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Research Article

Flexible Surface Acoustic Wave Device with AlN Film on Polymer Substrate

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Surface acoustic wave device with *c*-axis-oriented aluminum nitride (AlN) piezoelectric thin films on polymer substrates can be potentially used for development of flexible sensors, flexible microfluidic applications, microsystems, and lab-on-chip systems. In this work, the AlN films have been successfully deposited on polymer substrates using the DC reactive magnetron-sputtering method at room temperature, and the XRD, SEM, and AFM methods reveal that low deposition pressure is beneficial to the highly *c*-axis-oriented AlN film on polymer substrates. Studies toward the development of AlN thin film-based flexible surface acoustic wave devices on the polymer substrates are initiated and the experimental and simulated results demonstrate the devices showing the acoustic wave velocity of 9000–10000 m/s, which indicate the AlN lamb wave.

1. Introduction

The surface-acoustic-wave- (SAW-) based microfluidic devices can be used not only for pumping, mixing, and droplet generation but also for biosensors and single-mechanism-based lab-on-a-chip applications [1]. By now, all SAW devices are fabricated on the stiff substrates instead of flexible's, suah as $LiNbO_3$ [2], Piezoelectric (PE) thin films on Si wafer [3, 4], diamond [5], Al_2O_3 [6] and so on. SAW on flexible substrate is cheaper and can be bent easily, which is fitted for portable microfluidic applications, such as wrist health-care monitor. In this paper, a SAW device with aluminum nitride (AlN) piezoelectric thin films is fabricated on the polymer substrates, and its resonance response is also investigated.

2. Experimental Details

Kapton polyimide film 100H (Dupont-Toray Inc., thickness 250 μm) was chosen as the flexible substrate owing to its excellent mechanical and electrical properties, chemical stability, and wide operating temperature range (-269°C to $+400^\circ$C). AlN was deposited by a home-made DC magnetron-sputtering system. The base pressure of the chamber was 1×10^{-4} Pa before deposition. The aluminum (Al) target of purity was 99.999% and a diameter of 20 mm was used and water-cooled. The distance between the target and the substrate was fixed at 70 mm. Before depositing the AlN film, an Al underlayer was deposited on the polyimide substrate as a transition with deposition pressure of 0.27 Pa and DC power of 300 W. AlN was then deposited on the Al-coated polyimide substrate in an N_2/Ar atmosphere. The effect of deposition pressure on the properties of the AlN films was investigated. The AlN deposition time for all samples is one hour, and the substrates were not intentionally heated.

The crystalline structure and crystal orientation of films were analyzed by X-ray diffraction (XRD-6000, Japan) using Cu-K_α radiation and scanned angle of $2\theta = 20^\circ \sim 70^\circ$. The degree of *c*-axis crystallization was examined by the full width at half maximum (FWHM) of the AlN (002) diffraction peak. The strain and crystallite size of the thin film were extracted from the XRD data by the standard method. Strain is calculated from $\varepsilon_z = (c - c_0)/c_0$ [7], where c_0 is the strain-free lattice parameter (4.979 Å) and the lattice constant c is equal to twice the interplanar spacing d,

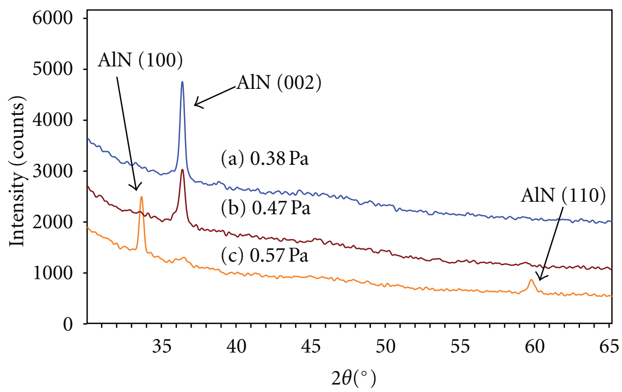

Figure 1: XRD patterns of AlN thin films deposited on polymer substrates with Al electrodes under different deposition pressures.

