HIGH FREQUENCY-HIGH TEMPERATURE ULTRASONIC TRANSDUCERS

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INTRODUCTION

Ultrasonic testing is a promising NDE technique for ceramic structural components. The lifetime of such components is controlled by defects and flaws. The critical flaw sizes for high performance ceramics are 25 μm and to detect such small flaws, the frequency of the transducers has to be >30 MHz [1-4]. Such transducers are usually made from ZnO, $LiNbO_3$, LMN composites [5], and PVDF piezoelectric materials However there are no reports of aluminium nitride (AlN) films being used for such applications In this paper the piezoelectric and dielectric properties of AlN films and their application to high frequency devices are discussed and compared with the conventional materials.

AlN has many potential applications such as high frequency SAW devices, optical devices operating in the UV region and substrates for highly integrated circuits etc. Its attractive properties are; (a) low relative dielectric constant (8.6) and high dielectric strength ($>2\times10^7$ V/cm), (b) high thermal conductivity (~200 W/mK) and high electrical resistivity ($\sim10^{13}$ Ωcm), (c) a wide band gap ~6.2 eV, (d) stability to high temperature and (e) high sound velocity (10,700 m/s) with Thickness Coupling Constant of 20%. The high sound velocity makes AlN an attractive material for upper-GHz range ultrasonic devices. MHz range applications of AlN have not been reported due to the difficulty of producing thick, 002-oriented films.

There are two ways to produce high-frequency transducers. The first involves careful lapping of bulk piezoelectrics, the second, deposition of films on a suitable substrate materials. For the first technique, a piezoelectric thick-disc is bonded to a suitable material as a backing or delay rod, then the piezoelectric disc is ground flat and parallel. The problem with such techniques in case of $LiNbO_3$ crystral is the accompanying deterioration of piezoelectric properties which can drop ~50% of their original values. Microcracking also occurs occasionally. This property reduction also applies to ceramics but without microcracking. Ceramics can be repoled after lapping so restore the piezoelectric properties to ≥80% of its original values. Devices made by such techniques are labour intensive and therefore expensive. The second method involves deposition of piezoelectric materials on suitable substrates by reactive sputtering or a CVD process. Reactive sputtering techniques are slow and expensive whereas CVD is simpler and inexpensive. ZnO and PZT films are deposited using reactive sputtering techniques whereas AlN films can be obtained by both methods. These techniques usually result in good bonding between substrate and film and, as the film thickness can be controlled, no further lapping is necessary for use in high frequency transducers. The second method is usually used for manufacturing high-frequency transducers of frequency >60 MHz. AlN and ZnO have similar piezoelectric properties but AlN has a very high dielectric strength (~100× greater than ZnO) which makes it more attractive.

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EXPERIMENTAL PROCEDURE

AlN films were deposited on 1/4 to 1/2" thick, platinum-coated quartz, sapphire and LMN-composite ceramic substrates. The substrate materials were first highly polished and cleaned and the platinum electrodes were sputtered thereon. The latter were annealed at >600°C. A simple CVD process (described elsewhere [6]) deposited AlN using argon gas as carrier for the $AlCl_3$ and NH_3 reactants. The rate of film deposition was ~55 nm/s at a substrate temperature of 1140°K. The AlN film thickness and surface morphology was studied via SEM. X-ray diffraction was used to determine film texturing and their piezoelectric properties investigated with an impedance-analyzer and a d_{33} meter. The dielectric strength was measured by applying a dc field to electroded AlN films. The ultrasonic response was measured as a function of temperature in a specially built high-temperature coaxial sample holder. The piezoelectric and dielectric properties measured are listed in Table I. Also listed are the properties of competitive piezoelectric materials

