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Use of mass loading to operate a thin film ultrasonic transducer in the 300 kHz–10 MHz frequency range

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Abstract Thin film ultrasonic transducers have been designed which operate over an important frequency range, 300 kHz to 10 MHz. The transducers were made using piezoelectric aluminium nitride films a few microns thick. The films would have a fundamental thickness mode resonance at 1–3 GHz if fabricated as an unsupported film, however operation at much lower frequencies has been demonstrated when the transducers are fabricated on bulk substrates. This would enables them to be used in ultrasonic non-destructive testing in circumstances where the film can be deposited directly onto the object under test. We have found that the major factors influencing the below-resonance operation of the thin film transducers are the device impedance, the spectrum of the excitation pulse, and any mechanical (mass) loading applied to the back face of the transducer. Results are presented showing that the evolution of device impedance as a function of device area could be predicted using a PSpice model of the thin film transducer. The ability of the transducer to generate longitudinal mode pulses rather than shear wave pulses was found to depend on increasing the mechanical loading at the back face of the transducer. This mechanism for pulse generation was confirmed by Finite Element Modelling using PZFlex.

Keywords Thin film piezoelectric · Ultrasonic · Modelling

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1 Introduction

Thin piezoelectric films such as aluminium nitride (AlN) are widely used in filters and resonators for high frequency communications [1, 2]. For example, film bulk acoustic resonators (FBAR) are designed to operate at high-Q at precise GHz frequencies defined by the thickness mode resonance in the film. Ultrasonic measurement and imaging on the other hand are typically broadband applications and require transducers which produce a short pulse in the frequency range 300 kHz to 10 MHz. This is generally achieved by exciting a piezoelectric plate, usually piezoelectric ceramic material 0.1–1.0 mm thick, at its thickness mode resonance frequency and using acoustic backing layers to damp out any ringing beyond a few cycles.

We have explored the use of AlN thin films to make broadband ultrasonic transducers in which the films are operated far below their thickness mode resonance frequency. The thin film transducers are fabricated by vacuum deposition [3] directly onto the substrate or component into which the ultrasound will be transmitted. Thin film transducers have particular benefits where low profile devices are required and an additional benefit of AlN is its very high Curie temperature <1000°C. We have investigated applications in ultrasonic non-destructive testing and monitoring at high temperatures [4], acoustic emission [5], and monitoring of bearings by a pulse-echo technique [6].

Since AlN has acoustic velocity 10,000 ms^{-1}, films which are a few microns thick will have resonant frequency around 1 GHz. This is too high for our intended applications and the transducer will therefore be operating far below resonance. Ref. [7] describes a somewhat similar problem, although using a bulk piezoelectric transducer rather than a thin film transducer. We have found that the principles of below resonance operation of the thin film transducers are as follows: The transducer is non-resonant all the way up to the high frequency cut-off of the pulser-receiver. This differs from usual pulse excitation where the pulse is assumed to be an ideal step or impulse with components at all relevant frequencies. Under these circumstances, the electrical signal applied to the film does not cause resonance in the transducer but instead the signal is replicated as a mechanical strain by the transducer according to the piezoelectric constitutive equations. Therefore an excitation signal with the appropriate frequency content will force the transducer to operate at the required frequency. Additionally the frequency of operation will be controlled by electrical and mechanical design of the transducer and accompanying circuit.

2 PSpice model of impedance of thin film transducer

PSpice was used to make a 1-D transducer model incorporating electrical and acoustic properties, looking in particular at the effect of varying the electrode area. The model was validated by comparing experimental and predicted impedence curves for thin film devices with area 0.1–10 mm^2. Investigation of the frequency response of the same set of devices was reported elsewhere [8].

PSPICE simulation A PSpice (Cadence) simulation was used based on the 1-D thickness mode for lossy ultrasonic transducers by Puttmer [9]. The acoustic part of the model consists of the thin film, an acoustic medium (air) on the back face, and a front face load corresponding to the substrate (glass) which was used as the transmission medium in the experiments. Acoustic attenuation in the substrate was ignored and the front and back electrodes were assumed to be too thin to have any mechanical effect. The pulser and transducer were connected with a lossy RLCG type coaxial cable which was represented by discrete components in the PSpice model.