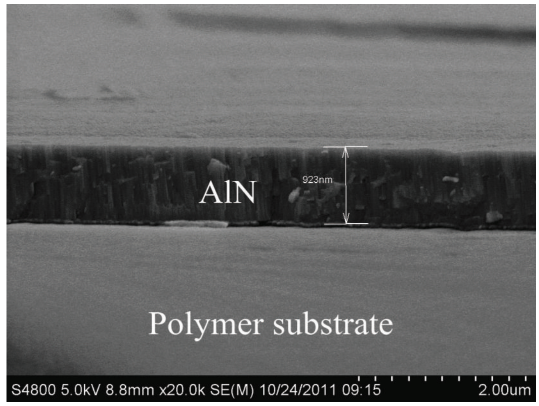

Figure 2: The SEM micrograph of AlN thin films on polymer substrate.

measured from the position of the (002) peak using Bragg-equation. Crystallite sizes were calculated from the Debye-Sherrer formula [8]: $D = K\lambda/(\beta\cos\theta)$, where K is the shape factor of the average crystallite with value of 0.94, λ the X-ray wavelength (0.15406 nm for Cu target), β the FWHM in radians, θ the Bragg angle, and D the mean crystallite dimension normal to diffracting planes. For cross-sectional columnar structure observation, the microscopic film was observed using a Scanning Electron Microscope (SEM) (S4800, Hitachi, Ltd., Japan). The surface morphology and root mean square (rms) surface roughness of the AlN films were measured by atomic force microscopy (AFM) (SPI-3800N, Seiko, Japan).

To study the SAW propagation characteristics on flexible substrates, two-port resonators were designed and fabricated by conventional deep UV photolithography and lift-off process. Al was used as the electrodes with a thickness of 150 nm and each transducer consisted of 10 pairs of IDTs. The distance between the two transducers was 10λ, where the SAW wavelength λ is determined by the IDT pitch. The aperture was 80λ and the distance between the IDTs and the adjacent shorted reflecting gratings was designed as 5.375λ to ensure the formation of a standing wave at center frequency. The frequency characterization was carried out using Agilent 8722ES network analyzer.

3. Results and Discussion

Figure 1 shows the XRD pattern of the AlN films deposited at different deposition pressures. In Figures 1(a) and 1(b), AlN film shows a main XRD peak near $2\theta = 36.1°$ which corresponds to the AlN (002) crystal orientation. The results demonstrate that the AlN crystal structures are perpendicular to the polymer substrate with a good (002) orientation. The FWHM of the AlN (002) peak with 0.38 Pa is 0.321°. The grain size is 274 Å and the strain is 0.4%. Figure 2 is an SEM micrograph of the cross-sectional structure of the AlN films deposited on the polymer substrate at the deposition pressure of 0.38 Pa. It is obvious that the film shows a neat arrangement and exhibits a typical (002)-oriented columnar structure. The surface morphologies and the rms surface roughness of the AlN are measured by AFM, as shown in Figure 3. With the increase of the deposition pressure, the rms surface roughness increases. The smoothest AlN film is obtained at the deposition pressure of 0.38 Pa with the rms surface roughness of 4.8 nm.

Two-port resonators (Figure 4) have been fabricated on the AlN film deposited with an N_2/Ar flow ratio of 1 : 2 and pressure of 0.38 Pa. The AlN film for the resonators has a the thickness of 1.23 μm, FWHM of 0.321° and grain size of 274 Å. Two types of SAW samples were fabricated with different wavelengths of 7.128 μm and 6 μm, respectively. The resonance frequency of a SAW device is determined by the equation $f_0 = V_p/\lambda$, where f_0 is the central frequency, V_p the phase velocity of the acoustic wave, and λ the acoustic wavelength.

