Design and Experimental Studies of Gallium Arsenide Bulk Acoustic Wave Transducer Under Lateral Field Excitation

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***Abstract*— We have decided to develop high sensitive piezoelectric sensors in Gallium Arsenide (GaAs) for biological detection in liquid environment. The lateral field excitation is used to generate bulk acoustic waves through GaAs(001) membranes. This crystallographic plane is used to obtain the highest coupling coefficient. Gallium Arsenide presents interesting alternative to quartz crystal concerning resonant biosensors thanks to its piezoelectric, acoustic properties, and its common micro-fabrication processes. This study opens up new opportunities to fabricate high sensitive sensors using low cost microfabrication processes.**

Keywords—Gallium Arsenide; Transducer, Bulk Acoustic Wave; Microfabrication

I. INTRODUCTION

Thickness shear wave transducers are often used for biological sensing. Most of these resonators are in quartz crystal such as the famous Quartz Crystal Microbalance (QCM) commercially available. The Q-Sense E4[1] of Q-Sense company is probably the best example of the effectiveness of that instrument. Poitras[2] et al detects *Escherichia coli* bacteria with QCM-D technology of Q-Sense until 3 x 10^5 bacteria/ per mL. Quartz benefits high frequency temperature stability[3]. However, quartz micromachining is not so easy and it’s a major constraint for complex devices. GaAs is very common in the field of microelectronics (e.g. High-electron-mobility transistor in GaAs-AlGaAs heterojunction) and optoelectronics (e.g. laser diode). In addition of these interesting optical and electronic properties, Gallium Arsenide has also piezoelectric properties comparable with those of quartz[4], [5]. Unlike it, GaAs has the possibility to be micromachined in advanced micromachining technique such as Silicon. This offers opportunities of miniaturization and batch fabrication, relatively interesting for the production of low cost and efficient devices. It has rather good mechanical properties, such as a better fracture strength than quartz[4], what makes it an ideal candidate for acoustic transducers. And finally, another attractive feature is the ability of direct biofuntionalization of its surface, that’s useful for any biosensing or chemisensing applications. The use of Gallium Arsenide (GaAs) as piezoelectric material promises good prospects for resonant devices[6], [7].

Commonly shear wave excitation, in most QCM devices, is induced by two electrodes placed on each side of the quartz crystal; this is called thickness field excitation (TFE). There are some limitations when the device is used as biochemical or chemical sensor in liquid. In that case the need to have metal electrodes at the surface interacting with the medium to be investigated is a restriction. Electrodes and excitation mode of the sensor can therefore become a critical design factor. Lateral Field Excitation (LFE) [8]–[10] which is characterized by two electrodes on the same surface can overcome that limitation. Quartz microbalance with lateral excitation has been successfully tested in liquid and are operative for biological detection as proven by York[11] and Hu[12]. It offers a higher Q value over TFE device and also a better stability.

In this paper, we expose the optimization of the design of the GaAs transducer. Then we demonstrate the possibility to process GaAs microdevice using common and low cost microfabrication procedure in a few steps. The device geometry obtained after process is accurately characterized. Finally, impedance measurements on resonant devices are discussed.

II. DESIGN

A. Background

The geometry of the resonator was designed to facilitate analyses in liquid environment. The device is composed of a resonant membrane excited by a lateral field. This electrode configuration allows us to separate the electric part from the liquid area. The thickness shear mode of vibration is used to limit the propagation into the liquid and then reduce the energy loss. Moreover, relatively high resonant frequencies are used with these modes improving the sensitivity of the device. These shear modes, called *m*, can be generated in the membrane for specific crystallographic orientations of substrate and orientations of electric field. Thanks to an analytical model based on the Christoffel-Beckmann method, we determined the

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best configuration to reach highest electromechanical coupling coefficient k_m. The (100) is preferred and the [110] electric field orientation allows us to obtain the highest value of k_m = 6.7% [13]. Fig. 1 shows the slowness curves of the three waves propagating in the (100) GaAs plane. The slowness curves were obtained using the GaAs parameters given in 0The curves show the symmetry of the crystal in the (100) plane. According to piezoelectric constants, the quasi-longitudinal wave, called a-mode, cannot be excited by a lateral electric field whatever the orientation in the (100) plane [13] On the contrary, b- and c- modes (quasi-shear modes) can be excited and the maximum value is obtain when the electric field is aligned along the $[0\ \bar{1}\ 1]$ or [0 1 1] direction.

