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Shear mode AlN thin film electro-acoustic resonant sensor operation in viscous media

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Abstract

A shear mode thin film bulk acoustic resonator (FBAR) operating in liquid media together with a microfluidic transport system is presented. The resonator has been fabricated utilizing a recently developed reactive sputter-deposition process for AlN thin films with inclined *c*-axis relative to the surface normal with a mean tilt of around 30°. The resonator has a resonance frequency of around 1.2 GHz and a *Q* value in water of around 150. Sensor operation in water and glycerol solutions is characterized. Theoretical analysis of the sensor operation under viscous load as well as of the sensitivity and stability in general is presented. The theoretical predictions are compared with experimental measurements. The results demonstrate clearly the potential of FBAR biosensors for the fabrication of highly sensitive low cost biosensors, bioanalytical tools as well as for liquid sensing in general.

Keywords: Thickness mode resonator; Quasi-shear polarized acoustic wave; FBAR; AlN; Tilted films; Biosensor

1. Introduction

In recent years, the thin film electro-acoustic technology has made substantial progress particularly in view of high frequency Thin film bulk acoustic resonators (FBAR) for filters in telecom applications. The driving force behind the development of the thin-film technology has been the need to replace the use of expensive single crystalline substrates in the lower GHz region with piezoelectric thin film materials which would provide a wider choice of substrate materials and the prospect of mass production of low cost components integrated with the associated electronics. Reactive sputtering is a commonly used method for the deposition of thin films, since it is compatible with the planar technology in addition to being a low temperature technique with excellent thickness uniformity. A number of attempts to utilize FBAR devices for different sensor applications, including both gaseous and liquid phase sensing, have been reported in the last decade [1,2]. They report of limited success for in-liquid operation since they have been restricted to the longitudinal mode of operation which results in acoustic energy being radiated out into the liquid through compressional motion. The shear polarization has proven to be the preferred choice for liquid operation of bulk acoustic resonators as well as of plate mode and surface acoustic resonators. Shear acoustic waves do not produce any compressional motion into the liquid and thereby no energy leakage [3]. Quite recently, it was reported of a low temperature reactive sputter deposition process for AlN films with a 30° tilt of the *c*-axis, which does not require any additional hardware modification and is completely independent of the properties of the substrate as well as is characterized with an excellent tilt uniformity [4]. It has also been demonstrated experimentally that the inclined AlN thin films grown with the latter process are suitable for the fabrication of shear mode TFBARs for liquid phase mass sensors such as biosensors and that mass loading from different concentrations of albumin could be resolved [5].

One of the most successful examples of electro-acoustic liquid phase sensors has been the commonly used quartz crystal microbalance (QCM) [6]. There are, however, a number of significant differences between the QCM and the FBAR sensors as follows.

First of all, the frequency of operation of FBARs is typically about 200 times higher than that of QCM. Most generally, this leads to a much higher mass sensitivity, as the latter is a square function of the frequency. Another frequency dependent

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effect is the acoustic wave attenuation, normally considered as an absorption process due to material viscosity. For most of the materials the acoustic wave attenuation increases with the square of frequency leading to a quality factor degradation directly proportional to the frequency of operation. Thus, the beneficial effect of the increased sensitivity on the resolution at high frequencies is moderated by the increased device instability [7]. In other words, these frequency dependencies have a significant impact on the overall sensor resolution [7] and a trade-off is to be pursued.

Secondly, FBARs are generally made of polycrystalline materials, which introduce some uncertainties in the materials properties.

Thirdly, because of the significantly higher frequency of operation FBARs are much more thinner than QCM making them more fragile and susceptible to external loadings. Further, the thickness of the piezo-material becomes comparable with that of the electrodes, which in turn makes the FBAR heavily loaded with a non-piezoelectric material, thus presuming a significant impact of the electrode material and thickness over the sensor performance. Hence, the latter will lead to substantial deviations in the frequency shift due to viscosity variations (see below) from the Stockbridge–Kanazawa theory [8,9]. A more precise theoretical treatment, based on the Nowotny–Benes model [10], including the influence of the electromechanical coupling as well as that of the electrodes and the acoustic wave polarization angle is provided inhere. In this analysis the damping due to viscous loads is specifically addressed since its understanding will allow FBAR design optimization for in-liquid operation in view of improved sensitivity-to-noise ratio. The theoretical calculations are compared with experiment.

2. Experimental

2.1. Fabrication

Standard FBAR structures with a tilted AlN film were fabricated on 4 in. Si wafers using the reactive sputtering process presented in [4]. The bottom (and eventually the top) 200 nm thick Al electrodes were patterned with standard lithography and dry etching processes. Next, a 2 μm thick AlN film was deposited and subsequently patterned to open contact holes to the bottom electrode from the top side. The overlap between the top and bottom electrode defines the active area of 300 μm × 300 μm within which the acoustic wave is excited. The top electrode has an asymmetric geometry to suppress the lateral excited modes [11]. Figs. 1 and 2 show a schematic of the resonator in cross-section as well as top view of the fabricated resonator respectively. Finally, the silicon wafers are etched from the backside, thus defining the freestanding thin film membrane. This is done both to isolate the resonator acoustically from the substrate as well as to create a cavity underneath the resonator containing the liquid to be analyzed. The cavity is further connected to the top Si surface through a series of horizontal and vertical channels, which form the microfluidic transport system for analyte delivery to the bottom electrode of the resonator, see Fig. 3.

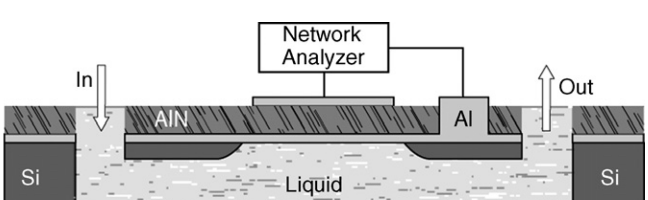

Fig. 1. Schematic illustration of a shear mode FBAR resonator together with a microfluidic transport system.

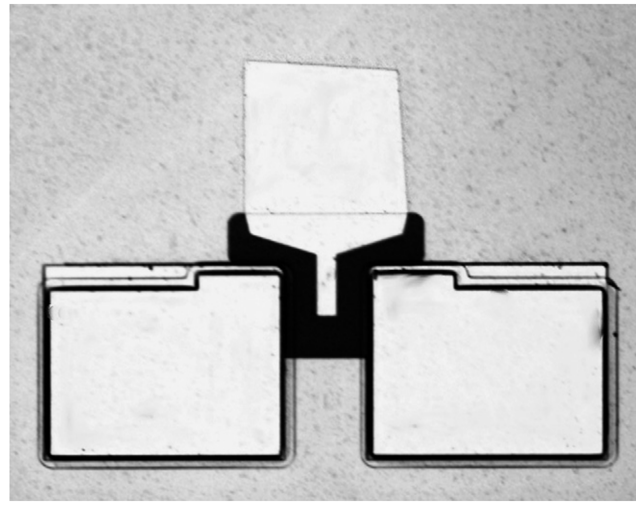

Fig. 2. Top view of the resonator. The ground contact pads are connected via contact holes to the bottom electrode, while the signal contact pad in the middle is connected to the top electrode.

2.2. Electrical characterization

One port electrical characterisation was performed with a HP 8720D network analyzer by measuring the resonator admit-

Fig. 3. Photographic image of the measurement set-up. The probing to the contacts is performed with a pico-probe seen at the bottom of the photograph. The inlet and outlet pipes seen on either side of the pico-probe are connected to the microfluidic channel system of the resonator via an o-ring seal.