RESULTS AND DISCUSSION

002 oriented AlN films can be deposited by a normal CVD process on a variety of substrate materials with a growth rate of 55 nm/s. The growth rate for ZnO and CdS is <5 nm/s and the apparatus involved is expensive. The only advantage of ZnO and CdS over AlN is the lower substrate temperatures, but most substrates used for depositition can withstand higher temperature. CVD, production of AlN films requires >700°C. A typical CVD, AlN film microstructure is shown in Figure 1 with the X-ray diffraction data. The latter shows that the 002 peak intensity is high, suggesting ~100% orientation of the film. The SEM microstructure shows an assembly of densely-packed columnar AlN grains of uniform diameter (0.14 μm). This structure was obtained on a variety of substrate materials. Considering the properties listed in Table I, ZnO and CdS are similar to AlN but, due to the high sound velocity in AlN, its Figure of Merit value (125) is higher than that of CdS or ZnO, making it a superior piezoelectric material for high frequency transducers. The dielectric strength of AlN is two-orders-magnitude higher than ZnO and CdS so higher voltages can be applied to AlN films, increasing the potential output-energy from devices made with AlN. A commercial, 100 MHz device made from a ZnO film on a quartz delay rod excited by a -150 V spike, showed 5 dB less signal strength than an AlN transducer of similar configuration. Although the quartz substrate is acoustically mismatched with the AlN, it shows better output compared with ZnO films on the same substrate with a better acoustic match. Longitudinal-wave transducers with of 6 and 12 mm diameter and with frequency 100 and 60 MHZ respectively, were made with AlN films on a quartz delay rod. The back reflected signal spectra from these transducers are shown in Figures 2 and 3.

The high temperature stability of devices made from AlN films was explored. The devices were placed in a specially designed furnace with a coaxial device-holder. The ultrasonic responses were studied as a function of temperature. The back reflected ultrasonic signal from an AlN film on a platinum-coated quartz-substrate was monitored and no deterioration of signal with temperature was observed (apart from the attenuation loss associated with ionic and structural relaxations in the quartz). Ultrasonic response measurements were impossible >1430°K due to surface oxidation of the film at these temperatures. To avoid such oxidation, a high temperature inert ceramic coating is required and further research is being undertaken to develop such a material. The only other material that can be used for devices up to 1300°K is $LiNbO_3$. Bulk $LiNbO_3$ is difficult to use however since suitable high temperature bonding to the backing or delay rod is required. Occasional microcracking is observed during the bonding of such materials. The thermal shock resistance of $LiNbO_3$ is very poor whereas AlN is good (high thermal conductivity) and no cracking was observed when the AlN was introduced into a furnace >1200°K. The AlN/quartz substrate device, signal spectra at room temperature and 1220°K are shown in Figure 4. AlN films are a very good candidate for high temperature applications.

TABLE I. PIEZOELECTRIC AND DIELECTRIC PROPERTIES OF MATERIAL USED FOR HIGH FREQUENCY TRANSDUCERS

Material	Relative Dielectric Constant	Dielectric Strength v/cm	Density g/c	Thickness Coupling Coefficient %	Radial Coupling Coefficient %	Piezoelectric Coefficient g_{33} 10^{-3} Vm/N	Piezoelectric Coefficient d_{33} 10^{-12} C/N	Sound Velocity m/s	Figure of Merit M
ZnO (0° orientation)	8.84	$\sim 5\times 10^5$	5.68	28	–	135	10.6	~6400	101
CdS (0° orientation)	9.53	$\sim 5\times 10^5$	4.82	15	–	122	10.3	~4500	35
SiO_2(X-cut)	4.58	$\sim 5\times 10^5$	2.65	10	–	57	2.3	~5700	62
AlN (0° orientation)	8.6	$\sim 20\times 10^6$	3.26	~20	–	66-105	5-8	~10 700	125
$LiNbO_3$ (36° Y cut)	39	$\sim 5\pm 10^5$	6.64	49	40	116	40	~7400	46
PVDF	10	$\sim 1\times 10^5$	1.8	20	–	160	14	2150	5.5
FERROELECTRIC CERAMICS									
PZT7	235	$\sim 5\times 10^4$	7.6	50	51	40	150	4800	5.1
SPN	420	$\sim 5\times 10^4$	4.46	46	46	29	127	6900	5.2
PMN (lead meta-miobate)	190	$\sim 5\times 10^4$	6.0	37	14	42	85	4600	5.0
LMN (9262) Composites	140-180	$\sim 5\times 10^4$	4.4-4.7	70-85	7-20	38-50	50-80	6000-6800	11-17