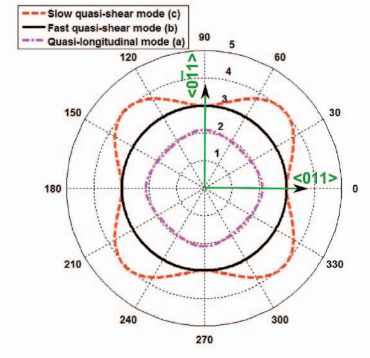

Fig. 1. Slowness curve of GaAs(100) plan

The resonant frequency f_R is given by eq.1 and for the [110] electric field orientation no coupling occurs between the different thickness shear modes of vibration.

$$f_R = \frac{n}{2t_{me}} v_m \left(1 - \frac{8k_m^2}{n^2\pi^2}\right)^{\frac{1}{2}} \qquad (1)$$

where t_{me}, v_m and n are the thickness of the membrane, the velocity of the selected mode *m* and the positive odd number respectively.

TABLE I. PHYSICAL PROPERTIES OF GALLIUM ARSENIDE

Properties		Gallium Arsenide	
		Values	***Ref.***
Stiffness constants [GPa]	c_{11}	118.8	[14]
	c_{12}	53.8	
	c_{44}	59.4	
Piezoelectric constant [C/m^2]	e_{14}	-0.16	
Permittivity [F/m]	ε	$9.73 . 10^{-11}$	
Density [kg/m^3]		5.307	
Isotropic loss		0.02	[15]
Velocity [m/s] Propagation direction [100]	Long.	4735	[14]
	Trans.	3347	
Coupling coefficient	k_m	6.7 %	[13]

B. Device Geometry

As explained in the last section, the device is excited by a lateral electric field. Both electrodes are then situated on the same side (Fig. 2). The total thickness t_w of the wafer is about 625 µm. As the resonance frequency depends on the membrane thickness t_{me}, if we want to have a fundamental resonant frequency situated between 20 to 40 MHz, the value of t_{me} must be in the range [40µm 80µm]. In our work, by taking into account the constraints of microfabrication, the thickness is limited to 50µm. The associated theoretical resonant frequency is then f_R = 34.65 MHz. The membrane is embedded to trap the energy inside it and avoid any attenuation of the amplitude of vibration at the resonance frequency A small cavity, sealed by a glass cover on the bottomside, will be used for fluid circulation in further studies.

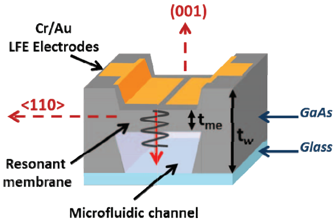

Fig. 2. Schematic of the resonant device

III. MICROFABRICATION

A. Microfabrication steps

First, Gallium Arsenide crystal surface should be cleaned and etched to remove any metallic or organic contaminants. Organic solvent as Acetone and Ethanol were used with sonication for a few minutes each to remove most of organic contamination (Fig. 3). Ammonium hydroxide solutions (NH_4OH) are often employed to eliminate greasy residues and metal ion contaminants[16]. A further advantage is that NH_4OH eliminates native GaAs oxide. Therefore, this precleaning step can improve etch reproducibility in the initial etch step thanks to the control in native oxide thickness[17]. Moreover ammonium hydroxide keeps the initial stoichiometry of the material.

