Flexible and transparent surface acoustic wave microsensors and microfluidics

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This paper reports the development of flexible and transparent (FT) surface acoustic wave (SAW) technology, and FT-SAW based various sensors (temperature, humidity, UV-light and strain) and microfluidics on polymer and glass. The devices on polymers have the Rayleigh and Lamb resonances, while those on glass have the Rayleigh mode only. All the modes have large signal amplitudes. FT-SAW based sensors show excellent sensitivities, comparable to or better than those on rigid substrates. The temperature sensitivity of the sensors on PI is more than one order of magnitude larger than those on rigid substrates. The humidity sensitivity can be further increased significantly by using a graphene oxide (GO) sensing layer. All types of the sensors have excellent stability and reliability. FT-SAW also demonstrated very good capability to deliver microfluidic functions such as acoustic streaming and particle concentration etc. The results demonstrated the FT-SAW have great potential for applications.

1. Introduction

Surface acoustic wave (SAW) are essential devices with widespread applications in communications, sensors and microfluidics etc.1-3 They are normally made on rigid piezoelectric (PE) substrates such as LiNbO3 or on PE thin films such as ZnO deposited on rigid substrates, severely restricting their applications in flexible and transparent electronics.4 Flexible and transparent electronics are an emerging technology with great potential and innovation for applications owing to their excellent properties and advantages over traditional solid state electronics. Recently, many novel flexible electronic devices and microsystems have been reported such as flexible electronic displays5, electronic skin6 etc. Polymers such as polyimide (PI) and polyethylene terephthalate (PET), and are the most commonly used flexible substrates. We have developed flexible and transparent SAW technologies recently, demonstrated their excellent performances and potential for applications. Here we report on the development of...
flexible and transparent SAW technology and various sensors and microfluidics based on these SAW devices.

2. Experimental

All the SAW devices were fabricated by photolithography with a ZnO PE layer with a thickness between 1.0 to 4.2 μm deposited by DC sputtering on PI or PET (~100 μm), or glass substrates. For the strain sensors, special glass, Willow Glass obtained from Corning Glass, was used which has a thickness of 100 μm. The deposition conditions for the ZnO layers can be found in our previous paper. Aluminum was used to fabricate the interdigitated transducers. Figure 1a &b show a schematic of the flexible SAW, and an image of the fabricated devices on a polyimide substrate. The wavelength, \( \lambda \), of the devices varies from 10 to 32 μm. The distance between the two IDTs is 10-40 wavelengths. The transmission spectra of the devices were characterized by Agilent Network Analyser (E5071C). A LabVIEW based program was developed to implement automated measurements of frequency shift of the devices. For humidity and strain sensing, home-made setups were used for the characterization. The crystal structure of the ZnO layers were assessed by X-ray diffraction and scanning electron microscope (SEM), showing all ZnO layers have columnary structure, perpendicular to the substrate with grain sizes in the range of 30-60 nm, while the surface roughness is in the range of 5-10 nm for all films, excellent for PE applications.

3. Results and discussion

Figure 1c &d show the spectra of a SAW device on PI substrate with \( \lambda = 10 \) μm and ZnO of 4.0 μm. For all the SAW devices on PI film, they have two well-defined resonant peaks, namely the Rayleigh (R-) wave and Lamb (L-) wave mode. Generally, the transmission property is poor for the device with a thin ZnO layer, and improves rapidly with the increase of the ZnO layer with two large resonances as shown in Figure 1c. The phase velocity, \( v_p \), of the L-wave approaches its limit of ~5510 m/s of the ZnO plate, while \( v_p \) of the R-mode reaches the intrinsic value (~780 m/s) in the PI film as \( \lambda \) increases. The results are summarized in Figure 1d together with the results obtained from theoretical calculation. The R-mode velocity increases with the decrease of the wavelength, while that of L-mode increases with the increase of wavelength, both approaching to those of the ZnO layer, in excellent agreement with the theoretical calculation. On the other hand, the transparent SAW devices on glass typically have one resonance only, namely the Rayleigh mode due to the similar acoustic velocities in both the ZnO layer and glass substrate.