Figures 5(a) and 5(b) present the measured S_{21} spectra of the fabricated SAW resonators with the wavelengths of 7.128 μm and 6 μm, respectively. The measured S_{21} spectra take the form of the Sinc function as expected for uniform IDT SAW devices [9]. The resonance frequency of the SAW resonator with the wavelength of 7.128 μm is 1.355 GHz, corresponding to the acoustic wave velocity of 9658 m/s, whereas the resonance frequency of the SAW resonator with the wavelength of 6 μm shifts to 1.605 GHz, corresponding to the acoustic wave velocity of 9630 m/s, showing that the acoustic wave velocity is not affected by the device structure. The results have clearly demonstrated the piezoelectric effect of AlN film on polymer substrate.

To confirm whether the resonant frequency is generated through PE effect, the frequency response of the resonators has been modeled by the commercial software COMSOL Multiphysics. As the simulation diameters, the thicknesses of Al IDTs, AlN film, Al underlayer, and polyimide substrate are set to be the same as used in devices and are 150 nm, 1.23 μm, 70 nm, and 100 um, respectively. Figures 6(a) and 6(b) show the simulated results of the SAW resonators with the wavelengths of 7.128 μm and 6 μm, respectively. Since the resonance frequency has the largest total stored energy, the SAW resonator with the wavelength of 7.128 μm has the resonance frequency of 1.415 GHz, corresponding to the acoustic wave velocity of 10086 m/s, and that with

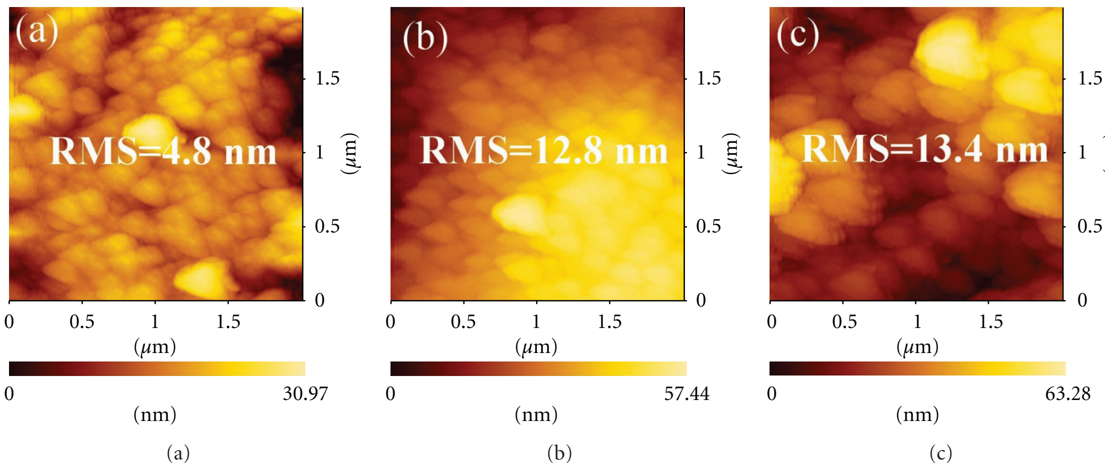

Figure 3: Surface morphologies of AlN films on polymer substrates under different deposition pressures: (a) 0.38 Pa, (b) 0.47 Pa, and (c) 0.57 Pa.

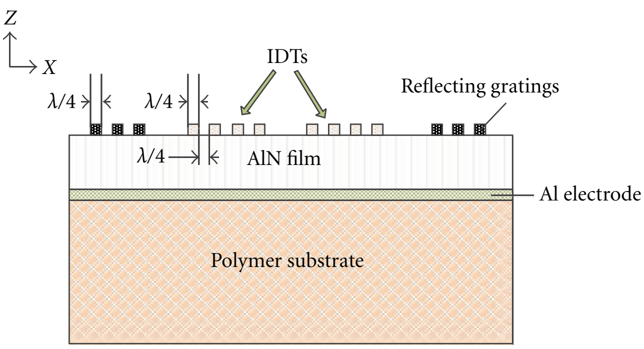

Figure 4: The structure of 2-port SAW resonator on polymer substrate.

the wavelength of 6 μm has the resonance frequency of 1.66 GHz, corresponding to the acoustic wave velocity of 9960 m/s. The experimental results are in good agreement with the simulated results.