The resonant element of the device is a thin membrane directly integrated inside the bulk crystal. Our GaAs wafer is 625 ±25 µm thick and should consequently be etched to reach a membrane thickness which is between 50 to 100 µm. In order to obtain a flat and undamaged surface, an anisotropic wet etching is preferred. The main advantage of wet etches to dry etches is their ability to cause no change in mechanical or physical properties on and just beneath the surface. There are many different etchants that have been employed to etch anisotropically GaAs, but orthophosphoric acid based solution provides very smooth[13], [18] surfaces and a control of etch depths at the level of tens angstroms[17].The etching solution is composed of an oxidizer and an acid (or a base) respectively H_2O_2 and H_3PO_4 in our case. Ga and As oxide were formed by oxidation of GaAs with H_2O_2 solution following by the dissolution of these elements by chemical attack with H_3PO_4.

According to previous studies in our group [13] the best ratio is 1 H_3PO_4 : 9 H_2O_2 : 1 H_2O at 0°C which gives smooth and flat membranes even for long etching. Solution is mixed during the process with a magnetic stirrer at 200 rpm. The etch rate is then around 0.95 $\mu m.min^{-1}$. A thick photoresist (4 µm) is used as mask for wet etching.

After etching, a positive photoresist is sprayed with a spraycoater (thickness of 7 µm) for a lift-off process. A few nm of chromium and then 400 nm of gold are deposited on the structured GaAs surface by sputtering.

Finally the same etching step as previous is used on the bottom side for a longer time.

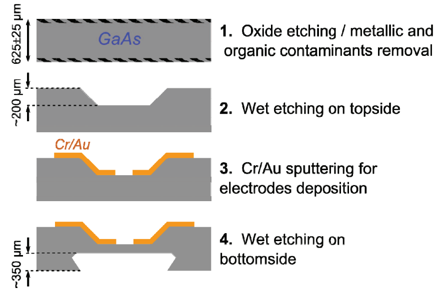

Fig. 3. Microfabrication flow chart

B. *Profile and characterization*

The orthophosphoric based solution etches anisotropically Gallium Arsenide. In this material, there are two different and chemically inequivalent (111) planes. The (111)A plane composed on a top layer of Ga atoms and the (111)B composed of As atoms. Commonly, the (111)A plane etches with a factor 2 - 5 slower than other faces ((100), (110) or (111)B) [17].

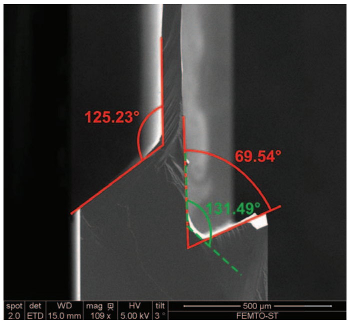

Fig. 4. SEM image of membrane cross section

The profile at the edge of the membrane is determined by the plane which have the lowest etch rates in the cross sectional plane of the surface ((110) plan).

A membrane cross section was investigated with Scanning Electron Microscope (SEM) to measure accurately angles of planes involved in the cross sectional plane (100) (Fig. 4). We note that angles of IF and OF planes are not complementary

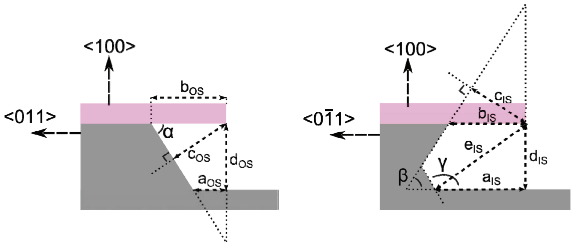

Fig. 5. Crystallographic etch profiles for GaAs(100) along <0 $\bar{1}$ 1> (a) and <0 1 1> (b) direction

A theoretical model of the geometry (Fig. 5) was created for calculation, needed for modeling resonance of the membrane. Particular lengths were calculated such as the under-etched length:

$$b_{OS} = \frac{d_{OS}}{R_{OS}\sin(\alpha)} \qquad (2)$$

Where R_{OS}, d_{OS} and α are respectively the anisotropy ratio, the depth of the etching and the angle of the (111)A plane with (100) plane.

