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Flexible and bendable acoustofluidics based on ZnO film coated aluminium foil

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ABSTRACT

ZnO coated Al foil of 50 μm thick was used to fabricate flexible and bendable acoustofluidic devices with various wavelengths (from 64 to 800 μm). Different acoustic wave modes (including Lamb waves and Rayleigh waves) were obtained experimentally and verified from theoretical analysis. Flexibility and deformability of the ZnO/Al foil acoustic wave devices were demonstrated by (1) deformation testing by bending the acoustic wave devices with strain values up to 1.375%; (2) fatigue testing by bending the devices for 2000 cycles. Using Lamb waves and Rayleigh waves generated from the ZnO/Al foil acoustofluidic devices, functions of droplet streaming and pumping were demonstrated using the flexible acoustic wave devices under different bending and twisting positions.

1. Introduction

Flexible and bendable electronics and micro-electromechanical system (MEMS) devices have recently been received significant attention for a wide range of applications such as compact electronics packaging (e.g. smartphone internal components), flexible displays, surgical treatment, wearable medical sensing, drug delivery, micro-total analysis system (μTAS) and wearable consumer devices [1–7]. They have demonstrated superior advantages over rigid solutions for flexibility, deformability, space reduction, integration and operation within complex shapes and structures. Flexible ultrasonic or acoustic wave sensors/actuators have been proposed for non-destructive ultrasonic testing [8–10], energy harvesting [11,12], and sensing in liquids [13]. Acoustic wave (AW) technologies, especially thin film surface acoustic wave (SAW) devices, have been investigated extensively for integrated lab-on-chip and μTAS applications [14–21]. ZnO thin film based SAW microfluidic devices fabricated on the flexible polymer substrates have also been demonstrated [22–24]. However, there are significant challenges with realizing efficient acoustic microfluidic functions on these polymer substrates, including significant attenuation and dissipation of acoustic wave and energies into polymer, poor film crystallinity and poor adhesion of thin film on the polymer substrates.

This paper, for the first time, theoretically analysed and experimentally demonstrated the efficient and high performance flexible and deformable acoustofluidics based on ZnO films (5 μm) deposited onto commercially available aluminium foil (50 μm). The Al foil substrate promotes texture growth of ZnO film, provides good film adhesion, and reduces film stress during film deposition, all of which are superior compared to those on a polymer substrate. Al foils, compared with their polymer counterparts, have distinct advantages of deformability (forming and then maintaining temporary shapes) and re-deformability (easily returning back to their un-deformed shape), and they thus solve many common problems associated with most of polymer based flexible devices (for example, large energy dissipation and permanent deformed shapes). Using commercially available large area Al foils and thin film process, mass production or roll-to-roll processes with a low cost could be realized to fabricate high performance flexible/deformable acoustic wave sensors and microfluidic devices. However, there is not any report on flexible acoustofluidics using Al foils as substrates, although Al foil has been used as flexible electrodes on rigid $LiNbO_3$ based SAW substrates [24].

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2. Experimental

ZnO films (5 μm thick) were sputtering deposited onto commercial aluminium foil (with thicknesses of 50 ± 5 μm in rectangular shapes with dimensions of 250 mm × 150 mm) using a Zn target (300 mm × 100 mm) at a DC power of 500 W, an Ar/O_2 flow ratio of 50/50 SCCM (standard cubic centimetre per minute) without any intentional substrate heating. During the deposition, the substrate holder was rotated to improve uniformity. The substrate to target distance was 20 mm and gas pressure was 5 mTorr.

The Al foils coated with ZnO films were attached onto a silicon carrier wafer, and the SAW delay lines were fabricated by patterning Cr/Au interdigital transducers (IDTs) using a conventional lift-off process. The IDTs were designed with a spatial periodicity or wavelengths of 64–800 μm, with 30 pairs of fingers and an aperture of 4.9 mm. The distance between the centres of a pair of IDTs was 10 mm. The frequency response spectra of the SAW devices were measured using a vector network analyzer (Agilent E5061B).

Flexibility, deformability and re-deformability of the Al foil based devices were demonstrated by substrate bending characterizations. The device (with a wavelength of 64 μm) was bent to different angles with different strains and the transmission signals were continuously measured using the network analyser. Fatigue and cycling performance of the device were evaluated by bending the device with a fixed strain 0.6% for up to 2000 cycles, and the surface morphology and transmission characteristics were continuously monitored during bending. The bending was created by a mechanical bending vise where steel tubes with different diameters were put under the Al foil at the bending centre. The device was then taken out and straightened again.

