Viscosity response of shear horizontal surface acoustic wave on AlN/sapphire structure

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

The effect of viscous liquid loading on SH-SAW devices on AlN/sapphire structure has been experimentally investigated. The sensitivity of the devices to liquid (glycerol/water mixtures) viscosity changes is measured to be approximate 8.2×10^{-9} m^2 s/kg, which is only about 30% of that of commonly used quartz Love wave devices. This indicates that, when used for mass sensing in liquid, the AlN SH-SAW devices have better tolerance to viscous perturbation.

Introduction: The fast-growing biosensor technology has broad applications in areas such as environmental monitoring, food hygiene and clinical diagnosis. Much research work has been carried out on SH-SAW devices for their merits of relatively high mass sensitivity, low cost, fast response and low signal attenuation in liquid [1]. In an actual liquid environment, besides the mass loading mechanism, liquid viscosity and density also have significant influences on the interpretation of liquid-phase sensing results. Therefore, it is of practical importance to investigate the device's response to viscous liquid loading. In prior work, we reported a high velocity SH-SAW device based on an AlN(0001)/$Al_2O_3(11\bar{2}0)$ structure and its concomitant high mass sensitivity [2, 3]. In this work, the viscosity sensing characteristics of the SH-SAW device are investigated by loading the device with glycerol/water mixtures and monitoring the transmission spectrum of the SH-SAW.

Experiment: An AlN(0001) thin film with a thickness of 2 µm was deposited on an $Al_2O_3(11\bar{2}0)$ substrate by a plasma source molecular beam epitaxy system. The SH-SAW mode was excited by aligning the input and output interdigital transducers (IDTs) along the $Al_2O_3[1\bar{1}00]$ azimuth. Each of the delay line devices utilised in the experiments had 50 pairs of aluminum IDTs with a wavelength λ of 24 µm, a thickness of 120 nm, an acoustic aperture of 70 λ, and a delay length of 200 λ. The sensing path between the input and output IDTs was electrically shorted by a 120 nm-thick aluminum thin film to ensure that the SH-SAW propagating on the sensing path would only be perturbed by the mechanical properties of the overlaid liquid [4]. The centre frequency of the SH-SAW measured by a network analyser (HP 8753D) was $f_0 = 255.5$ MHz and the corresponding phase velocity ($v_0 = f_0\lambda$) was ~6132 m/s. To maintain the integrity of liquid flow and prevent unwanted wetting of IDTs, an acrylic flow cell, which confined a 2.9 mm wave–liquid interaction length, was glued onto the inner IDT region by UV light curable epoxy (Dymax 1186-M). The schematic of the flow cell is shown in Fig. 1. The device with the flow cell was mounted onto an impedance-matching printed circuit board which used RF SMA connectors for the electrical contacts. Glycerol/deionised water mixtures were injected into the flow cell with different weight/weight concentrations, ranging from 0 to 75%. The viscosities of mixtures were measured by Cannon-Fenske routine viscometers. Liquid loading on the device led to an entrainment of a thin liquid film with exponential decay of the shear movement. The characteristic decay depth δ of the entrainment is given by [5]:

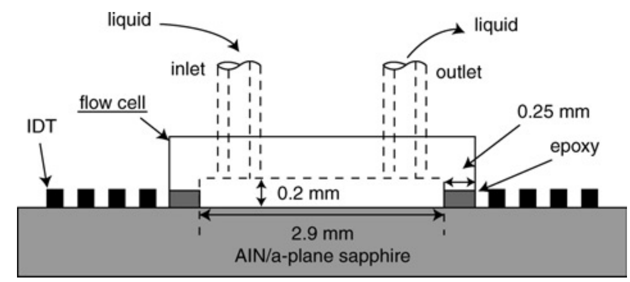

Fig. 1 *Cross-sectional view of AlN SH-SAW device with flow cell*

$$\delta = \sqrt{\frac{2\eta}{\rho\omega}} \tag{1}$$

where η and ρ denote the viscosity and mass density of liquid, respectively, and ω stands for the angular frequency of the device. The calculated δ in the experiment ranges from 35 nm for water to 485 nm for a 75% glycerol/water mixture, which is much smaller than the inner height of the flow cell (0.2 mm). Therefore, the size of the flow cell has no significant influence on the energy distribution of the SH-SAW in the glycerol/water mixtures. During the experiment, the transmission characteristics of the device were monitored by the network analyser while the liquid remained standing still on the device surface. Changes in both the insertion loss and phase at the centre frequency ensuing from liquid loading were recorded.

