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Optimization of high frequency 45° acoustic mirrors for lab on chip applications

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Abstract

Ultra high frequency (~1GHz) ultrasonic bulk acoustic waves (BAW) characterization has been already integrated in a lab-on–a-chip silicon platform. The acoustic wave guided in three dimensions (3D) was achieved via 45° mirrors in a silicon wafer and applied for the characterization of chemical solution and fluids actuation in micro-channel. The main problem is that strong conversion mode occurs at the silicon-air interface with the incidence angle of 45°. To avoid conversion mode we need to optimize the reflection on the 45° mirrors in order to maximize the acoustic energy of the longitudinal wave and reduce signal to noise ratio. We demonstrated that longitudinal wave transmission is efficiently strengthened using gold coating (average gain factor of 8 compared to reference case without mirror coating). The experimental validation of the losses improvement is achieved using S_{21} scattering parameter in a transmission acoustic integrated system.

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Keywords: Coating layer, Reflection losses, Conversion mode

1. Introduction

Microfluidic chips have proven ideal tools to precisely handle small volumes of cell suspensions in significantly less time [1]. Acoustic microfluidics, including surface acoustic wave (SAW) and bulk acoustic wave (BAW) technologies, have been developed intensely in the emerging lab-on-a-chip-based field applications, such as flow mixing [2], bio-sample detection [3] and micro-objects trapping [4], because of the advantages of non-contact particle manipulation, high power efficiency and non-destructive effect for living cells [5]. The developed surface acoustic wave (SAW) technology onto lab-on-a-chip platforms has opened new applications in microfluidics and led to a variety of achievements in particle handling and patterning [6]. However, such systems need special piezoelectric crystal substrates that add more technological constraints than utilizing a piezoelectric transducer in bulk acoustic wave method (BAW). The method proposed by Lund University based on bulk acoustic standing wave force in microfluidic system led to attractive progress in the field of particles and cells handling [7], but the working acoustic frequency range is limited within dozens of MHz due to the matching of half-wavelength and

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geometry of the micro-channel. For the purpose of single cell property measurement, utilization of an ultra high frequency (~ 1GHz) acoustic wave is necessary to achieve a high sensibility and resolution. Due to the acoustic wavelength in this frequency range which is approximately around the biological cell dimension, the acoustic wave would be very sensitive to the elastic properties and enable the actuation of micro-objects and single cells. Besides, at higher frequencies the SAW devices become too fragile for practical use. Thus, we have proposed the design of an ultra high frequency BAW based microfluidic platform.

We have already developed an ultra high frequency (~1GHz) ultrasonic bulk acoustic waves (BAW) system integrated in the lab-on–a-chip silicon platform [8-9]. Thanks to the fabrication of a microsystem, the acoustic wave guided in three dimensions (3D) was achieved via 45˚ mirrors in a silicon wafer [8], and this ultra high frequency acoustic wave (1GHz) was successfully applied for the characterization of chemical solution and detection of particles in micro-channel [9]. It is well known that using silicon or silica 45˚ mirrors, a huge amount of incident longitudinal wave would be converted into shear wave after reflection at the silicon (silica) – air interface. However, for cell characterization or cell manipulation, the acoustic wave has to cross a microfluidic channel with liquid in which the shear wave has a drastically attenuation. Thus the reflection coefficient of the longitudinal waves has to be improved in order to optimize the SNR for characterization application but also for actuation application so that most of the energy is coupled to the liquid (even for lower frequency range: 300 MHz). For this purpose, we optimized the reflection on the 45˚ mirrors via acoustic matching layer in order to maximize the acoustic energy of the reflected longitudinal wave.

2. Materials and Method

The microsystem is constituted of two adjacent 45° mirrors and a pair of ultrasonic transducers used as emitter/receiver. The acoustic wave is generated by the emitter in vertical direction, then reflected by the first 45° mirror and transmitted in a direction parallel to the wafer surface before being reflected again by the second 45° mirror. The schematic view of the mirrors and piezoelectric ZnO transducers under the silicon substrate is shown in **Figure. 1(a-b)**.