For effective microfluidic droplet manipulation, the surfaces of the devices were coated with a 200 nm thick hydrophobic layer of CYTOP^{TM} (Asahi Glass Co. Ltd.). The devices were mounted onto a bulk aluminium alloy test-holder in order to minimize the possible heating effects. For SAW generation, the devices were actuated using an RF signal generator (Agilent Technologies, N9310A), which was amplified using a broadband power amplifier (Amplifier Research, 75A250). The signal generator and the amplifier both had 50 Ω output resistance, and we used 50 Ω wires to connect the signal generator, the amplifier and the device to minimize internal reflection of the RF signals. Thus the system had less signal loss during the signal transmission path. The de-ionized (DI) droplets of 2.5 μL were placed onto the flexible devices, 2 mm in front of the SAW IDTs. The microfluidic behaviour of de-ionized water droplets were recorded using a high speed video camera (Vision Research, phantom V7.3) working at a frame rate of 4000 frames/s. Droplet pumping speeds were estimated based on the recorded videos and the frame rates.

3. Results and discussions

3.1. Frequency and vibration mode characterization

Fig. 1 shows the measured frequency (S11) spectra of the devices with two types of wavelengths, and different peak positions corresponding to different wave modes have been marked. The Lamb waves (including A_0 and S_0 modes) can be clearly identified for most of the devices which matches the theoretical values calculated based on the substrate thickness. The measured results of frequency values for different devices with different wave modes are summarized in Fig. 2.

If thicknesses of the ZnO film and Al foil are fixed, with the increment of wavelength (λ) of acoustic waves, the wave modes will change from a pure Rayleigh type wave (when the wavelength is significantly smaller than the thickness of the device) into a mixture of Lamb and Rayleigh waves and then finally into pure Lamb waves (when the wavelength is much larger than the thickness of

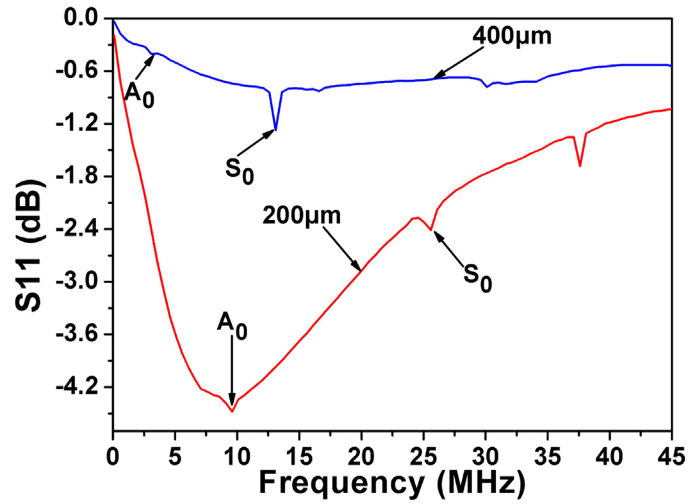

Fig. 1. Frequency response (S11) spectra of the Al foil SAW devices with different wavelengths (200 and 400 μm).

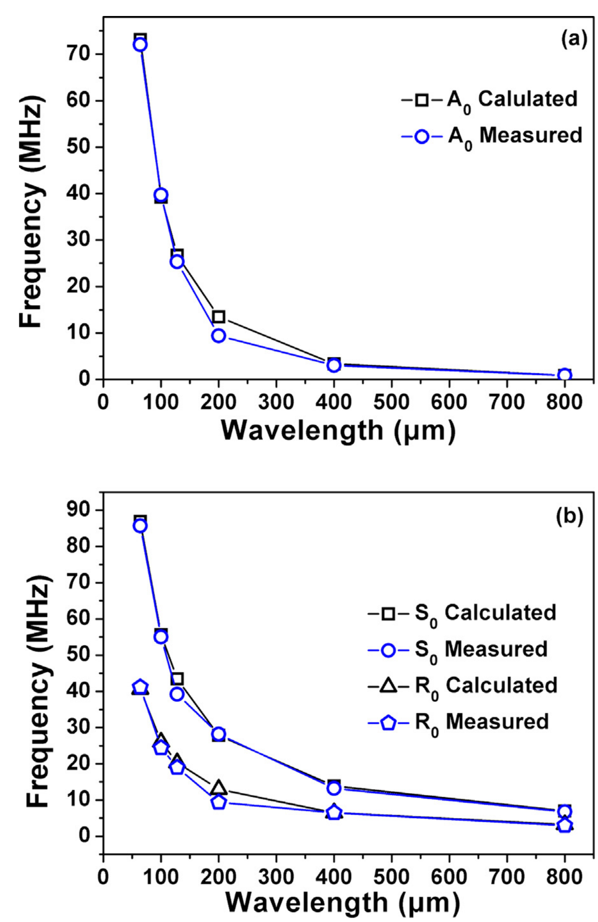

Fig. 2. Comparison of calculated and measured frequencies of A_0 modes (a); R_0 and S_0 modes (b) for the devices with different wavelengths.