Mass sensitivity of dual mode SAW delay lines on AlN/sapphire structure

J. Xu, G. Hu, G.W. Auner and H. Ying

A surface acoustic wave (SAW) and a leaky shear horizontal SAW (SH-SAW) have been simultaneously excited along $Al_2O_3[1\bar{1}00]$ on an $AlN(0001)/Al_2O_3(11\bar{2}0)$ structure. Both modes are highly sensitive to surface mass loading. The measured mass sensitivities are in good agreement with theoretical prediction, and are comparable or higher than those reported on other SAW devices.

Introduction: There have been growing demands in recent years for highly sensitive surface acoustic wave (SAW) sensors that are able to detect minute quantities, especially in the chemical and biological fields. AlN is a promising material to fulfil such a task because of its high SAW velocity and good piezoelectricity [1]. Compared to conventional bulk piezoelectric materials such as quartz and $LiTaO_3$, its thin film structure provides additional flexibility to integrate with substrate materials to modulate the phase velocity v, electromechanical coupling coefficient K^2, etc., and excite higher velocity SAW modes [2]. High velocity leaky SAWs have been reported on anisotropic thin film structures [3] and some may possess special features such as SH polarisation [4, 5], which makes them suitable for aqueous biosensing due to much less attenuation in liquid than SAWs. In this Letter we quantitively study the mass sensitivities of the coexisting SAW and SH-SAW on the $AlN(0\,0\,0\,1)Al_2O_3(1\,1\,\bar{2}\,0)$ structure by loading the device with an Al thin film. The results would serve as good references for the development of highly sensitive dual mode sensors which can work in either gas or liquid environments.

Experiment: $AlN(0\,0\,0\,1)$ thin films of 1.4 to 2.2 μm thickness were grown on $Al_2O_3(1\,1\,\bar{2}\,0)$ substrates by a plasma source molecular beam epitaxy system. The epitaxial relationships determined by reflection high energy electron diffractions are $AlN[1\,\bar{1}\,0\,0]//Al_2O_3[0\,0\,0\,1]$ and $AlN[1\,1\,\bar{2}\,0]//Al_2O_3[1\,\bar{1}\,0\,0]$. SAW delay lines inclined at a 15° interval from the $Al_2O_3[1\,\bar{1}\,0\,0]$ azimuth were fabricated. Each device has a wavelength λ of 22.8 μm, 50 pairs of Al interdigital transducers (IDTs), and a delay length of 200 λ. Strong resonance of a higher velocity mode was observed in addition to the SAW along $Al_2O_3[1\,\bar{1}\,0\,0]$. A typical frequency response of such a dual mode device propagating along $Al_2O_3[1\,\bar{1}\,0\,0]$ was measured by an Agilent 8751 network analyser (shown in Fig. 1). The calculated phase velocity of the second mode is about 6082 m/s, higher than both the SAW velocity (5812 m/s) and the bulk SH wave velocity (6042 m/s) of the $Al_2O_3(1\,1\,\bar{2}\,0)$ substrate along the same direction. This indicates a leaky nature of the second mode as coupling to the bulk SH wave of the $Al_2O_3(1\,1\,\bar{2}\,0)$ is possible. The SH polarisation of the second mode was further confirmed by a liquid loading experiment, in which attenuation of 25 dB occurred on the SAW in contrast to only 4 dB on the second mode.

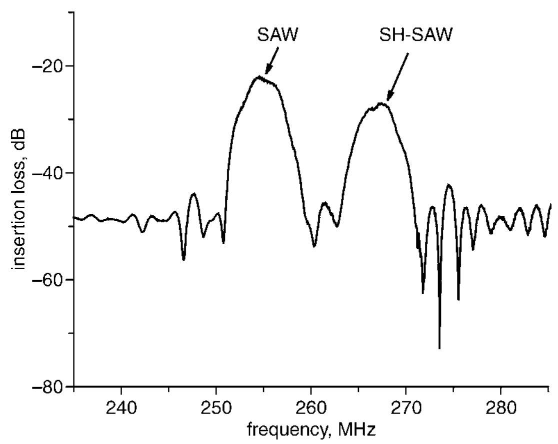

Fig. 1 *Frequency response of dual mode SAW device*

We carried out mass loading on the device by coating the inner IDT region with sputtered Al for its relative large modulus to density ratio [6], so that the modulus effect on the resonance frequency can be neglected [7]. The device was wire-bonded onto a testing circuit board with a hard mask to protect IDTs from shorting during deposition. An Al layer, covering half of the entire delay length, was deposited by DC magnetron sputtering and an RF vacuum feed through was utilised to enable in situ signal monitoring by a network analyser. Temperature compensation was also implemented by a thermally stabilised mounting base to minimise the associated frequency drift.

