Design and fabrication of AlN-on-Si chirped surface acoustic wave resonators for label-free cell detection

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Abstract. Chirped surface acoustic wave (SAW) resonators based on aluminum nitride (AlN) thin films have been designed and fabricated to comprehend the wave propagation characteristics induced by interdigitated transducers (IDTs) deposited on their surfaces. From the simulation results, design and geometry of the metal fingers including their width and pitch play critical roles on the wavelength of the acoustic wave and the mechanical displacement, which subsequently set the device resonant frequency. A single-step metal lift-off process involving photolithography and electron beam metal evaporation has been used to pattern and deposit Cr/Au IDT on AlN-on-Si wafers.

1. Introduction

Aluminum nitride (AlN) has been an excellent III-V nitride piezoelectric material for being used in micro-electro-mechanical systems (MEMS) because of its outstanding properties (e.g., high electro-mechanical coupling, high thermal stability, good electrical insulation, and CMOS-process compatibility). Therefore, in recent years, MEMS-based devices have been integrating AlN thin layers either as an acoustic wave generator for SAWs and bulk acoustic waves (BAWs) or as an actuation element for low-frequency cantilever resonators. In case of cantilever excitement, by having a very thin structure, an AlN film can further miniaturize the ultimate integrated sensor system, eliminating unnecessary external piezoelectric block stack [1-4]. Moreover, this type of MEMS actuation can basically avoid non-ideal shapes of resonant frequency curves, which are normally found in electrothermal piezoresistive MEMS cantilevers excited using p-diffused or implanted heating resistors [5-7]. Besides actuation, this piezoelectric material can be used as a read-out sensing element,
hence offering a higher degree of freedom for device integration. For specific sensing application, the Rayleigh SAW has both longitudinal and transversal (shear) waves [8]. The longitudinal waves propagate along the plane and only in the material with limited interaction to the surrounding environment. Meanwhile, shear waves can maintain high sensitivity towards sensing objects in liquids because of their transversal direction, which consequently leads to their suitability for biomedical/chemical sensing applications [9]. In this work, SAW resonators based on 500 nm AlN thin film grown and patterned on a silicon (111) wafer have been developed to be used for biosensors.

2. Simulation

Prior to device fabrication, the SAW resonators have been designed and simulated to investigate the effect of the influencing parameters. In this case, the wave is generated by a conductive comb-shaped periodic structure, which converts electrical energy into mechanical energy by utilizing the piezoelectric effect. A finger and its spacing widths construct a half period \( \lambda = \frac{1}{8} + \frac{1}{4} + \frac{1}{8} \) of the wave. The wavelength (\( \lambda \)) is equal to the distance between two adjacent IDT pairs, so that one periodic of wave is equal to two fingers and two spaces (figure 1(a)). A standard IDT has the same width for all fingers and spaces. Since the electrode’s polarity of two adjacent IDT is opposite, the frequency of acoustic wave can be predicted by the velocity of the wave over the wavelength which subsequently related to the natural resonant frequency (eigenfrequency) [10]. Meanwhile, the \( v_{SAW} \) is the speed of surface acoustic wave propagation on the piezo-material AlN (5790 m/s) [11].

To investigate the characteristics of the produced waves, finite element modeling (FEM) has been performed utilizing COMSOL Multiphysics®. Due to the periodic geometry of IDT, the simulation model only needs a small part of the SAW. As a result, the mechanical displacements and the natural resonance frequencies were obtained (figure 1(b)).

![Figure 1.](image)

**Figure 1.** (a) Design of IDT geometry of an SAW resonator with periodic electrodes used in simulation. FEM results show the distribution of the waves for (b) standard and (c) chirped IDTs.

From the extracted simulation data, the maximum mechanical displacement of the devices occurs at \( \lambda \) of ~80 \( \mu \)m, which corresponds to an ideal \( w_f \) of 20 \( \mu \)m. The mechanical displacement is not evenly spread because of the involved piezoelectric material properties such as stiffness, coupling, and elasticity matrices, which can limit its own natural vibration [12]. This value is close to the region where the longitudinal wave is more dominant than the shear wave. Therefore, the device operating frequency needs to be considered and chosen carefully. Moreover, further simulation and characterization will be performed to explore the feasibility and sensitivity of this resonator for biological cell monitoring.
Unlike the typical design of an IDT, where all the fingers and spaces have the same width, a chirped IDT, with gradually increasing finger and spacing width (λ) from 80 µm to 136 µm and an interval of 2 µm (figure 1(c)), has been proposed and designed for this sensor. Because of various width and spacing for each finger are different, all geometry parts of the SAW have been included to the simulation, instead of only using mirrored or simplified models as in standard IDTs. By varying the finger width, the bandwidth of the resonator can be increased to provide a wide spectrum of accessible SAW wavelengths, which then lead to a large manipulation or sensing range of the device [13].

To observe their different characteristics (e.g., eigenfrequencies), both standard and chirped IDTs have been simulated, in which they have 29 finger pairs with different sizes in one device. As seen in figure 2, the eigenfrequency of the device with a chirped IDT is higher than that of the resonator with standard IDTs.

