Program Digest, 2019 IEEE International Ultrasonics Symposium (IUS)
Glasgow, Scotland, October 6-9, 2019

A comparison between DCMS, HiPIMS and a novel 'HiPIMS+Kick' deposition for piezoelectric thin-films

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Abstract—**High power impulse magnetron sputtering (HiPIMS) has been shown to improve optical and semi-conductor thin-film coatings through increased density [1], crystallinity and more control over deposition parameters [2]. Here, HiPIMS and, a new technique, HiPIMS + 'Kick' are investigated in relation to deposited piezoelectric coatings and compared with a standard DCMS coating. To assess improvements for acoustic generation, these films have been characterized using SEM and XRD techniques for material parameters, simulations have been done to model acoustic output and further work is to be done to find d_{33} parameters.**

Keywords— thin-films, materials, HiPIMS

I. Introduction

Current ultrasonic imaging relies on ceramic materials such as lead zirconium titanate (PZT) and polyvinylidene diflouride (PVDF). These ceramics have a complex manufacturing process, particular for high frequencies, as well as relatively low Curie temperatures, limiting their operation above 250ºC. Piezoelectric thin films, such as aluminium nitride (AlN) and zinc oxide (ZnO) have long been desirable for ultrasonic imaging transducers due to their ability to operate at high frequencies and temperatures, being fully flexible and having a cheap, simple manufacturing process. Until recently, however, thin films have been unable to compete with standard transducer materials such as PZT and PVDF since their acoustic properties are much lower [3]. These properties include d_{33}, which is 3.4pmV^{-1} for AlN [4] compared to values as high as 513 pmV^{-1}[5] for more conventional piezoelectric materials. This work focuses on whether use of the newly developed high-power impulse magnetron sputtering (HiPIMS), which vastly increases the quality of optical coatings [6], can similarly increase the acoustic output of piezoelectric thin films. Deposited thin films were characterized using scanning electron microscopy (SEM) and x-ray diffraction (XRD) to examine the crystal structure, while simulations were used to predict the effect of the change in material properties on the ultrasonic behavior of the thin films. In order to develop a more complete understanding on the effect of the HiPIMS deposition on films for ultrasonic applications additional experimental work is required to confirm the effects observed in simulations.

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II. Experimental set-up

The proprietary material comprises a flexible substrate which is coated with a piezoelectric thin film; namely Wurtzite zinc oxide, through reactive magnetron sputtering. A comparison was made between depositions using three different methods; a conventional DC power supply, a HiPIMS supply and a novel HiPIMS+kick. HiPIMS+kick uses the same premise as HiPIMS but includes an additional positive voltage 'kick' to further increase density and reduce stresses in deposited material. The films obtained from the different sputtering procedures were characterized through SEM and EDX. All

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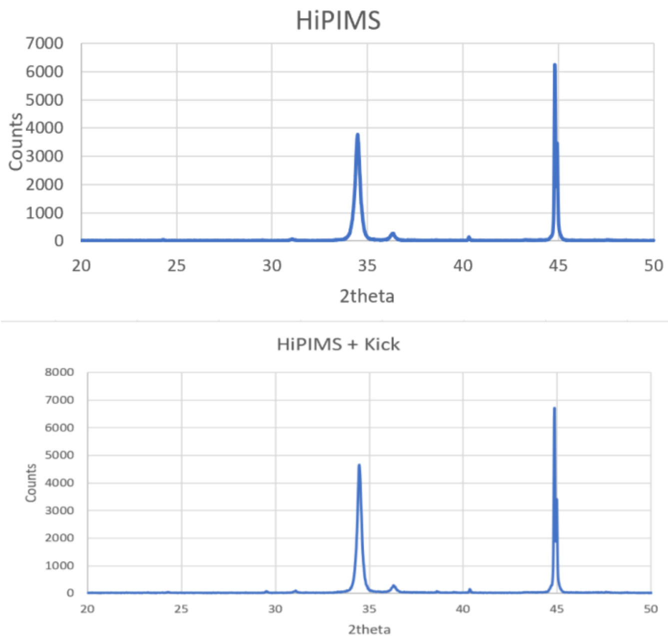

