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Modification of Piezoelectrics Surfaces by Diamond-Like Carbon Films and Application to SAW Devices

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Abstract. Diamond-like carbon (DLC) coatings on single crystal piezoelectrics, such as ST quartz, and Y-Z lithium niobate substrates, have been studied with the aim of providing the designers of Surface Acoustic Wave (SAW) devices with a new palette of different properties of the most useful materials in this field.

A process for reliable deposition of DLC films on the surface of the oxide piezoelectrics has been investigated. The properties of these complex structures have been characterized electrically and acoustically. Speeding up of surface acoustic waves by DLC films, with the film thickness of 0.1–2.0 μm, on these single crystals has been studied. Useful SAW velocity increase of 0.5–2% has been confirmed.

In addition, reflecting arrays have been prepared with slanted periodic DLC strips alternating with Al or Au strips on Y-Z lithium niobate substrate and their reflection properties have been studied.

Keywords: SAW, piezoelectrics, velocity, reflection

Introduction

The diversity of Surface Acoustic Wave (SAW) device specifications defines a wide selection of substrate materials. The materials with low or high sound velocity, temperature stable or variable, strong or weak piezoelectrics characteristics have their different places in SAW applications. A possibility to engineer a material that is tailored for a specific SAW device application may in principle help to obtain unrivalled performance of the device.

Different attempts have been made for modifying surface properties of most common piezoelectrics, such as quartz, lithium niobate. Thin-film coatings, say diamond-like carbon (DLC) films [1–3], on $LiNbO_3$ surface do show the effect of accelerating surface related waves. The choice of speeding-up coatings is not wide and this is the reason for the intensive search of such materials with different acoustical and physical properties. Diamond and diamond related materials are very attracting candidates for this purpose. Hard carbon thin films have been well studied in many different industrial sectors and their production reaches quite large volumes, as for example in wear protection and surface hardening. Elastic properties, such as Young modulus, for the family of carbon films cover from soft (say hydrogenated amorphous carbon films) to hard characteristics (say polycrystalline diamond films) [4]. As a result, this feature opens possibilities of modification of SAW velocity on the surface of piezoelectrics for SAW device application.

In this paper we report on successful deposition of DLC thin films on ST quartz and Y-Z lithium niobate substrates, processing and tentative applications to SAW filter technique.

Processing Details

DLC films were deposited on Y-cut $LiNbO_3$ and YX quartz substrates using H_2-CH_4 plasma in a PECVD system. To ensure good adhesion, a few nanometer thick SiC layer was deposited prior to DLC film deposition. The samples were not intentionally heated during film growth and the substrate temperature (about 60°C) was defined by the plasma conditions. The DLC films were deposited using $[CH_4]/[H_2] = 0.5$, rf power of 150 W, pressure of 130 mTorr and rf induced bias voltage of about -290 V. The SiC interlayer was produced using $[CH_4]$:$[H_2]$:$[SiH_4]$:[Ar] = 25:600:150:10, rf power of 50 W, pressure of 500 mTorr and rf induced bias voltage of about −95 V. These conditions resulted in reliable growth of DLC films with the thickness ranging from 0.3 to 2.0 μm.

Hydrogen-free tetrahedral amorphous carbon (Ta-C) films, with a typical thickness of 0.12 μm, were grown on YX quartz substrates in a filtered cathodic vacuum arc (FCVA) system. During the film growth, the carbon plasma was focused to a spot of 50 mm in diameter. Arc current was kept constant at 60 A and carbon ion energy was controlled at 40 eV. The substrate temperature was kept at room temperature. No SiC interlayer was intentionally incorporated into Ta-C/quartz samples.

The hardness of the films, monitored by Nano-indenters II, was around 19 and 38 PGa for the DLC and Ta-C films, respectively. Micro-Raman scattering was excited using the 514.5-nm line of an Ar laser beam.

DLC and Ta-C films were found to be reliably patterned by rf plasma etching in oxygen atmosphere. Aluminum (or Cr/Cu, or Cr/Au) thin-film layouts were formed on top of DLC and Ta-C films by conventional wet photolithography. They served as masks for plasma etching. Vertical walls of DLC strips without any signs of underetching were obtained in ordinary etching conditions with parallel electrodes, while changing to plasma excitation by electrodes outside the quartz chamber allowed repeatable obtaining of gentle slope defined by strong underetching.

SAW Velocity Data

Rayleigh-wave velocity modification by the coatings was deduced from comparison of responses of two identical delay lines fabricated on the same substrate. A rectangular area of DLC or Ta-C film was left in the acoustical track of one of the delay lines (see Fig. 1).