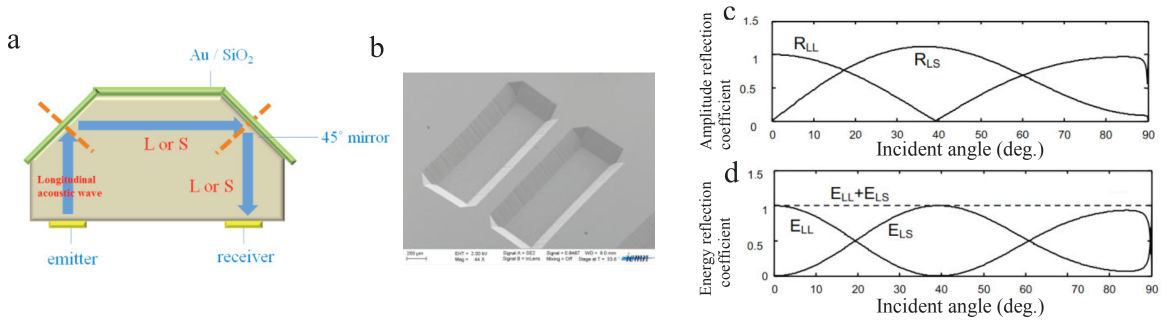

Fig. 1. a) Scheme diagram of the microsystem; Reflection coefficient of LL mode for longitudinal converted to longitudinal wave and TL mode for longitudinal to shear wave, for a longitudinal wave incidence at silicon-vacuum interface; b) SEM image of the cross-section of the 45° mirrors; c) in amplitude and d) in energy. (ultrasonic characteristics of silicon : V_L = 8457 m/s; V_T = 5887m/s)

As shown in **Fig. 1 (c-d)**, at the 45˚ incident angle, most of the longitudinal wave energy is transferred to shear wave energy due to the conversion mode. Thus the generated longitudinal wave will be converted into shear wave after being reflected by the first mirror, but this shear wave cannot be converted back to a longitudinal wave on the second mirror. To minimize conversion mode, we deposit coating layers on the mirrors to improve the reflection of the longitudinal wave on the mirror. The amplitude of reflection coefficient for the longitudinal wave can be calculated from the following formula:

$$R_{LL} = \frac{U_L}{U_I} = \frac{\sigma^2 \sin 2\theta_I \sin 2\theta_S - cos^2 2\theta_S}{\sigma^2 \sin 2\theta_I \sin 2\theta_S + cos^2 2\theta_S} \quad \text{with } \sigma = \frac{V_S}{V_L} \tag{1}$$

And the coefficient for conversion into the shear wave is

$$R_{LS} = \frac{U_S}{U_I} = \frac{2\sigma \sin 2\theta_I cos2\theta_S}{\sigma^2 \sin 2\theta_I \sin 2\theta_S + cos^2 2\theta_S} \qquad (2)$$

Where θ_I is the angle of incidence, θ_S is angle of reflection.

Calculation at 1GHz frequency harmonic wave in **Fig. 2 (a-b)** showed that for 0.6 µm Au layer and 3.8 µm SiO_2 films, the reflection coefficient from longitudinal wave to longitudinal wave R_{LL} reach the maximum value (close to 1) and longitudinal wave to shear wave R_{LS} is at the minimum value (near 0). It indicates that nearly all the longitudinal wave energy is kept even when the acoustic waves are reflected twice by the two 45˚ mirrors. The simulation has shown clearly another optimum matching layer thicknesses which is quite twice the previous value. The minimum thickness was chosen for coating layer fabrication. With thicker metallic layer deposition, higher internal stress would be introduced and lead to heterogeneity of the film on the mirror surfaces.

