Fabrication of SHF range SAW devices on AlN/Diamond-substrate

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Abstract—Preparation of piezoelectric AlN thin films on diamond substrates, and their application to SHF SAW devices are discussed. It is confirmed that DC-TFTS method enable to prepare highly c-axis oriented AlN films on polycrystalline diamond substrates. The AlN surface was smooth enough to fabricate fine electrodes with the width of the order of sub-microns. Transversal filters working around 5 GHz were fabricated to characterise SAW propagation on the Al-electrodes/AlN/diamond-substrate structure. The theory and measurements of the devices suggested that the largest reflectivity of Al-grating is achieved when the thickness of electrodes is about 0.20p for the AlN thickness is 0.85p, where p is the grating electrode pitch. Considering the facts, a one-port resonator was fabricated, which has relatively thick electrodes in order to realise high Q-factor. The measured Q-factor and capacitance ratio of the resonator were 650 and 155, respectively. It is seen from these results that the optimisation of the thickness for the electrodes as well as AlN films is very important to develop high performance SHF SAW devices using Al-electrode/AlN/diamond-substrate structure.

I. INTRODUCTION

High performance SAW devices working in a GHz range are necessary for realising modern communication systems, high speed signal processing, etc. Because of the highest sound velocity of diamond, a structure consisting of a diamond substrate covered with a piezoelectric thin film[1][2] is promising for developing SAW devices in SHF range. In particular, an AlN/diamond structure is one of the strong candidates for SAW device applications[3][4].

![Figure 1](image1.png)

**Fig. 1. Velocity and Coupling factor of SAWs propagating on AlN/diamond-substrate as functions of AlN thickness. (Free surface)**

Figure 1 shows, for example, the velocity $V_{SAW}$ and coupling factor $K^2$ of SAWs propagating on a free surface of the AlN/diamond structure as a function of the AlN thickness ($h_{AlN}/\lambda$). As shown in the figure, it is expected that the AlN/diamond structure supports SAWs with very large $V_{SAW}$ of about 9.7 km/s and relatively large $K^2$ of about 1%, when the $h_{AlN}/\lambda$ is about 0.4 ~ 0.5. In addition, the velocity dispersion is also relatively small, which is useful for device applications. Such high speed SAWs may enable to develop SAW devices in a GHz range without employing ultrafine electrodes, which causes a deteriorated Q-factor as well as the difficulty in production.

From the point of view, this paper discusses the preparation of AlN thin films on diamond substrates for SAW device applications. Transversal filters are fabricated for the characterisation of SAW propagation on the Al-electrodes/AlN/diamond-substrate structure. Based on the results obtained, one-port resonators are fabricated using thick electrodes of 0.2 µm for increased Q-factor, and their total performance is evaluated.

II. PREPARATION OF ALN FILM ON DIAMOND SUBSTRATE

Piezoelectric AlN thin films are deposited on polycrystalline diamond/Si substrates by DC-TFTS (Target Facing Type of Sputtering with DC-power source) with an arc-killer for suppressing anomalous discharge. It is previously reported[5] that the DC-TFTS method is most effective in preparing high quality ZnO thin films at relatively low temperature. Al disks with purity of 99.999% as targets and $N_2$ of 99.9998% as a gas source were employed for the AlN film deposition. During the deposition, the substrate temperature and deposition rate were kept at 150°C and 0.1 µm/h, respectively. The thickness of CVD deposited diamond layer on Si is about 20 µm[6].

Figure 2 shows the results of XRD analysis for the deposited AlN film. It is seen from Fig. 2(a) that the c-axis oriented AlN is deposited. From the rocking curve (see Fig. 2(b)), FWHM corresponding to the AlN (002) peak is estimated to be 4.4°. Both figures clearly confirm that the DC-TFTS method enables to deposit highly c-axis oriented AlN films on diamond substrates.

Figure 3 is an AFM image of the deposited AlN surface. Densely grown AlN grains with the diameter of about 100 nm can be seen from the image. The surface roughness $R_a$ of the AlN film was estimated to be about 5 nm; this suggests that the surface may be smooth enough to fabricate SAW devices consisting of sub-micron Al electrodes.
III. SHF SAW DEVICES ON AlN/DIAMOND STRUCTURE

SAW devices working around 5 GHz were fabricated, and SAWs propagating on AlN/diamond-substrate structure were characterised. Throughout this section, the AlN thickness of all devices was fixed at 0.85 μm (= 0.425λ), by which it is expected that SAWs propagating on a free surface posses relatively large $V_{S\text{AW}}$ of about 9.7 km/s and $K^2$ of about 1% (see Fig. 1).

A. SAW transversal filters on Al-electrodes/AlN/diamond-substrate structure

At first, a simple SAW transversal filter was fabricated using the AlN/diamond-substrate structure, where two Al IDTs having the electrode periodicity ($p_1 = \lambda$) of 2 μm were fabricated directly on the AlN film. The normalised electrode thickness $h/p$ of the device is 0.07, where $p$ is the grating electrode pitch and equal to $p = p_1/2$. The design parameters of the device are shown in Fig. 4(a). The Al IDT electrodes of 0.5 μm width were fabricated by electron-beam lithography and lift-off techniques, which enable to fabricate electrodes of the width of sub-microns[7]. The AFM image of the fabricated Al ITD electrodes (see Fig. 4(b)) clearly shows that the fine electrodes are successfully fabricated without any remarkable defect.

