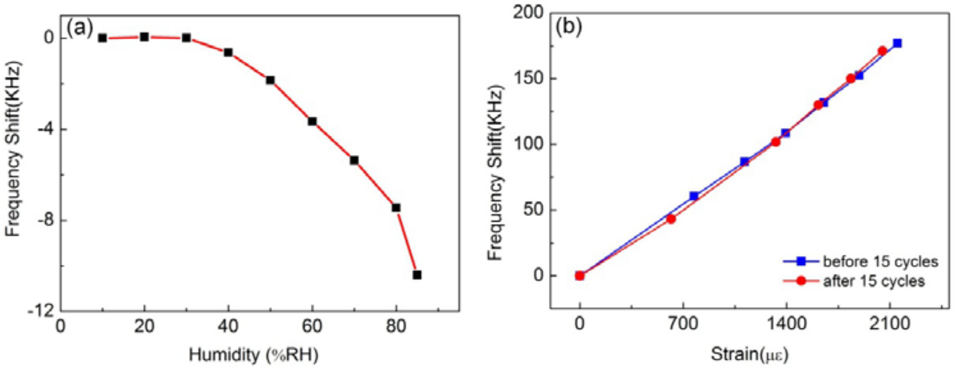

Fig. 5. (a) The frequency shift under different humidity, which is very small compared with that under different strains and temperatures. (b) The strain sensing performance before and after 15 cycles (~2 hr) of humidity changes from 90%RH to 30%RH at 40°C.

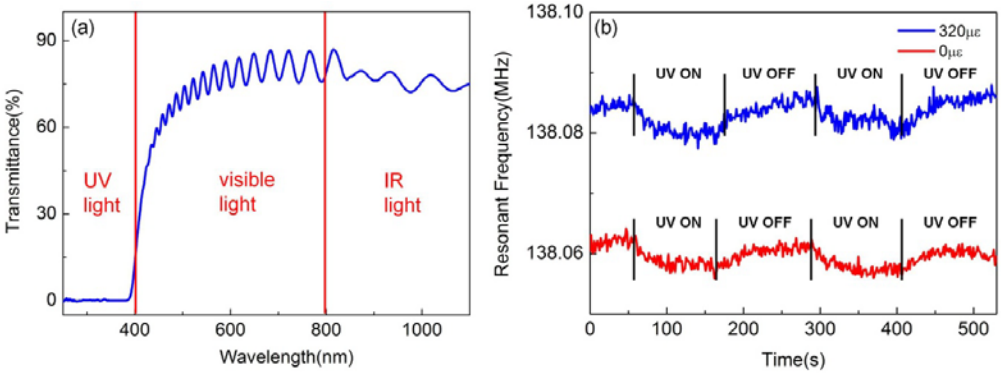

Fig. 6. (a) Full-region optical transmittance of the ZnO/flexible glass structure. (b) Real-time frequency response under large intensity of UV light with different applied strain, and the frequency shift is ~5 KHz.

ZnO is a semiconductor with wide band gap, and the Willow glass has good transparency. The strain sensor may be affected by the environment light which consists of three bands of light regions: ultraviolet (UV) light (200-400 nm), visible light (400-800 nm), infrared (IR) light (800-1100 nm). The optical transmittance of ZnO/flexible glass structure is shown in Fig. 6(a). The optical transmittance of the ZnO/flexible glass is more than 80% in most of the visible and IR light regions, but is nearly 0% for the UV light region. The small portion of visible and IR light are absorbed mostly by defects in the glass and ZnO layer, and may increase the temperature of the device, but the temperature increase was well below 2 °C when a UV-filtered light was exposed to the device for 10 min. Therefore the effect of these lights can be ignored. UV light has higher energy and would generate electron and hole pairs in ZnO surface layer, which shifts the resonant frequency of the SAW devices as reported in our previous work[8]. Therefore, UV light would be the main cause that environmental light would affect the performance and sensitivity of the SAW strain sensors. To clarify this, we have investigated the influence of the UV light to a bare SAW strain sensor. The frequency shift of the sensor under different strains is shown in Fig. 6(b) subjected to repeated UV light on and off. For both the cases, the resonant frequency decreases by ~5 kHz when the UV light intensity increased from 0 to 7.7 mW/cm^2. This frequency shift is very small compared with those induced by the applied strain and rising temperature. On the other hand, the UV light intensity used is well above that of the environmental UV light, yet the frequency shift induced is only 5 kHz which is equivalent to a strain of 55 με, within the experimental scattering range. Therefore environmental light effect can be ignored even if a bare SAW sensor is used to measure the strains.

CONCLUSIONS

Flexible SAW devices on ZnO/flexible glass have been fabricated. The XRD and AFM characterizations showed the good crystal quality and surface roughness of the ZnO piezoelectric layers. The SAW devices as a strain sensor have been characterized, and the sensors have very high sensitivity. The sensitivity increases from ~87 to 137 Hz/με when the ZnO thickness increases from 2 to 3.5 μm. The sensors showed excellent flexibility and can withstand strains up to 3000 με which is 4~6 times larger than those of SAW sensors on rigid substrates. The sensors have remarkable stability and reliability after hundreds of times bending under large strains. The effects of environmental variables (temperature, humidity, UV light) on the sensor performance have been investigated. The temperature has a significant effect on the performance of the SAW strain sensor, while humidity and light have limited effect.

ACKNOWLEDGMENTS

This work was supported by the NSFC (Nos. 61376118, 61171038 & 61204124). The authors thank the Innovation Platform for Micro/Nano Device and System Integration and Cyrus Tang Centre for Sensor Materials and Applications at Zhejiang University.

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