Fig. 1. XRD spectrum of proprietary material deposited by HiPIMS (top) and HiPIMS+Kick

depositions were done with the support of Kurt J. Lesker using a PVD75 system and MAGkeeper sputter cathodes. The power supply used was a Starfire Industries Impulse PSU. Depositions were done at a sputtering pressure of 5 mTorr, with 30 sccm of Ar and 6 sccm of O_2 using a 99.99% purity ZnO target. A calibration step was undertaken pre-deposition to calculate the time necessary to deposit approximately one micron of ZnO. For the HiPIMS and HiPIMS + Kick depositions, the pulse width was 40µs at 1196Hz. The positive “kick” had a voltage of 100V, width of 50µs and delay of 4µs. Characterization of the deposited films was then characterized at the Thin Films, Sensors and Imaging group at the University of the West of Scotland.

III. Results and Discussion

A. XRD

Initial results, as seen in figure 1 above, show that both HiPIMS and HiPIMS+kick deposited crystalline ZnO with strong c-axis growth. XRD shows that each deposition has resulted in a clear, sharp (002) Wurtzite peak, however, some interfering layers can be seen in the data, corresponding to (101) ZnO. Figure 1 shows a peak at the corresponding 2θ-

TABLE I. Thicknesses and deposition rates for each sample

Sample	Thickness (nm)	Deposition rate($\mu m h^{-1}$)
DCMS	970	0.070
HiPIMS	863	0.055
HiPIMS + Kick	917	0.037

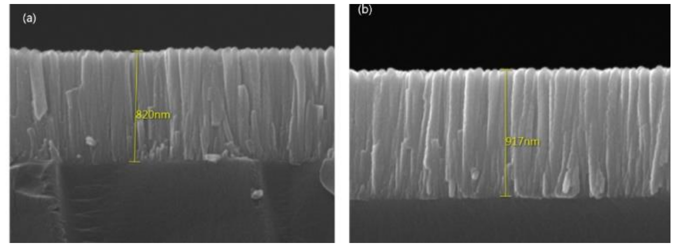

Fig. 2. SEM micrographs of (a) HiPIMS deposition, and (b) HiPIMS+Kick

angle 34.4º for zinc oxide, with the HiPIMS+kick method resulting in a more intense peak although this could be due to this film being thicker than the HiPIMS sample.

B. SEM

Thicknesses were measured using SEM images and, as can be seen in Table 1 below, HiPIMS and HiPIMS + Kick reduce the deposition rate compared to conventional DCMS sputtering. For all three depositions, sputter time was estimated to deposit 1µm of material. Thicknesses of three samples were measured; DC = 970nm, HiPIMS = 863nm, and HiPIMS+kick = 917nm. The relationship between the physical and crystal properties of the film, such as thickness, stoichiometry and crystal structure are also related to the ultrasonic performance of the film, particularly the d_{33} value. This allows the suitability of the HiPIMS deposition method for producing piezoelectric films for ultrasonic transducers to be assessed, and for refinements in the deposition process to be made.

Although it was expected that the HiPIMS deposition would show a reduced deposition rate to DCMS due to increased self-sputtering within the HiPIMS plasma [7], it was hoped that the positive kick during the HiPIMS + Kick run would bring the deposition rate back up to close to the DCMS. This was not the case, and in fact, the HiPIMS + Kick run had around half the deposition rate that DCMS had and 2/3 of the HiPIMS rate, as can be seen in Table 1.