Figure 5 shows the insertion loss ($IL$) and reflection characteristics ($S_{11}$) of the fabricated device. Note in Fig 5(a) that the effect of electrical feed thorough is removed by the time gating function available in the network analyser. The figure clearly shows that the measured result is in good agreement with the theoretical curve calculated by COM based simulation. The minimum insertion loss of the device was 10 dB at 4.87 GHz. These results confirm that the AlN/diamond structure supports SAWs having very large $V_{S\text{AW}}$ and relatively large $K^2$ predicted by the theory.

By precisely adjusting the COM parameters and evaluating details of the SAW propagation on Al-electrodes/AlN/diamond-substrate structure, $V_{S\text{AW}}$ and the reflectivity per one electrode $κ_{12}$ were estimated to be 9.67 km/s and −0.01, respectively, for $h/p = 0.07$. It is also seen from the Fig. 5(b) that the fabricated device has
the fabricated SAW transversal filter.

relatively large electrical resistivity, which may be caused by the very thin electrodes. When one attempts to develop practical devices, especially resonators and/or resonator based filters, these small reflectivity of about \(|0.01|\) and large electrode resistivity of roughly 20 Ω definitely cause remarkable deterioration in their performance.

From the point of view, SAW transversal filters having thicker electrodes were fabricated and evaluated. Figure 6 shows $S_{11}$ of the device having the identical structure in Fig. 4(a) but $h/p$ being increased to 0.25 (250 μm). Comparing Fig. 6 with Fig. 5(b), one can see that the IDT resistivity was remarkably reduced by the increased electrode thickness.

The insertion losses of the fabricated SAW transversal filters are shown in Fig. 7 with $h/p$ as parameters. As can be seen in the figure, the largest reflectivity is obtained for $h/p = 0.20$, which suggests that $\kappa_{12p}$ may not change monotonically with $h/p$. In order to discuss this behaviour, the SAW propagation characteristics were numerically evaluated, in particular, for the devices with thick Al-electrodes. The modified version of FEMSDA[8] was used in the numerical computation. The numerically evaluated $V_{SAW}$, $k_{12p}$ and $K^2$ are shown in Fig. 8 as a functions of $h/p$. For comparison, the figure also shows $V_{SAW}$ and $\kappa_{12p}$ (●) estimated from the experimental result in

**B. One-port resonator**

One-port SAW resonator working around 5 GHz was fabricated to show one of the more practical applications of the AlN/diamond-substrate structure. An IDT and a pair of reflectors were configured as shown in Fig. 9, where $h/p$ was determined to be 0.20. It may be noted that other parameters such as the number of electrodes and aperture length have not yet been optimised for the highest performance.

**Fig. 5.** Insertion loss and reflection characteristics of the fabricated SAW transversal filter.

**Fig. 6.** $S_{11}$ of SAW transversal filter consists of thick electrode ($h/p = 0.25$).

**Fig. 7.** Insertion loss of SAW transversal filters with $h/p$ as parameters.

**Fig. 8.** SAW propagation characteristics as a functions of $h/p$.
The experimental result on $S_{11}$ (see Fig. 10(a)) shows that the resonant and anti-resonant frequencies of the device are 4.746 GHz and 4.759 GHz, respectively. By applying a simple equivalent circuit model to the measured admittance shown in Fig. 10(b), the $Q$ factor and capacitance ratio $\gamma$ were estimated to be 650 and 155, respectively. The estimation was carried out for the devices having the identical structure except for $h/p$. As a result, no significant resonant characteristics were obtained for $h/p = 0.07$, while relatively low $Q$ factor of 350 was obtained when $h/p = 0.25$. The result concludes that carefully determined $h/p$ is most effective in achieving high performance SAW devices.

**IV. Conclusion**

The AlN film/diamond-substrate structure, which supports SAWs with very large velocity and relatively large electromechanical coupling, was shown to be effective in developing practical SAW devices in SHF range.

It was confirmed experimentally that the AlN thin film deposited on polycrystalline diamond substrate by DC-TFTS method are highly c-axis oriented with FWHM of less than $5^\circ$. Since the AlN film has smooth surface of $R_a = 5$ nm, it is possible to fabricate fine electrodes of the order of sub-microns required for developing SHF SAW devices.

In order to characterise SAW propagation, simple transversal filters with various electrode thickness working around 5 GHz were fabricated on the AlN/diamond structure. Experimental results showed that the structure supports SAWs having the velocity of about $9.7 \text{ km/s}$. Both experiments and numerical analyses showed that the reflectivity of the grating electrodes does not change monotonically with $h/p$. This is caused by the mode-interaction occurring in the range of $h/p = 0.10 \sim 0.15$ when the AlN thickness is $0.425\lambda$.

When the large reflectivity is required for developing SAW resonators, etc., it was shown that $h/p$ should properly be determined.

One-port SAW resonators having electrode thickness of $h/p = 0.07$, 0.20 and 0.25 were fabricated on the pro-
posed structure. The highest Q-factor of 650 at the resonant frequency of 4.746 GHz was achieved, when $h/p = 0.20$. From the results, the change in the electrode thickness definitely impacts the SAW device performance; $h/p$ as well as $h_{AlN}/p$ should carefully be determined when one attempts to develop SAW devices on the Al-electrodes/AlN/diamond-substrate structure.

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