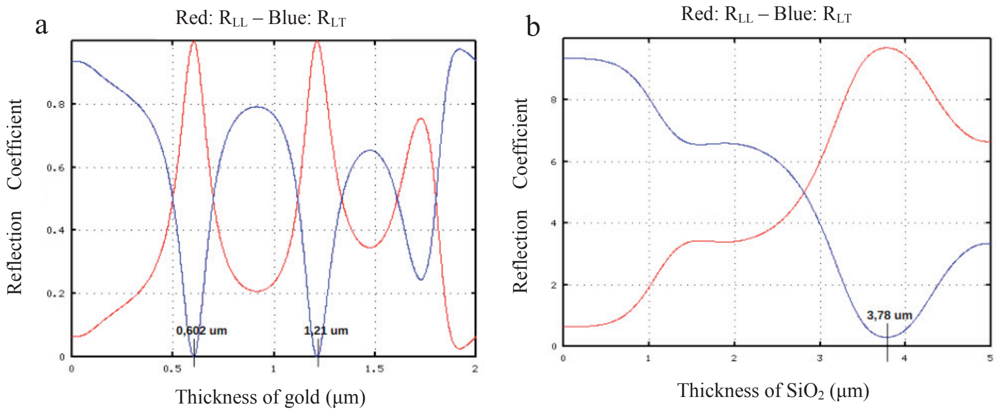

Fig. 2. Simulation of the reflection coefficient from longitudinal wave to shear wave for an incidence angle of 45˚ and a central frequency of 1 GHz: a) Reflection coefficient with Au coating layer and b) with SiO_2 deposited on mirror surfaces. Red line is the reflection coefficient from longitudinal wave to longitudinal wave, and blue line indicates longitudinal wave converted to shear wave.

3. Experimental results

In this paper, we study and compare the acoustic effect of different acoustic matching layer on the 45˚ mirror surfaces. We demonstrated that shear wave transfer is limited in the mode conversion and longitudinal wave transmission is efficiently strengthened. The 45˚ silicon mirrors were fabricated by wet etching technology and bulk acoustic wave transmission was achieved in three dimensions (3D). 800 nm Gold (compatible with central frequency of 0.8 GHz) and 3800 nm SiO_2 film (compatible with central frequency of 1 GHz) were deposited on the mirror surfaces separately to evaluate acoustical performances. We characterized the S_{21} scattering parameter between transducers emitter and receiver [10]. The spectrum of the transmitted wave is also analysed thanks to an inverse Fourier transform of the longitudinal acoustic echo. The transmitted acoustic wave amplitude is increased by an average factor of 8 in the case of a single gold layer evaporated on the mirrors, as well as an average ratio of 7.4 in the case of SiO_2 deposited on mirrors. Meanwhile, we measured the ratio of bandwidth with and without gold coating layer. We observed that the partial adhesion of the surface of SiO_2 film produced a decrease of the acoustic reflection value, as the thickness is above 3 µm.

Here L means the remaining longitudinal wave after reflection by a 45˚ acoustic mirror, and S means the converted shear wave after reflection. We mainly took into account the LLL acoustic signal (the remaining longitudinal wave after two reflections) which could be easily read on the curves, from the data processed by the ROHDE&SCHWARZ ZVA8 Vector Network Analyzer (VNA). Other peaks such as LSS and SSS signals (the converted shear wave after two reflections) were too weak to be distinguished from electronic noise. As shown in **Fig.** 3, S_{21} modulus of the impulse response of the system is compared with acoustic matching layer of 800 nm gold deposited on the mirror surfaces. Due to the limitation of ZnO film sputtering technology, we measured a dispersion of the thickness of transducers on the whole wafer and lead to the dispersion in the values of the gain with coating layers. The central frequency of the transducers fabricated had a central frequency varying from 0.8 GHz to 1.2 GHz. The 800 nm gold layer is matched for 800MHz acoustic transducers thus there will be a low impact on the gain depending on central frequency dispersion.