Polymer substrates have a very low acoustic impedance (2 Mrayls) which is much smaller than that of the AlN layer (36 Mrayls). The Al underlay enhances the electromechanical coupling coefficient as an electric field can be induced between the IDT electrodes and the Al underlay [10]. Moreover, the *c*-axis-oriented thin AlN films have relatively large thicknesses at about $d = 0.2\lambda$, where λ is the acoustic wavelength; therefore, the detected acoustic waves are the symmetrical S_0 Lamb waves which theoretically have the acoustic wave velocity near 10,000 m/s [11–13] in AlN. The velocity of the experimental results is slightly smaller than the simulated and theoretical results, possibly due to the defects of the AlN film and the slow-down effects by the Al-coated polyimide substrates. Figures 7(a) and 7(b) show the simulated results of AlN without Al and polyimide substrates. It is clear that the resonance frequency of the SAW resonator with the wavelength of 7.128 μm is 1.524 GHz, corresponding to the acoustic wave velocity of 10863 m/s, whereas the resonance frequency of the SAW resonator with

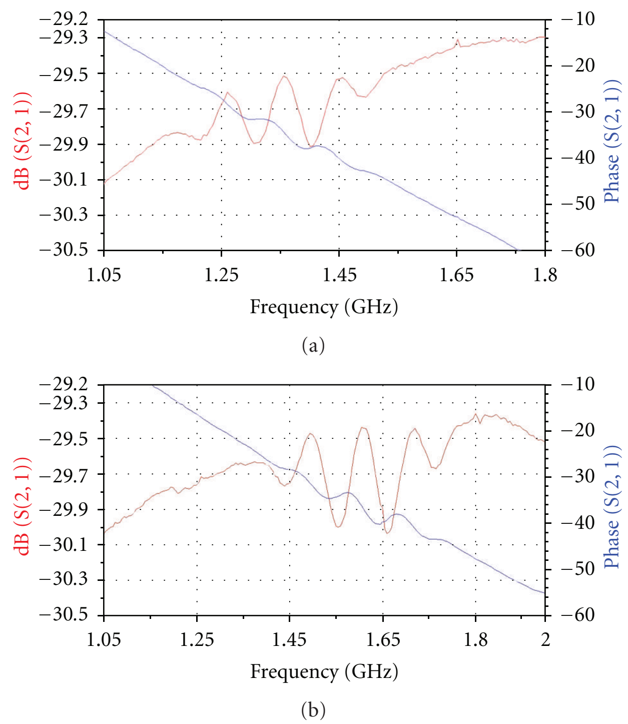

Figure 5: The measured S_{21} spectrum of the fabricated SAW resonators with a wavelength of (a) 7.128 μm and (b) 6 μm.

the wavelength of 6 μm shifts to 1.81 GHz, corresponding to the acoustic wave velocity of 10860 m/s; both are higher than those in SAW with Al-coated polymer substrate. This result shows that Al-coated polyimide substrates would decrease the resonance frequency due to the low wave velocity of Al-coated polyimide substrate.

4. Conclusions

In this research, we have synthesized and characterized the AlN thin films on Dupont Kapton polyimide substrates by

