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Fully integrated FBAR sensor matrix for mass detection

K. Tukkiniemi\textsuperscript{a}, *, A. Rantala\textsuperscript{a}, M. Nirschl\textsuperscript{b}, D. Pitzer\textsuperscript{b}, T. Huber\textsuperscript{b}, M. Schreiter\textsuperscript{b}

\textsuperscript{a}VTT Technical Research Centre of Finland, Tietotie 3, Espoo, FI-02044 VTT, Finland
\textsuperscript{b}Siemens AG, Corporate Technology, Otto-Hahn-Ring 6, 81739 Munich, Germany

Abstract

A fully integrated Film Bulk Acoustic Resonator (FBAR) based mass detection sensor matrix was developed for label-free in-vitro DNA and protein diagnostics. A 64 pixels sensor matrix was post-processed on top of a CMOS readout circuitry at wafer level. A novel and patented resonance frequency detection method was developed. To our knowledge this is the first realized full integrated FBAR matrix sensor.

FBAR; full integrated; mass sensor matrix; CMOS; bioelectronics

1. Introduction

Commercially available sensor systems for bio-molecules today are mainly based on optical detection techniques. Besides complex and expensive optical readout, usually expensive biochemical labeling of the molecules being detected is necessary. Although label-free optical methods do exist, these methods are expensive, and in many cases also not suitable for highly sensitive detection, as needed with certain hormone and cancer diagnostics. For a point of care (POC) system label-free detection techniques other than optical are desired. Film Bulk Acoustic Resonator based sensor technology provides a high sensitive label-free approach. The selectivity is achieved by local surface functionalizations providing both a high specific binding of target molecules and a sufficient suppression of unspecific binding. The decisive advantage of the FBAR technology over present available quartz crystal microbalances which are based on the same detection principle is the possibility to implement a considerable number of small resonators on one chip which enables multiplex sensing e.g. in medical diagnostics.

2. FBAR sensor element

Figure 1 shows a simplified schematic of the integrated FBAR. The resonator is formed by a piezoelectric thin film embedded between a top and bottom electrode. The electrodes are contacted to the CMOS integrated sensor read-out. Contact lines and electrodes are passivated from the surrounding fluids. As template for a biochemical surface functionalization, a thin Au layer is deposited on the top.

* Corresponding author. Tel.: +358-40-721 0370; fax: +358-20-722 7012.
E-mail address: kari.tukkiniemi@vtt.fi.

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Acoustic vibrations are excited by applying an alternating electric field across the piezoelectric layer. The acoustic resonance frequency is mainly determined by the acoustic impedance and dimension of thin films in the acoustic path of the resonator. To prevent a dissipation of the acoustic energy into the substrate and reflections from the wafer backside an acoustic mirror is implemented consisting typically of pairs of $\lambda/4$ thin films with high and low acoustic impedance, respectively. The acoustic isolation at the top depends strongly on the surrounding medium and the excited acoustic mode which is determined by the film texture with respect to the electric field orientation. Inherently, typical piezoelectric materials such as AlN and ZnO grow very well c-axis textured on metal electrodes, i.e. the c-axis is perpendicular oriented to the resonator surface. For the resonator design as given in Fig. 1, this enables a pure longitudinal thickness mode operation only. This mode is well applicable to sensors in gaseous ambience. In liquids, however, which is of interest in biosensor applications the resonator will be severely damped resulting in poor Q-factors and low resolution. To overcome this problem, a thickness shear mode operation is required. Opposite to the longitudinal mode, for shear mode relatively high Q-values and thus higher resolutions are maintained due to the poor acoustic coupling of shear waves to the liquid. To achieve a shear wave excitation for the given FBAR configuration, a parallel inclination of the c-axis is needed. Remarkable shear coupling occurs for inclinations of larger than $10^\circ$ already.

A dedicated process for the deposition of piezoelectric ZnO thin films suitable for shear mode excitation was developed [1], optimized with respect to homogeneity and reproducibility and implemented in a back-end processing of shear mode resonators on active CMOS wafers (Fig. 2, 3). The complete process was shown to be...
CMOS compatible and full functionality of monolithically integrated shear FBARs was proved. A typical effective shear coupling $k_{\text{eff}}$ of approx. 0.14 and a parallel Q-value of about 250 in air and 150 in water, respectively, was derived by fitting the measured impedance characteristics to the BVD-model. The mass resolution was found to be about 1ng/cm².