3. Device fabrication

To fabricate the SAW resonators, a 525 µm thick Si (111) wafer with 500 nm AlN film on top of it was used, in which the AlN layer was deposited using plasma vapor deposition with nano-columns technology (PVDNCTM, Kyma). The wafer has been firstly diced to 10 × 10 mm² chips and since the utilized AlN-on-Si wafer comes with an insulating/protective layer on the surface, this layer has to be removed. A standard cleaning procedure was then applied to the wafer using acetone in an ultrasonic bath for 5 minutes (Bandelin Sonorex TK 52) as depicted in figure 3(a). Next, a 1.6 µm thick photoresist (AZ 5214E, Microchemicals GmbH) was spin-coated on the substrate at 5000 rpm for 35 seconds (figure 3(b)), continued by a soft-bake process at 110 °C for 50 seconds. The soft-bake process was required to evaporate the solvent making the photoresist more solid. Lithography exposures were performed in two steps with image reversal method. The first exposure after the soft-bake process was performed for 27 seconds using a positive mask (figure 3(c)). Meanwhile, the second one was conducted after a post-bake process without the mask (i.e., flood exposure, τ = 80 s) as seen in figure 3(d). A portion of the photoresist that was exposed at the first exposure became soluble. However, the flood exposure process reverted the photoresist to the opposite, the soluble area became insoluble (figure 3(e)). After the exposure steps, the resist was developed in photoresist developer (AZ726 MIF, Microchemicals GmbH).
Afterwards, a dual layer of metal (figure 3(f)), 30 nm/300 nm chromium and gold (Cr/Au) layers, on top of the sample, especially atop the AlN layer, using e-beam evaporation. This was followed by a lift-off process, which removed the photoresist and metal on top of it, leaving only the metalized fingers and contact pads. The lift-off process was performed in an ultrasonic bath (35 kHz) using acetone for about 5 minutes. Finally, the fabricated IDT structure with Cr/Au electrode was achieved (figure 3(g)).

Figure 3. The fabrication process sequence of the chirped IDT involving (a) AlN/Si wafer preparation, (b)-(e) photolithography, (f) metal deposition, and (g) lift-off process.

Figures 4(a) and (b) depict the images of the fabricated SAW resonator captured using optical microscope and scanning electron microscopy (SEM), respectively. In this structure, the metal fingers of the IDT have been successfully deposited on AlN using e-beam evaporation. In order to have a closer investigation on the morphology of the fingers, SEM measurements have been carried out. From the SEM images, it can be observed that the dimension of the smallest finger (i.e., 20 µm width) on the fabricated device fits to the design with a deviation of only 0.25 %. The $\lambda$ can then be measured as 79.8 µm. It is very critical to validate the expected resonant frequency of the device because according to the simulations (figure 2), a deviation of 2 µm can change the eigenfrequency by 423 kHz. If the eigenfrequency changes, the sensitivity of the SAW can be affected because of a transformation of the wave propagation mode (transversal, shear or lamb) [13]. To minimize such deviations, the precision of the mask is therefore very important.

Figure 4. Micrographs of an SAW device taken by an (a) optical and (b) scanning electron microscope.
4. Surface topography
To investigate the surface topology of the fabricated electrodes and the AlN layer further, atomic force microscopy (AFM) measurements have been performed. From figure 5(a), the topography of a finger part of an IDT is shown, in which the AlN and Au parts are depicted as dark and bright colors, respectively. The height of the Cr and Au layers as the main part of IDT can be measured using an AFM line scan image analysis showing a height of 289.6 nm (figure 5(b)). The slope of the electrode is quite steep, which is an advantage of the image reversal method during the photolithography process. The measurement of electrode height leads to the investigation of relationship between the thickness of the gold layer, the phase velocity, and the coupling coefficient of propagation in an SAW device [14]. Moreover, from the AFM measurements, the surface topography of the AlN and Au layers has been revealed as shown in figure 5(c). In this case, average roughness values of the gold surfaces on the finger and the AlN surfaces were measured to be ~7 nm and ~10 nm, respectively. This relatively rough surface can be attributed to the metal evaporation process during the device fabrication.

![Figure 5](image_url)

**Figure 5.** (a) Optical micrograph of the sample showing different areas of the AlN and Au layers. (b) AFM topography image of an IDT finger to measure the height of the Cr/Au bilayer. (c) 3D AFM profiles of AlN and Au surfaces.

5. Conclusion
In this work, a chirped surface acoustic wave (SAW) resonator has been designed and fabricated on an AlN-on-Si substrate. The SAW was generated by a chirped interdigitated transducer (IDT), in such a way that the pitch of the IDT electrodes differs gradually. Therefore, the finger arrangement in the chirped IDT pitch makes its working frequency range wider. Meanwhile, the analysis has been done by simulating standard and chirped IDTs to investigate the resonant frequencies of the corresponding SAW devices. On the other hand, the device fabrication process is similar and compatible with MEMS and/or CMOS technology, offering an easier integration. For the validation of the fabrication process, several characterization methods based on optical microscope, SEM and AFM have been conducted to investigate the material surface topography and morphology. Further assessments of the device are still necessary in terms of their mechanical properties, e.g., measured resonant frequencies.

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