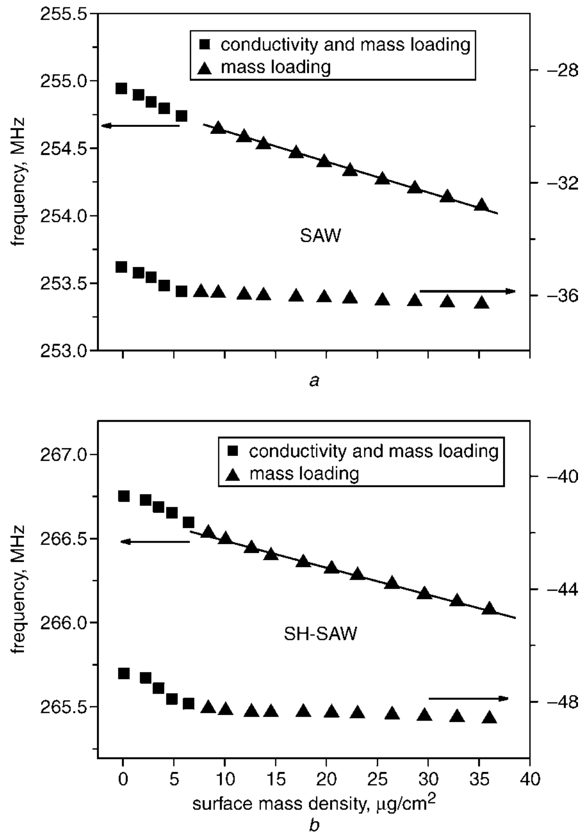

Fig. 2 *Signal response of SAW and SH-SAW to surface Al coating*

Upper and lower curves represent frequency and insertion loss, respectively
a SAW
b SH-SAW

Results and discussions: The dynamic changes in frequency and amplitude are plotted for both modes in Fig. 2 against the surface mass density of Al calculated from the calibrated deposition rate and Al density. For both modes, the frequency shifts can be distinguished as two stages. The first stage, featured by a larger negative slope, is believed to be triggered by the mass loading as well as piezoelectric shorting induced by a dramatic surface conductivity increase at the initial stage of Al deposition [7]. The transition towards the second stage occurs when the conductivity effect saturates and the remaining frequency shifts are purely due to mass loading. The two-stage behaviour is also corroborated by the insertion loss data, in which the first stage features discernable amplitude loss as a result of the piezoelectric shorting [7] while the second one has negligible loss – a good approximation to the ideal mass loading effect. The mass sensitivity S_m is defined as [8]:

$$S_m = \lim_{\Delta\rho_s \to 0} \frac{1}{c\Delta\rho_s}\left(\frac{\Delta f}{f_0}\right) \qquad (1)$$

where $\Delta f/f_0$ is the fractional change in resonance frequency, $\Delta\rho_s$ is the change in surface mass density, and c the fraction of the wave path under Al mass loading ($c = 0.5$ in our case). The theoretical S_m for SAWs on isotropic substrates was derived by Wenzel [8] as:

$$S_m = -K(\sigma)/(\rho\lambda) \qquad (2)$$

where ρ is the density of AlN, which is 3.26 g/cm^3 [6], and $K(\sigma)$ is a function of Poisson's ratio – σ, which is defined by $v_S/v_L = \sqrt{(0.5-\sigma)/(1-\sigma)}$ with v_S and v_L being the bulk shear wave and longitudinal wave velocities of AlN. The calculated theoretical S_m for the SAW mode at a wavelength of 22.8 μm is ~181 cm^2/g, assuming $\sigma \cong 0.27$ for AlN. Applying (1) to the linear fitting lines of the second stage in Fig. 2, the experimental mass sensitivities are derived as ~−173 and −120 cm^2/g for the SAW and SH-SAW, respectively. A good agreement has been reached between the experimental and theoretical mass sensitivity for the AlN based SAW. The slight difference may be due to the influence of the anisotropic sapphire substrate. The mass sensitivity of the SH-SAW is lower than that of the SAW, which can be attributed to its deeper penetration depth into the substrate. Table 1 lists the mass sensitivities of our device as compared to the delay lines fabricated on other substrates. As shown in Table 1, both modes demonstrate comparable or higher sensitivities than their counterparts on quartz and $LiTaO_3$ substrates. If ideal frequency resolution of 1 Hz could be achieved on the device circuit, the minimum detectable mass derived from the corresponding mass sensitivity is 23 and 31 pg/cm^2 for the SAW and SH-SAW, respectively.

Table 1: Mass sensitivities of different SAW delay line devices

Delay line devices	Wavelength (MHz)	S_m (cm^2/g)
AlN SAW	22.8	−173
AlN SH-SAW	22.8	−120
ST-cut quartz SAW [9]	32	−128
36° YX-$LiTaO_3$ SH-SAW [10]	40	−136

Conclusion: We have demonstrated a highly sensitive dual mode device working around 260 MHz on the AlN(0 0 0 1)/Al_2O_3(1 1 $\bar{2}$ 0) structure. The minimum detectable mass could be as low as 23 and 31 pg/cm^2 for the SAW and SH-SAW, respectively. Such a device is promising for either gaseous or aqueous detection when toggled between the SAW and SH-SAW mode.

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