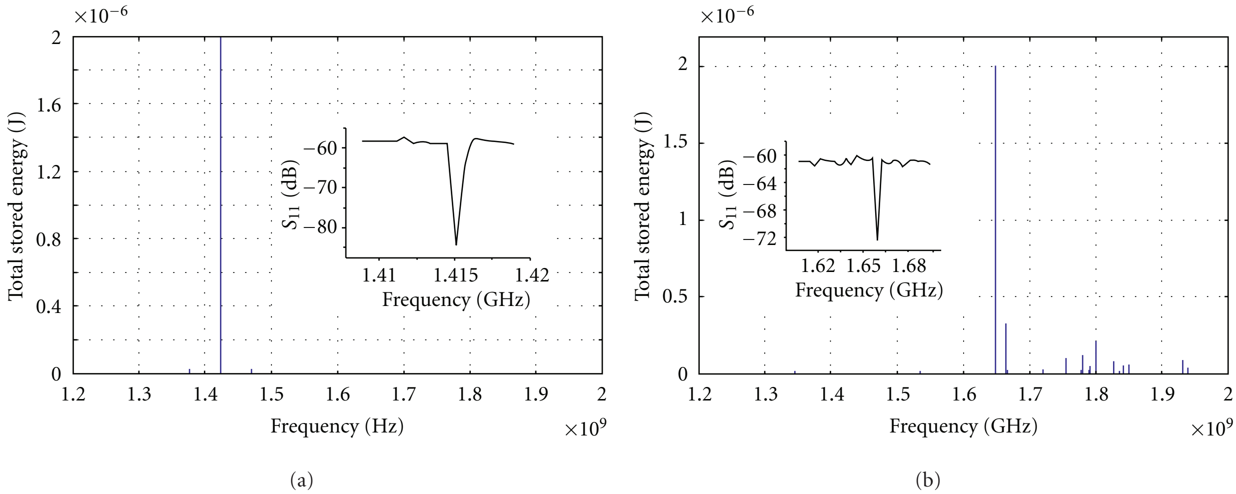

Figure 6: The simulated resonance response of the SAW resonators with the wavelengths of (a) 7.128 μm and (b) 6 μm.

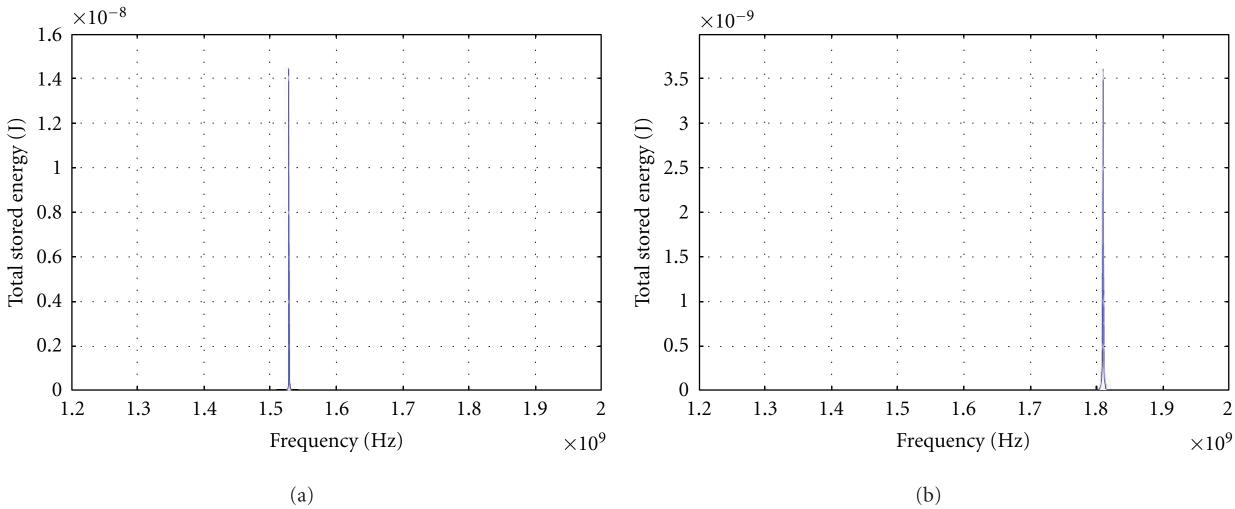

Figure 7: The simulated resonance response of the SAW resonators without Al and polymide substrates with the wavelengths of (a) 7.128 μm and (b) 6 μm.

DC magnetron reactive sputtering. The XRD, SEM, and AFM are used to characterize the orientation, cross-sectional structure, surface morphology, and thickness of AlN thin films. The results show that low deposition pressure is beneficial for AlN (002) orientation. Flexible substrate-based Lamb wave resonators have been fabricated. The experimental and simulated results demonstrate of the devices have the acoustic wave velocity of 9000–10000 m/s, and the deposited AlN film on polyimide substrate are high quality, and have successfully shown the piezoelectric effect.

Acknowledgments

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