Results and discussion: The propagation loss per wavelength ΔPL can be expressed as [6]:

$$\Delta PL = \frac{IL_{liquid} - IL_{air}}{d} \tag{2}$$

where d is the distance between input and output IDTs using the acoustic wavelength λ as the unit, IL_{liquid} is the device insertion loss when the flow cell is filled with liquid and IL_{air} is the device insertion loss with an empty flow cell. The subtraction of IL_{air} from IL_{liquid} precludes the effect of Fresnel reflection at the epoxy interfaces on ΔPL. The measured ΔPL of the AlN SH-SAW device under the glycerol/water loading is shown in Fig. 2. The propagation loss of the device increases with the increasing square root of viscosity and density product $\sqrt{(\eta\rho)}$ of the liquids. The monotonic increasing trend of the propagation loss has good agreement with the theoretical equation given as [6]:

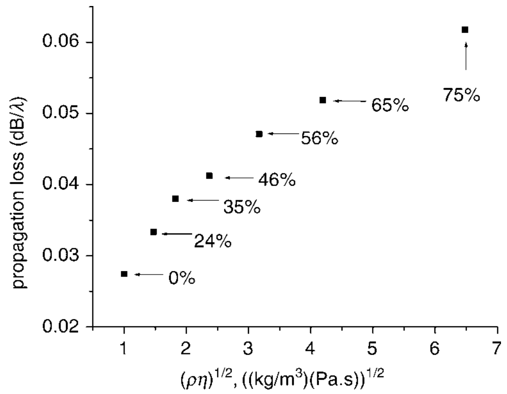

Fig. 2 *Measured propagation loss of AlN SH-SAW device against $\sqrt{(\rho\eta)}$ of glycerol/water mixtures*

n% denotes weight/weight concentration of glycerol/water mixtures

$$\Delta PL = \frac{40\pi}{\ln 10} S \sqrt{\frac{\omega\eta\rho}{2}} \tag{3}$$

where S is the sensitivity defined as S_m/ω, with S_m being the mass sensitivity [7]. The viscosity induced phase velocity shift of the device can be derived from the following equation [1]:

$$\frac{\Delta v}{v_0} = -\frac{\Delta\varphi}{\varphi_0} \tag{4}$$

where Δv is the phase velocity shift of the device, v_0 is the unperturbed phase velocity, $\Delta\varphi$ is the phase shift measured by the network analyser, and φ_0 is the unperturbed phase between input and output IDTs of the device. For a SH-SAW device under viscous liquid loading, the theoretical relative phase velocity shift $\Delta v/v_0$ was found to be proportional to the square root of viscosity and density product $\sqrt{(\eta\rho)}$ [7]:

$$\frac{\Delta v}{v_0} = -S\sqrt{\frac{\omega\eta\rho}{2}} \tag{5}$$

The plot of the experimental $\Delta v/v_0$ against $\sqrt{(\eta\rho)}$ (Fig. 3) demonstrates a linear relationship in agreement with the theoretical model. The linear regression line in Fig. 3 has a slight negative offset from the origin. Such extra relative velocity shift from the origin is believed to be induced by excessive liquid loading on top of the entrained thin liquid film as the inner height of the flow cell, 0.2 mm, is much larger than the maximum decay depth of 485 nm for a 75% glycerol/water mixture.

Utilising the linear regression line in Fig. 3, the sensitivity S in (5) is calculated as $\sim 8.2 \times 10^{-9}$ m^2 s/kg. This is equivalent to a mass sensitivity of $S_m = 131$ cm^2/g, which is close to the mass sensitivity (120 cm^2/g) of the AlN SH-SAW mode measured by metal coating experiments [3]. Compared to the reported sensitivities of 4.8×10^{-8} m^2 s/kg [6] and 2.6×10^{-8} m^2 s/kg [7] for the Love wave devices on SiO_2/ST-quartz structures, the AlN SH-SAW device is less sensitive to viscous liquid loading. This may be due to the fact that, under the same processing condition that defines the IDT periodicity (i.e. the wavelength), the high SH-SAW velocity ($\sim$6132 m/s) of the AlN SH-SAW device leads to a higher angular frequency than that of the SiO_2/ST-quartz Love wave devices. According to (1), this results in a smaller characteristic decay depth δ of liquid entrainment on the AlN surface, and the thinner entrained viscous liquid would induce less perturbation on the AlN SH-SAW device than on the SiO_2/ST-quartz Love wave devices. This is especially beneficial for SAW mass sensors used in liquid-based biological/chemical sensing as the excessive viscous loading effect of liquid may introduce unwanted error in the results [7].

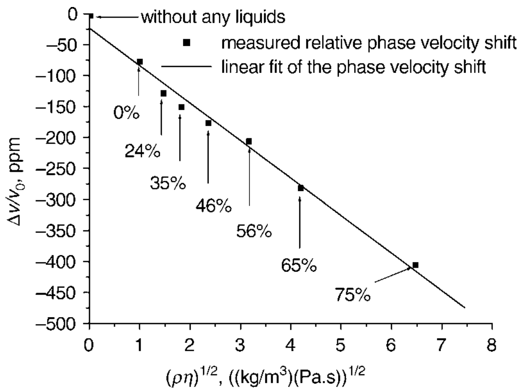

Fig. 3 *Relative phase velocity shift of the AlN SH-SAW device against* $\sqrt{(\rho\eta)}$ *of glycerol/water mixtures*

n% denotes weight/weight concentration of glycerol/water mixtures

Conclusions: Liquid viscosity loading effect on the AlN SH-SAW devices has been investigated. The derived device sensitivity was $\sim 8.2 \times 10^{-9}$ m^2 s/kg, which was relatively lower than the sensitivity values for conventional quartz Love wave devices. The fact that the AlN SH-SAW device has a higher mass sensitivity and is less susceptible to viscosity perturbation makes it a good candidate as a mass sensor in liquid-based biological/chemical sensing.

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