Investigation of high velocity pseudo-SAWs in layered systems by SAFM

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Abstract — We present first measurements on acoustic waves with longitudinal polarization in bare quartz and lithium tantalate substrates as well as layered systems carried out by a scanning acoustic force microscope (SAFM). Acoustic phase velocities were measured for microscopic areas showing a good agreement with numerical calculations. The influence of the penetration depth of longitudinally polarized pseudo SAW on the detection by SAFM is discussed.

Introduction

The technical development in the mobile communication systems show a trend towards higher operating frequencies for higher data rates. This creates a demand for new filter and signal processing devices at operating frequencies in the GHz range. The rapid development of the optical lithography down to 0.18µm feature size has opened this new field also for the SAW application. However, the application of the slow Rayleigh type waves for SAW devices reaches the technological limits at about 4 GHz. Thus there is large interest in SAW modes with higher phase velocities, that would allow for the fabrication of high frequency devices by the use of conventional optical lithography far above the structure resolution limitation.

Recently high velocity pseudo surface acoustic waves (HVSAWs) have been widely discussed particularly for high frequency SAW applications. These longitudinally polarized leaky SAWs offer phase velocities that are roughly up to a factor of two higher than the commonly used Rayleigh modes, thus doubling the operating frequencies at the same feature sizes. On the other hand, the wave behavior of these modes is still not well investigated. Since HVSAWs are almost polarized within the crystal surface having a very small particle displace component perpendicular to the surface only they can be hardly detected by optical methods.

Recently we have demonstrated the detection of transversely polarized SAWs by a scanning acoustic force microscope (SAFM) technique. Here we show first measurement of longitudinal polarized acoustic waves on ST-quartz and X-$LiTaO_3$ substrates.

Experimental

The experimental setup is based on a conventional SAFM operating in contact mode. Two SAWs are launched by opposing interdigital transducers (IDTs) at slightly different frequencies. Because of the nonlinearity of the tip-to-sample contact the cantilever acts as a mechanical diode. When two waves are present at the tip-to-sample contact a mechanical frequency mixing takes place and generates cantilever oscillations at the difference frequency. For higher sensitivity with respect to lateral oscillations of the in-plane polarized modes the torsional motion of the cantilever has to be investigated. The rotation as well as the deflection of the cantilever is measured optically by a position sensitive detector (PSD) and analyzed by a lock-in amplifier. The output of the lock-in is recorded simultaneously with the topography scan giving amplitude and phase images of the SAW field in the scanned area. The reference signal for the lock-in is generated by externally mixing the RF voltages driving the IDTs.

Splitfinger IDTs with 1000 electrode fingers and 350 µm aperture were fabricated on ST-cut quartz with X propagation direction (Euler angles: 0°, 132.75°, 0°) and X-cut $LiTaO_3$ with wave propagation in the direction 42° rotated with respect to the Y-crystal axis (Euler angles: 90°, 90°, 42°). The width and the thickness of Al finger electrodes of the IDT was 1.8 µm and 60 nm, respectively. For the study of the wave behavior of the HVSAW in layered system we deposited a 200 nm SiO_2 layer on top of ST-quartz by ac sputtering.

For the SAFM investigations the samples were rigidly mounted and wire bonded. No external electrical matching was performed. RF power from two generators was directly fed to the IDTs. Typical signals used in these experiments were nominally 10 to 20 dBm.

Results and Discussion

First, we have measured the frequency characteristics of the SAW delay line. All the samples show transmission peak at the frequencies where longitudinally polarized modes are expected. The insertion loss ranges from –35 to –45 dB.