Comparison with experimental results Simulated impedance characteristics are compared with experimental measurements in Fig. 1. The overall form of the curves is determined by the impedence characteristic of the film combined with the periodically varying impedance of the cable connecting the transducer to the instrument. It can be seen that the PSpice model has satisfactorily predicted the form of the impedance magnitude characteristics for thin film transducers of different areas.

3 Effect of mass loading

Mechanical effects on the generation of shear and longitudinal wave modes were observed experimentally in transducers with different back electrodes. Finite Element Analysis was used to confirm the proposed excitation mechanism.

Experimental observations It was observed that shear waves and longitudinal waves were generated differently by the thin film transducers depending on the type of back electrode used in the device. In the pulse-echo tests, the received pulse was transmitted through the steel block, reflected from the steel-air boundary at the far side of the block, and received back at the thin film transducer. The two types of received pulses can be distinguised because the shear wave velocity is approximately half that of the longitudinal mode. Results are shown in Fig. 2 for pulse-echo tests using transducers made from a 8.3 μm thick AlN film grown on a ferritic steel substrate. A JSR DPR 300 pulser-receiver was used with receiver gain 70 dB and

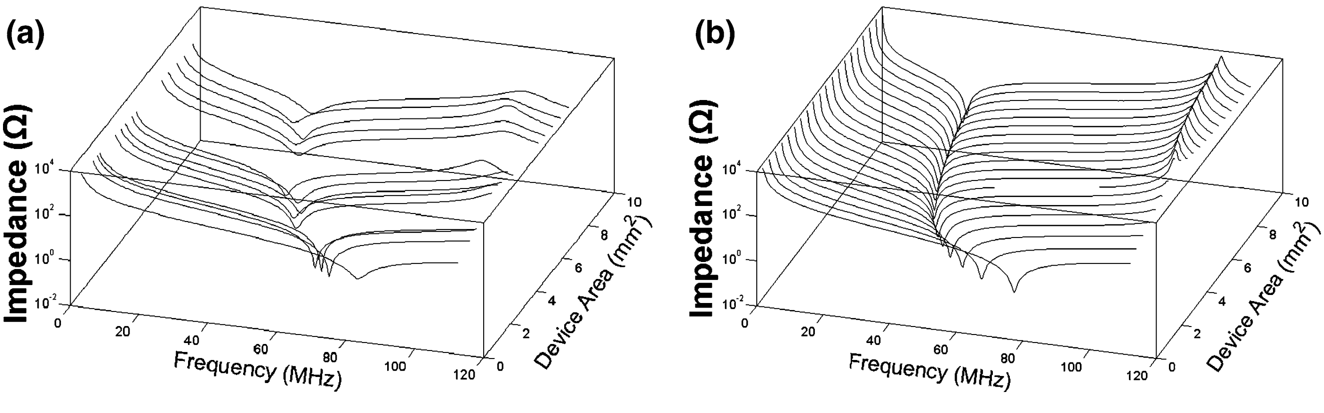

Fig. 1 Impedance of thin film transducers of area 0.1–10 mm^2, 4 μm thick AlN, with Cr/Au back electrode, on 1 mm thick glass substrate: (**a**) experimental results; (**b**) PSpice simulation