The measurements were performed either in the frequency domain, by combining frequency responses of both delay lines and analyzing the resulting interference beatings, or in the time domain, by comparing the delays of the impulse responses. The first method corresponded to phase velocity difference, while the second to the group velocity. However the phase velocity change can be deduced from group velocity data with knowledge of dispersion relation, and when a linear relation is valid, the phase velocity change may be estimated as about two times lower than the group velocity change. The phase velocity modification by DLC coatings on YZ cut $LiNbO_3$ is given in Table 1. We may conclude from this data, that the speeding up of the Rayleigh wave increases with the film thickness faster than linearly. To our understanding this fact reflects the structural changes during the film growth on substrates with substantially different lattice. The initial DLC film layers are more influenced by the substrate and their stiffness is lower, while consequent layers that are deposited on top of already formed DLC films become less influenced by the substrate properties. The SAW velocity change reflects integral properties of our thin films.

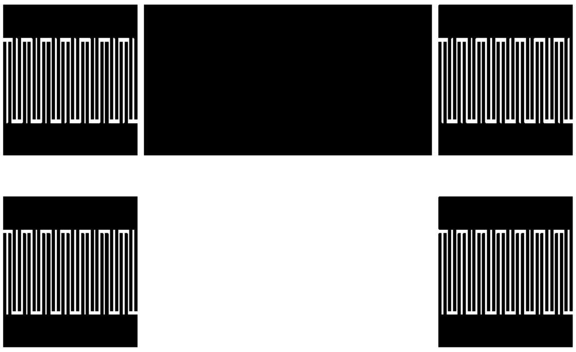

Fig. 1. Test sample layout for velocity change determination.

In some test samples measurements at the fifth harmonic of the central frequency could be reliably performed, thus giving some information on the dispersion properties of our films and on the dependence of their acoustical properties on the film thickness that in turn reflects the peculiarities of the film growth. Such data is presented in Table 2.

The results obtained for a 1 μm thick DLC film in Tables 1 and in 2 can be compared. This comparison indicates that the velocity increase at higher frequency is somewhat lower than can be expected from the linear assumption on the dispersion relation. This fact agrees with extensive study of the coatings dispersion on different substrates (on silicon) in [4, 5].

Table 1. SAW velocity modification by DLC films on YZ-cut $LiNbO_3$.

Film thickness h, μm	Relative phase velocity change $\Delta v/v$, % (Frequency response at 107 MHz)	Linear coefficient of phase velocity change at 107 MHz, A, %. ($\Delta v/v = A\, h/\lambda$)
1	0.54 ± 0.1	18 ± 4
2	1.9 ± 0.1	31.9 ± 4

Table 2. Fifth harmonic SAW velocity modification by DLC films on YZ-cut $LiNbO_3$.

Film thickness h, μm	Relative phase velocity change $\Delta v/v$, % (Frequency response at 538 MHz)	Linear coefficient of phase velocity change at 538 MHz, A, %. ($\Delta v/v = \mathrm{A}\, h/\lambda$)
0.7	1.2 ± 0.4	10 ± 4
1	1.8 ± 0.4	12 ± 4

Table 3. SAW velocity modification by DLC and Ta-C coatings on YX-cut quartz.

Film type	Film thickness h, μm	Relative group velocity change $\Delta v/v$, % (Impulse response at 198 MHz)	Linear coefficient of group velocity change at 198 MHz, A, %. ($\Delta v/v = \mathrm{A}\, h/\lambda$)
DLC	1	2.3	37
Ta-C	0.12	3.4	450

Due to lower coupling to SAW, the output signal of delay lines on quartz is obscured by electrical breakthrough in the cw regime. That is why more reliable data is obtained in the impulse regime. The data for two distinctly different types of films presented in Table 3 correspond so far to the group velocity measurements.

As expected from the density ratios and from the Young's modulus ratio, the DLC film speeds up the Rayleigh wave on YX quartz somewhat more than on $LiNbO_3$. However, as discussed above, the linear dispersion relation cannot be reliably applied to 1 μm thick films at different frequencies, so the comparison of phase and group velocity results for different substrates with this thickness of DLC film is very approximate. At the same time, the thickness of a more rigid Ta-C film is about 8 times smaller, and the linear dispersion relation may be applied with more confidence [4] to evaluation of phase velocity change as being about two times lower than the group velocity change. We would suggest that the figure of $\Delta v/v = 225\, h/\lambda$ could be a good estimate for the linear region of phase velocity change for such films on YX quartz. This value is very large and it may form the true basis for different new concepts of SAW devices.

Application Potential

Most thin film materials slow down the SAW velocity on $LiNbO_3$ and on quartz. This is usually due to mass loading by dielectric films and additionally to electrical loading of piezoelectric surface by conductive materials. Besides, topographic features like walls of strips or etched grooves introduce extra slowing down.