Three characteristic responses have been found in the electrical transmission for the quartz substrate allocated to the Rayleigh wave at 218 MHz, the transverse leaky wave at 350 MHz and the HVSAW at 402 MHz. However, the separation of the HVSAW and the longitudinal bulk wave is sophisticated since the phase velocity of both modes is very similar. For ST-X quartz the velocity v_{HVSAW}=5744.9 m/s for HVSAWs and v_{LBW}=5744.1 m/s for longitudinal bulk waves was calculated. The coupling factor of the HVSAWs is about k^2 =0.01%. Furthermore for the plain ST-X quartz sample theory predicts an extremely weakly localized HVSAW mode. Since the penetration depth is about 100 wavelength the acoustic energy is distributed over a wide penetration length. Taking into consideration the small coupling factor for the HVSAWs a very small oscillation amplitude at the surface is excited. However, the SAFM technique is sensitive to the oscillations at the very surface only. Therefore detection of deeply penetrating acoustic waves should be much more complicated than well localized SAWs. This was confirmed by the fact that no down converted oscillation signals were detected by the SAFM on bare ST-X quartz when operating the IDTs on the frequency of 402 MHz.

The situation completely changes when the surface is covered by a SiO_2 layer. Although a 200 nm SiO_2 layer represents for 14.4 µm SAW wavelength a kh value as small as 0.087 and the phase velocity remains almost unchanged the localization of HVSAW near the surface significantly increases. The longitudinal oscillation component is localized within about 25 wavelength. However, a SAFM mixing signal was clearly found and high quality measurements of the phase signal have been performed. The acoustic wavelength of 14.4 µm is measured from the distance between three phase jumps. For the operating frequency of 400 MHz the phase velocity v_E= 5750 m/s is estimated. This corresponds well with the theoretically predicted value of v_C =5744.9 m/s.

However, for applications high coupling as well as high velocity are of essential interest. Recently SAWs and leaky SAWs has been studied on $LiTaO_3$. For X-cut $LiTaO_3$ with 42° propagation direction (Euler angles: 90°,90°,42) the HVSAW is much better localized than for bare ST-X quartz and the coupling factor k^2=0.94% is much higher. Therefore a reasonable oscillation amplitude at the very surface is to be expected.

For the experiments the similar IDT structures as for quartz were processed on $LiTaO_3$. Two major responses were found at 217.2 MHz and 440.75 MHz. The lower frequency response corresponds to the Rayleigh type wave with phase velocity v=3124.5 m/s whereas the higher frequency can be assigned to the longitudinal bulk wave v_{LBW}=6346.3 m/s or to the HVSAW with a calculated velocity of v_{HVSAW}=6350.9 m/s. The velocity of the leaky mode is in fact predicted to be higher by about 4 m/s than the bulk wave velocity. The existence of waves with phase velocities higher than the longitudinal bulk wave is still under discussion. The verification of this prediction by delay line measurements is difficult since the measurement is influenced by wave propagation within the IDT. In fact the wave behavior of HVSAWs changes very significantly when the surface is covered be metal layers. The phase velocity v_C=6288 m/s decreases and the damping increases to 0.6 dB/wavelength.

The wavelength measured by the SAFM with a point resolution of 255 pixel per length scale was 14.4 µm. The error for the determination of the wavelength is about 0.4%. The IDTs were operated at 440.8 MHz. The phase velocity of v_E=6350 m/s was estimated. The measurement error is mainly determined by the error of the length measurement of the AFM scanner. The experimental value corresponds surprisingly well with the theoretical data for the longitudinal leaky waves. However, the accuracy of the measurement has to be increased to distinguish between bulk and leaky waves.

Conclusion

In conclusion, we presented SAFM measurements of longitudinally polarized acoustic modes on quartz and $LiTaO_3$. For the bare ST-X quartz detection of HVSAW by SAFM failed due to the large penetration depth into the substrate. However, when a fused silica layer is deposited on top of the surface, the wave becomes significantly more localized near the surface and the amplitude of the surface oscillations becomes accessible for SAFM phase measurements. We experimentally confirmed the existence of HVSAW in layered quartz systems with very small coupling constant. On $LiTaO_3$ HVSAW were also measured on the bare substrate.