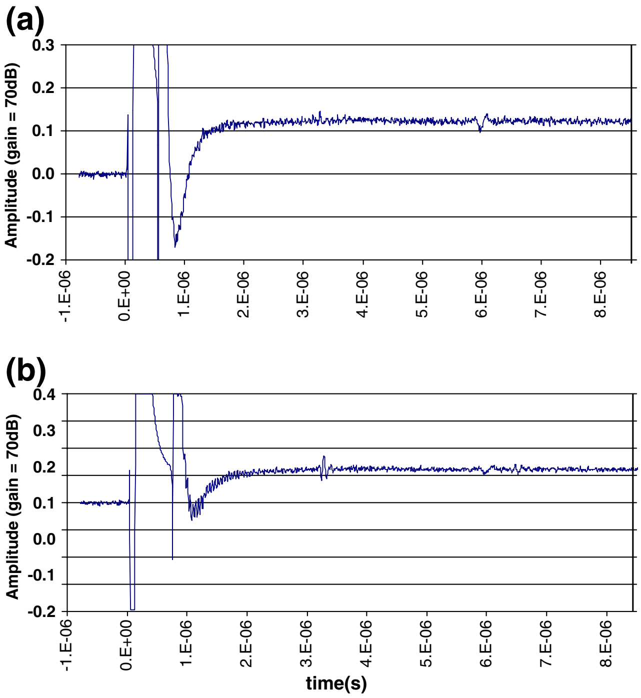

Fig. 2 Pulse echo results for thin film transducers fabricated with 8.3 μm AlN film on ferritic steel substrate showing generation of shear and longitudinal wave modes: (**a**) thin Cr/Au electrode (100 nm); (**b**) thick Ag electroplated electrode (0.5–2.5 μm)

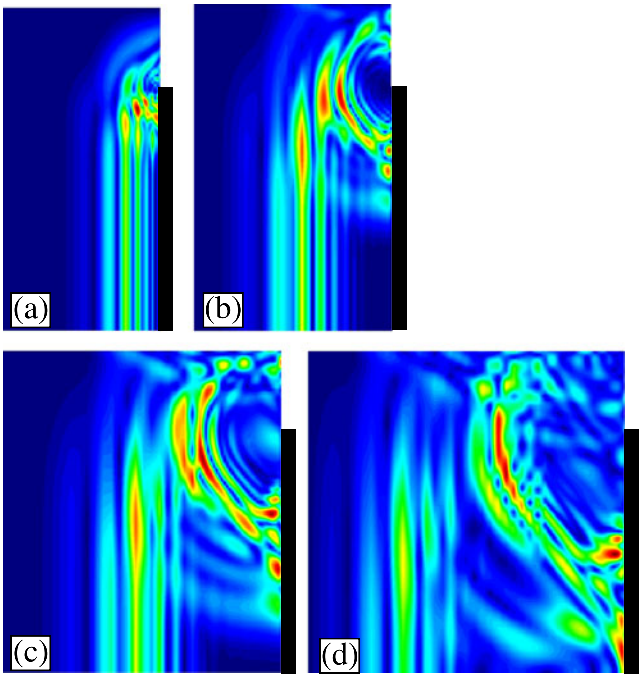

Fig. 4 Stress distribution obtained from PZFlex finite element model of thin film transducer on steel substrate. Time steps (**a**) 1.2 (**b**) 2.2 (**c**) 3.2 (**d**) 4.6×10^{-7} s. Half of the transducer has been modelled, transducer position shown by black bar on the right

bandwidth 2.5–50 MHz. Figure 2(a) is the result for a transducer with a low mass electrode made from a 100 nm sputtered layer of Cr/Au. The transducer generated predominantly shear waves which were transmitted into the substrate (reflected pulse received at 6 μs). Figure 2(b) shows that higher mass electrodes made using electroplated Ag, 0.5–2.5 μm thick, enabled the transducer to generate longitudinal waves in the substrate (reflected pulse received at 3 μs). A larger longitudinal wave signal is clearly visible for the higher mass electrode, whilst the shear mode stays approximately the same magnitude.

Explanation in terms of mass loading effect The effect of the thin or thick electrodes is summarised in Fig. 3. Note that in any piezoelectric material, thickness mode expan-

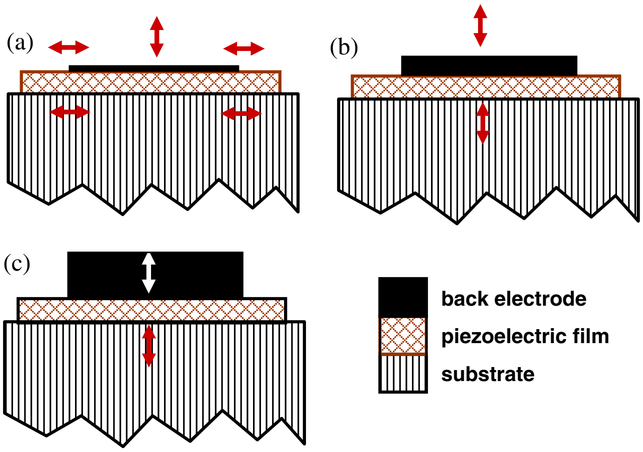

Fig. 3 (**a**) Thin electrode, low mass, e.g 100 nm Cr/Au. Shear waves propagate into substrate; (**b**) Heavy electrode, e.g. 2 μm electroplated Ag acts as mass load and promotes propagation of longitudinal waves into substrate (**c**) Very thick electrode acts as traditional acoustic backing layer. Sound propagates into the backing as well as into the substrate