C. Simulations

Simulations were performed to compare the acoustic output of DCMS and HiPIMS deposited ZnO. For these simulations, a simple, air-backed transducer facing into water was modelled. The simulations investigated the acoustic output of films with varying crystal density, efficiency and stiffness due to this being directly proportional to the expected increase in elasticity. As can be seen in Fig. 3., the response of the acoustic output to the changes in material properties had significant variations, with the increase in density having no real effect, while the increase in piezoelectric coefficient has a positive

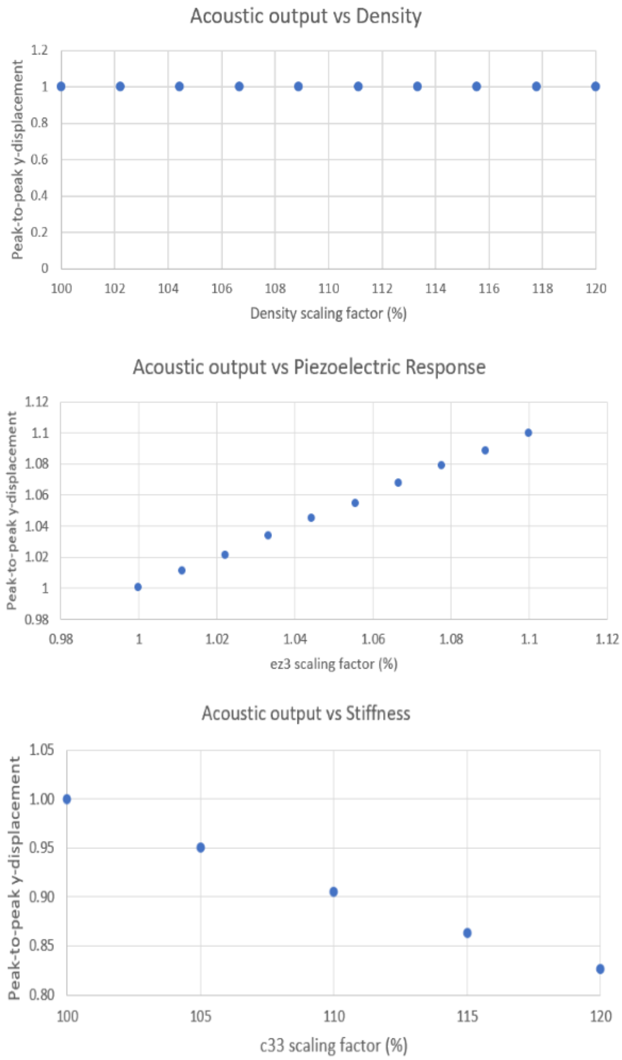

Fig. 3. Simulation results showing how acoustic output varies with differing material properties.

impact and the increase in stiffness has a negative effect.

By considering all the responses of all three changes it can be seen that the decrease in acoustic performance due to increased stiffness is the dominant effect, suggesting that, although HiPIMS is expected to improve the crystallinity of deposited thin films, this is not a positive change for an acoustic thin film.

These simulations showed that this increase in stiffness reduces the acoustic output of our films linearly which can be explained using the relationship below,

$$k_{33}^2 = \frac{e_{33}^2}{\varepsilon_{33}C_{33} + e_{33}^2} \qquad (1)$$

Where k_{33} is the coupling coefficient, e_{33} is the piezoelectric constant, C_{33} is the stiffness and ε_{33} is the dielectric constant of the material along the c-axis. Equation (1) clearly shows that, as the stiffness of a material increases, the conversion of energy from one form to another reduces, and in these simulations this effect is dominant over the improvements expected in the piezoelectric efficiency.

IV. Conclusion

Although HiPIMS depositions have shown improvements for optical and semi-conductor coatings such as Tantalum on Silicon [1] due to increased crystallinity, density and lower residual stress [8], it is unlikely that HiPIMS or HiPIMS + Kick are the future of acoustic coatings. This is due to increased elasticity reducing the acoustic output of piezoelectric films, although further investigation is required to correlate the simulated performance of HiPIMS thin films to experimental results.

Acknowledgment

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