This induces specific etching shapes at the edge of the membrane. Along the <0 1 1> direction facets are outwardly oriented (OF) whereas inward facings (IF) are developed along <0 $\bar{1}$ 1> direction. This geometrical configuration is the opposite on the bottom side. One of the delicate steps in process is electrodes deposition by gold sputtering. Gold tracks must cross the membrane edge in one single direction: the direction of outwardly oriented plane (Fig. 6).

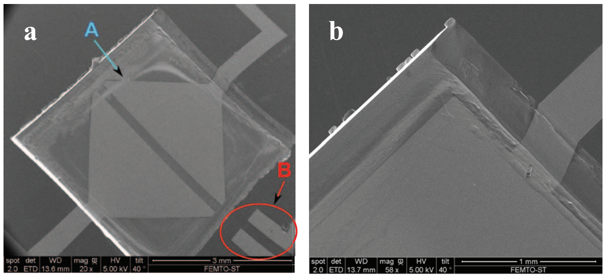

Fig. 6. SEM pictures of membranes upper face with gold electrodes

IV. VERIFICATIONS OF ACOUSTIC MODES

The experiment consists to measure impedance versus frequency and identifies resonant modes. As we said previously resonance frequency is entirely dependent on the thickness of the device. However, electrodes on the device excite not only bulk acoustic wave (BAW) into the membrane but also BAW in the substrate. A methodology was implemented to identify and discriminate membrane shear waves from overtone of the substrate resonance. Fig. 6a shows SEM image of the device upper face, each transducer is composed of two pairs (A and B, Fig. 6a) of electrodes, one of which (B, Fig. 6a) located on the substrate, is used to identify substrate modes. Indeed high overtone substrate modes (9th to 12th overtone) are located in the same frequency range as membrane modes (Fig. 7). And another pair of electrodes excites the membrane; we can, in this way identify membranes modes. The multitude of resonance around the fundamental membrane mode is explained by the variation in the membrane thickness.

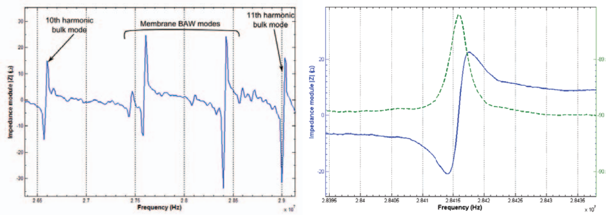

Fig. 7. Impedance versus frequency curves of substrate and membrane modes

In the TABLE II. , impedance modes measured previously are compared with theoretical values. These values are calculated with thickness ofmembrane and bulk which are obtained by profilometry. A quality factor of around Q = 8119 is reached for a membrane resonance at 27.99 MHz.

TABLE II. THEORETICAL AND MEASURED VALUES OF MEMBRANE AND SUBSTRATE RESONANCE

		Theoretical		**Experimental**	
		Frequency (MHz)	***Measured thickness (µm)***	***Frequency (MHz)***	***Corresponding Thickness (µm)***
Substrate resonance overtone	10th	26.65	617	26.59	631.86
	11th	29.32		29.02	
Membrane Resonance		27.99	59.6	28.42	58.88

CONCLUSION

We have determined the design of a bulk acoustic wave sensor in Gallium Arsenide which could be used for biochemical applications where the electronics part is separated from the liquid medium. This sensor was manufactured with collective and low cost techniques. The wet etching of Gallium Arsenide at low temperature is the most effective strategy to control thickness of etched membranes. In addition, the process has allowed us to make smooth and flat structures. Impedance measurements of resonance were investigated and the Q value obtained for fundamental membrane mode is quite good. Prospects of our work are to perform analyses in liquid medium. And then we will include a biofunctionnalized layer on the transducer for biological interaction measurements.

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