The gain and bandwidth ratio of Au and SiO_2 are compared as shown in **Fig. 3 (a-b)**. For the signal performance after gold coating, the gain of amplitude of LLL echo in S_{21} in time domain(in comparison to the reflections on silicon mirrors without any coating layer) varied from 7.22 to 8.72 and shows that the conversion mode from longitudinal to shear wave was limited and most of the longitudinal wave energy were kept. The increase of amplitude of the LLL signal reached 18 dB. Theoretically the bandwidth will be smaller after the gold matching layer coating on mirrors and the ratio should be lower than 1. However, the factual bandwidth ratio we obtained varies from 0.55 to 1.42. This phenomenon can be explained by the central frequency shift of the transducer (depending on the position on the wafer due to sputtering technology) as acoustic wave a reflected by the gold layer. we observed that as the bandwidth is enlarged when the central frequency of the transducer is shifted, but the gain then becomes lower.

For the performance of signal on mirrors with SiO_2 coating, the S_{21} gain of acoustic amplitude ranged from 5.4 to 9.2 which had a stronger dispersion. The differences of results are not only due to the central frequency of the transducers dispersion, but also due to the SiO_2 layer inducing partial adhesion on the 45° mirrors, as shown in **Fig. 3-c**.

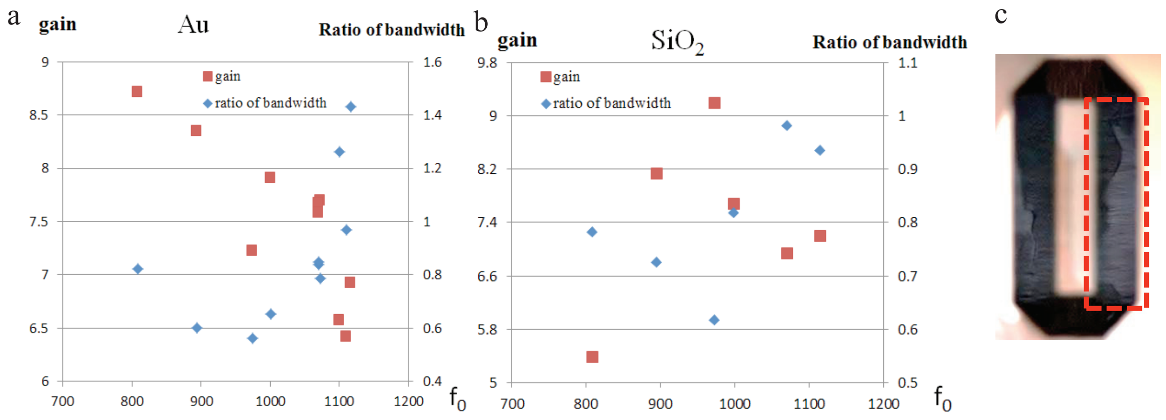

Fig. 3. Gain and bandwidth ratio comparison: a) with 800 nm gold layer introduction; b) with 3.8μm SiO_2 layer; c) SiO_2 film partially lift-off. f_0 is the experimental central frequency of transducer.

As the thickness of SiO_2 layer reaches above 3 μm, the inhomogeneity of the layer thickness also increased due to the internal stress. This partial adhesion of the SiO_2 layer surface will lead to acoustic wave scattering and introduce phase noise on the acoustic wave. Besides, for low frequency applications, such as at 300 MHz, the thickness of matching layer require multiple thickness compared to coating layer thickness at 1GHz frequency. Thus 10 μm SiO_2 film would be fabricated with a near impossibility to reach in our present technology. At 300 MHz, the 1.8μm gold layer is needed which can be easily obtained by sputtering and the homogeneity of the film thickness can be certified.

We concluded that the single gold film system offer a good compromise between acoustic gain and bandwidth, and the performance is comparable to multi-layer design system. The latter technology may induce stresses between the substrate and the coating, thus easily causing physical damage and inhomogeneity on the interface adhesion.

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