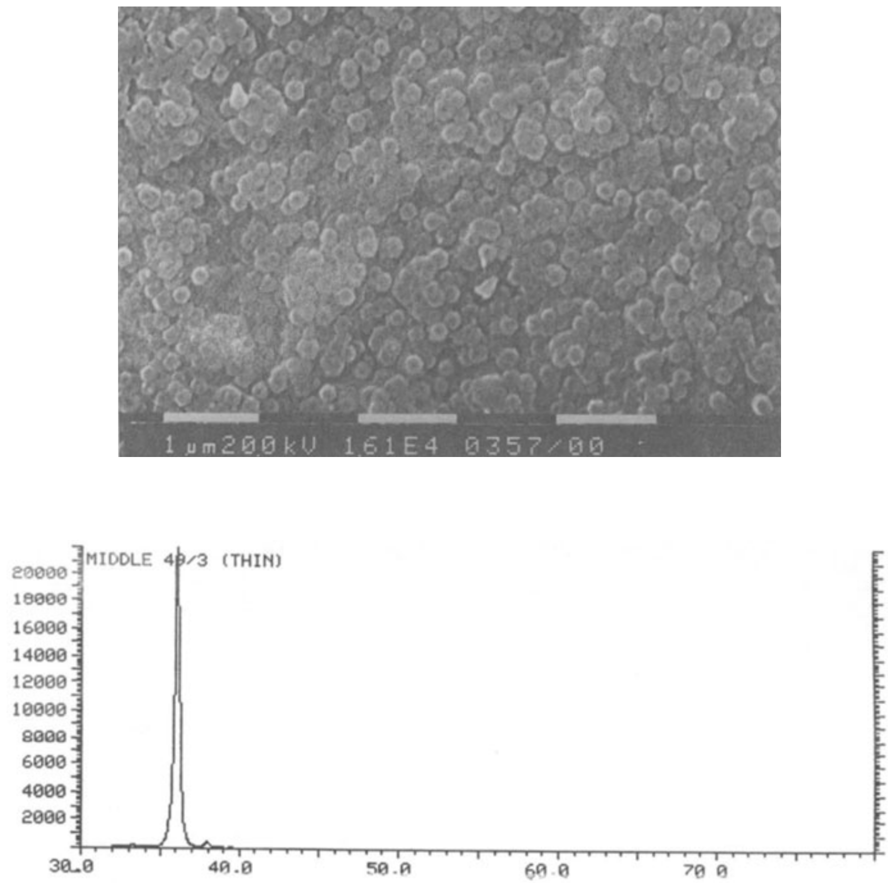


Fig. 1 SEM of surface morphology and x-ray diffraction of an AlN film deposited at 1140°K.

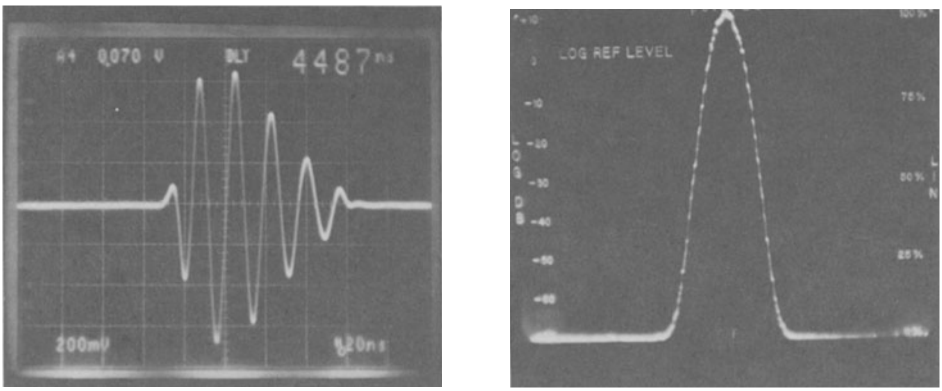


Fig. 2 Typical signal spectra of a 60 MHz transducers made from AlN film.