These SAW devices have been utilized to develop temperature, humidity, UV-light and strain sensors, showing excellent sensitivity to all variables, comparable to or better than those on rigid substrate. The temperature and strain sensors have excellent linearity with the frequency shifts for both R-mode and L-mode. The temperature coefficients for the R- and L-mode are different, thus one of the modes can be used as the temperature reference to develop the on-chip temperature-compensated humidity, strain and UV-light sensors. We have successfully developed on-chip temperature compensated humidity and strain sensors.

As ZnO is a hydrophilic material, moisture can be easily absorbed on the surface of the device, leading to increase of the mass, which shifts the resonant frequency of the sensor. By measuring the shift of the frequency, it is possible to identify the humidity of the environment. The humidity sensor shows a non-linear relationship with humidity variation. The frequency shift of the SAW sensors is in the range of 16 kHz/10% RH (relative humidity) at low RH levels, and increases to 34 kHz/10% RH at 80% RH region, comparable to those of SAW H-sensors on solid...
substrates. The performance of the humidity sensors can be improved significantly by using graphene oxide (GO) as the sensitive film as GO layer has much larger active surface area than the flat ZnO surface. Figure 2a is a schematic of the SAW sensor with GO sensing layer and a photo of the IDT area with a GO layer visible. It was found that the response speed of the GO SAW H-sensor is very fast. The rising time is about 1 s and the fall time is in the range of 5-6 s when the humidity is change to 10% RH to 80% RH as shown in Figure 2b. The sensitivity of the GO SAW H-sensor is up to 120 kHz/10% RH at 80% RH as shown in Figure 2c, about 4 times larger than that of SAW H-sensors with bare ZnO surface very stable at all the humidity levels, showing no deterioration over 8 days.

As polymer and Willow glass substrates are flexible, thus they are suitable for the development of strain sensors. We have developed SAW strain sensors using SAW devices on PET as well as on Willow glass substrate. Figure 3a is a photo of the measurement setup for strain characterization. Figure 3b is the response of the frequency of the SAW on a PET substrate upon cyclic bending of the device. The frequency response of the flexible SAW strain sensors have a very good linearity with strain with a broader strain range up to \( \pm 3000 \mu \text{e} \), more than 5 times larger than those on rigid substrates. The strain sensors are very stability and mechanically durable. The sensitivity for the SAW on PET is in the range of 30-40 Hz/\( \mu \text{e} \), much larger than those on solid substrate. Similarly, the strain sensitivity for the SAW on Willow glass substrate is in the range of 34.7 Hz/\( \mu \text{e} \), though slightly smaller than that on PET substrate, but still more than 5 times larger than those on solid substrates, demonstrated their superior properties and potential for applications.

Microfluidic characterization shows that the FT-SAW has similar microfluidic functions with performances slightly inferior to those on rigid substrates due to the weakening wave transmission. Figure 4a and b illustrate a schematic and an image of the acoustic streaming induced by SAW on PI. Figure 7c is the comparison of streaming velocity by various wave modes for SAW on different substrates. The velocities increase linearly with the RF signal voltage as observed from those on rigid substrates before. The acoustic velocity induced by the Sezawa mode from SAW on Si substrate is the largest as expected, followed by that induced by the Rayleigh mode on SAW on Si and glass substrate, and then those of the R- and L-mode from SAW on PI. Figures 7d-f are the comparison of nanoparticle concentration time and area induced by SAW on different substrates, showing the compatible performances of SAW on various substrates.
Fig. 7. A schematic and an image of SAW-based acoustic streaming (a) (b), comparison of streaming velocity on different substrates and wave modes (c), comparison of particle concentration by SAW on various substrates, including particle concentration area (d) and concentrated time (defined as $D_c/D_t = 0.1$) (e), and droplet volume as a variable for ZnO/glass substrate devices (f).

4. Conclusions

We have fabricated high performance flexible SAW devices on polymer and glass substrates, and obtained temperature, humidity, UV-light and strain sensors with high sensitivity using these devices. We also demonstrated the application of these flexible SAW in microfluidics. The performance of the microfluidics on polymer substrates is slightly inferior compared to those of Si substrate, but they have sufficiently good performance for pumping, mixing etc applications. The results demonstrated the flexible SAW have great potential for applications.

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