Generally velocity perturbation must be accounted for in SAW filter design, and in some structures, such as in reflecting arrays, it may cause complicated problems in very precise devices involving withdrawal weighting. Speeding-up elements alternating with slowing-down elements can help to compensate such effects. Besides, alternating reflecting elements from speeding-up and slowing-down materials may increase the overall reflection of the structure. Increased reflection can find application in wideband and low-loss filter designs. This idea is schematically illustrated in Fig. 2. Our experiments confirm the validity of this operational principle and the advantages of DLC films in such applications.

The value of reflection per period obtained with DLC strips on $LiNbO_3$ in 90 degrees reflection was relatively small, equal to 1% at 69.3 MHz, despite the comparatively large 1 μm thickness of the film. This value is about 3 times lower than the reflection from thin pure Al strips, but nevertheless it has already sufficient practical meaning for long reflectors. Such a value of reflection could be expected because the DLC films used in this study increase the SAW velocity only a little while comparatively tall strips can also reflect the wave as topographic discontinuities. These reflections may add with different phase shifts, and it is arguable whether the excessive film thickness is universally helpful in obtaining lager reflection with speeding-up coatings.

The very high amount of velocity change by Ta-C films discussed above validates strong hopes on the

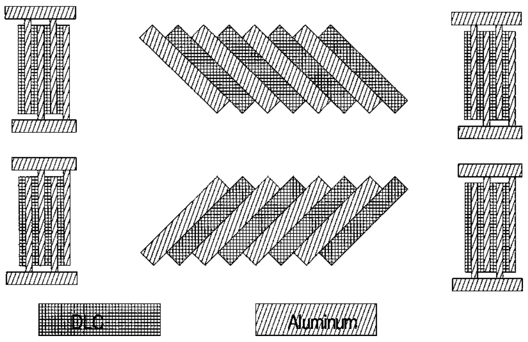

Fig. 2. Illustration of alternating strips with increased and decreased SAW velocity for application in reflecting arrays and transducers.

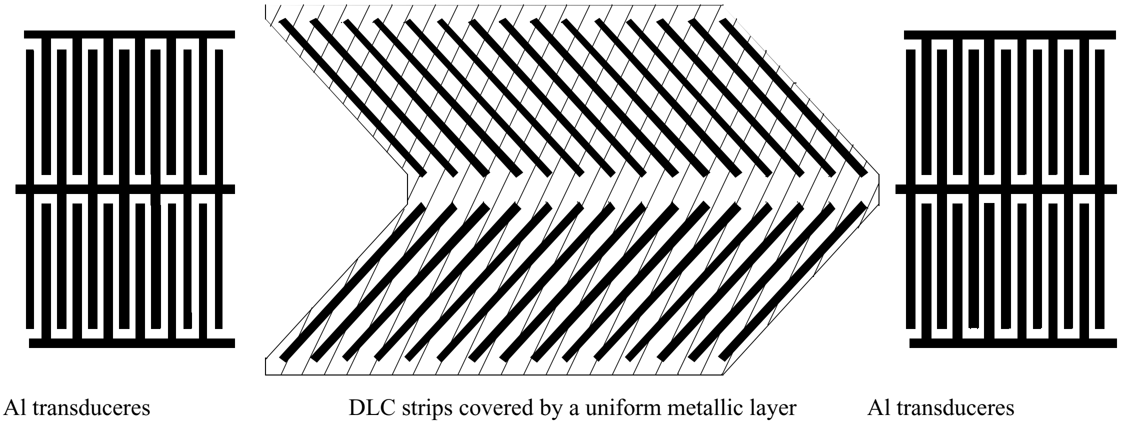

Fig. 3. Illustration of local insulation of uniform metal film from the piezoelectric substrate surface by DLC strips for application in reflecting arrays.

possibility to obtain a substantially higher reflection level with this material in future experiments. These relatively thin films are expected to give sufficient reflection, and their topographic features may possibly be disregarded. This potential property to ensure high reflection may find application in wideband reflecting structures.

Another useful characteristic of DLC films is their relatively low dielectric constant. For DLC films reported in this study it is equal to about 3.9. This value is lower than the average permittivity of $LiNbO_3$ (close to 50), and for this reason a DLC film serves as an efficient insulator of metal elements from the surface of this piezoelectric.

We have successfully tested this opportunity in reflecting arrays based on local insulation of a uniform metal coating from the $LiNbO_3$ surface by a previously fabricated layout of DLC strips (Fig. 3). In this case, the intrinsically small velocity perturbation by DLC strips automatically helps to avoid unwanted frequency shifts.

This new principle of local partial insulation may be applied for preferred excitation of different acoustical tracks in multi-track SAW devices. The combination of reflecting and isolation features may help to solve problems in unidirectional transducer designs.

Conclusion

DLC and Ta-C films described above possess the property to modify the surface of piezoelectrics that seem interesting for performance improvement in traditional designs of SAW devices. Moreover, some novel types of devices have been suggested and explored. More extensive study of these materials in combination with piezoelectrics appears beneficial for potential applications.

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