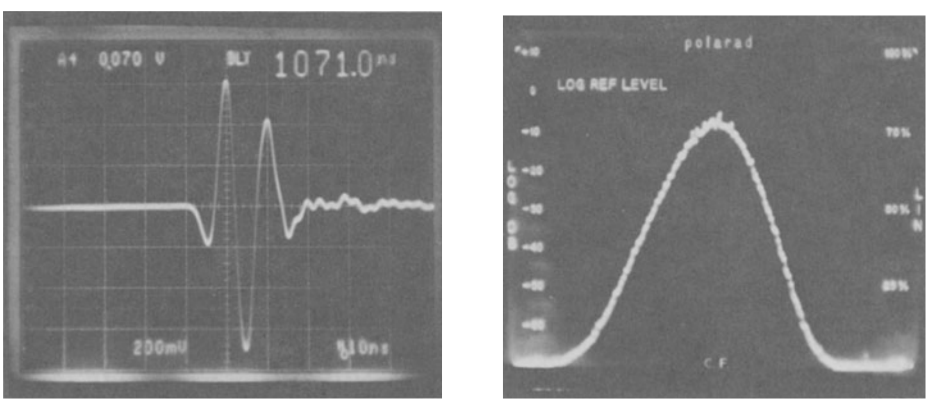
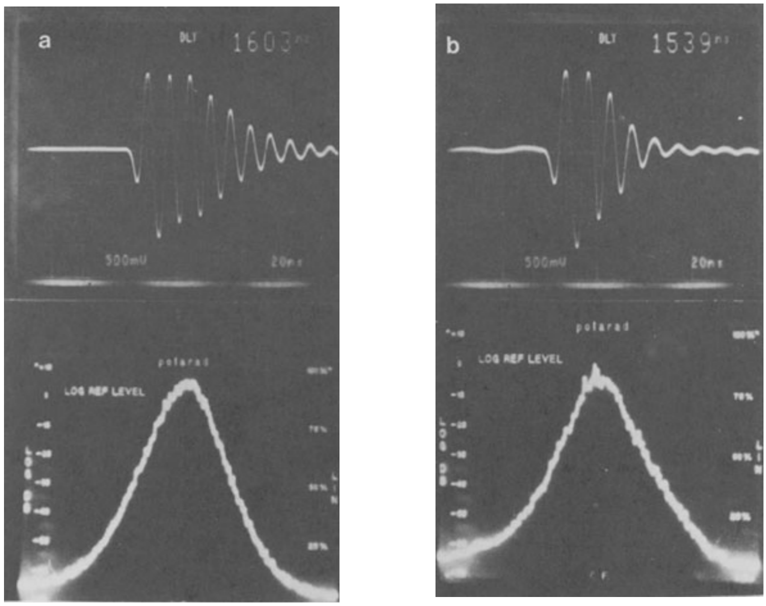


Fig. 3 Typical signal spectra of a 100 MHz transducer made from AlN film.



AlN FILM THICKNESS = 70μm
TEMPERATURE = 300K
FREQUENCY = 76 MHz

AlN FILM THICKNESS = 70 μm
TEMPERATURE = 1200 K
FREQUENCY = 72 MHz

Fig. 4 Typical back reflected signal spectra from an AlN-quartz delay rod transducer at (a) room temperature and (b) 1220°K using AlN.

CONCLUSIONS

AlN 002-oriented films appear superior for high-frequency >50 MHz, high power (signal strength) and high temperature ultrasonic compressional-wave transducers. This material showed the highest Figure of Merit (125) as compared with existing piezoelectric materials. Devices made from CVD, 002-oriented AlN films can be used up to high temperature (≤1430°K).

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