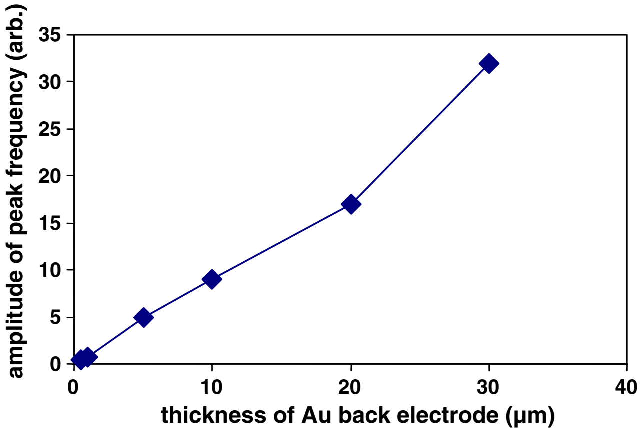

Fig. 5 PZFlex simulation showing increase in signal amplitude of longitudinal waves at the peak frequency with increasing thickness of an Au back electrode for a thin film transducer on a steel substrate

sion will be accompanied by some lateral contraction governed by the Poisson ratio. In Fig. 3(a) for a thin low mass back electrode shear wave generation dominates as the film undergoes lateral expansion and contraction. Solid coupling rather than more common fluid coupling between the transducer and the substrate ensures that the shear motion is transmitted. The film itself has insufficient inertia to transmit the longitudinal strain into the substrate. In Fig. 3(b) mass loading by a thick electrode such as 2 μm electroplated Ag promotes propagation of longitudinal waves into the substrate. The electrode layer remains thinner than an acoustic wavelength at the operating frequency and therefore fulfills the role of an added mass load rather than an acoustic medium. A back electrode of multiple wavelength thickness as in Fig. 3(c) would act as a traditional acoustic backing layer for which the acoustic impedance and acoustic attenuation would become significant rather than only the mass.

Confirmation of mechanism of pulse generation by thin film using finite element modelling PZFlex finite element software was used to model the propagation of ultrasonic waves into a steel substrate from a thin film transducer with a thin low mass back electrode. A sequence of results showing stress distribution in the substrate is shown in Fig. 4. This confirms that when the excitation pulse is applied, a shear mode pulse propagates from the edges of the electrode, travelling slower than the longitudinal mode pulse from the centre of the transducer. Further finite element simulations were carried out in which the thickness of the Au back electrode was increased from 0 to 30 μm. Results are shown in the graph in Fig. 5, where there is an increase in the amplitude of the longitudinal mode pulse at the peak frequency.

4 Conclusions

We have shown that AlN thin film transducers formed on a bulk solid substrate can be successfully operated in the medium frequency range 300 kHz to 10 MHz by excitation below resonance using a 2.5–50 MHz pulse. This enables applications to be developed in non-destructive testing and machine monitoring. In the frequency range of interest the thin film transducers are operating far below their thickness mode resonant frequency of approximately 1 GHz. In this regime broadband operation can be achieved, and a particular frequency range can be achieved by design of the transducer structure and the excitation circuit and by using excitation at the required frequency.

Impedance of thin film transducers with different electrode area has been modelled using a PSpice harmonic model, giving results which agree well with the experimentally measured impedance characteristics. Results from experimental measurements show that propagation of longitudinal mode pulses into the substrate requires mass loading of the back electrode. Without this, only shear waves will propagate into the substrate. This effect has been investigated by finite element analysis using PZFlex. This work shows the importance of both electrical and mechanical effects in determining the below-resonance operating frequency of thin film piezoelectric transducers.

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