3. Read-out

Oscillator based resonance frequency detection is a common method but FBAR impedance analysis is a more robust technique when FBAR sensor is employed in liquid atmosphere. Published [2] designs utilize a direct digital synthesis, where a test signal is generated using DSP, D/A-converted and the corresponding power is measured. This leads to a highly complex circuitry and the maximum frequency band is quite limited. The importance of a simple method is emphasized when the impedance analysis is utilized for a sensor matrix.

A novel, simple, but accurate impedance detection method was developed at VTT (patent pending). The core part of the analyzer is a voltage-controlled-oscillator (VCO). VCO frequency is swept over large frequency band and FBAR impedance response is acquired from the VCO output, Fig. 4. A dedicated algorithm resolves the series and parallel resonance frequencies. Read-out chip was fabricated in AMS 0.35µm CMOS process.

Detection limit is set by noise and drift caused by sensor and read-out. The noise-to-carrier ratio of the oscillator is inversely proportional to the product of resonator Q-value and the power consumed, and directly proportional to the oscillation frequency. Power consumption is limited by the sensor self-heating phenomena caused by the integrated electronics underneath sensor matrix. Self-heating will drift FBAR resonance frequency due to the temperature sensitivity of the sensor. Self-heating effect is minimized when time of a single measurement event is kept shortest possible. On the other hand white noise is decreased when number of measurement events is increased and results are averaged out. Working balance between drift and noise level must be found.

Fig. 5 shows resonance frequency measurement results from one pixel. Measurement is done with optimum measurement procedure and 100 results are displayed. At the beginning of the measurement resonance frequency has thermal induced drift but it stabilizes after 20 measurement events. Standard deviation for noise and drift calculated from the last 10 measurements is 3.6 kHz. Fig. 6 shows noise and drift difference between optimum and fast measurement procedure. Measurement time in the fast case was 1s and 5s in the optimum case for the whole 64-pixel matrix. By increasing measurement time five times the combined noise and thermal drift is decreased 25 times. Remaining drift is smaller than system’s noise level. By using optimum measurement procedure the heating effect was minimized without sacrificing too much measurement speed and noise level. Noise level is very much dependent on sensor quality. The best measured noise and drift was 2.4 kHz.
4. Measurements

First initial test of the system demonstrator, Fig. 7, proved the full functionality, i.e. the controlled interaction of the system components, in particular integrated sensor chip, packaged cartridge, fluidic, and user interface including data read-out and measurement control. In order to benchmark the performance of the integrated FBAR a measurement in liquid environment was performed. Bovine serum albumin in PBS buffer was rinsed over the sensor in concentrations increasing from 0.001 to 1 mg/ml and compared with the results received for the passive FBAR, i.e. the FBAR read-out using a network analyzer. Both read-out methods show equal behavior in the BSA solution. Having comparable noise and mass sensitivity, the limit of detection is equal, i.e. 1 ng/cm² for the both systems. This measurement procedure and the determination of the detection limit are described in detail in [3].

Fig. 7. Measurement system with a manual analyte injection.

Fig. 8. Frequency shift for different concentrations of BSA on the passive FBAR and the CMOS-integrated FBAR.

5. Conclusion

64-pixel FBAR sensor array post-processed on top of CMOS circuitry was implemented and its functionality was shown with bio-measurements. Film Bulk Acoustic Resonator based sensor technology provides a high sensitive label-free detection method for bio-medical applications. This work demonstrates the possibility to implement a considerable number of small resonators on one chip which enables multiplex sensing e.g. in medical diagnostics.

References

1. M. Link, M. Schreiter, J. Weber, R. Primig, D. Pitzer, R. Gabl. Solidly mounted zno shear mode film bulk acoustic resonators for sensing applications in liquids. IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, vol. 53, no. 2, February 2006, pp 492–496.

2. Schneider, T.; Doerner, S.; Hauptmann, P.R.; Richter, D.; Fritz, H. Fast impedance analyzer interface with direct-sampling-technique for highly damped resonant gas sensors. Sensors, 2005 IEEE; Oct. 30 2005-Nov. 3 2005, Page(s):4 pp.

3. M. Nirschl, A. Blüher, C. Erler, B. Katschiner, I. Vikholm-Lundin, S. Auer, J. Vörös, W. Pompe, M. Schreiter, M. Mertig, Film bulk acoustic resonators for DNA and protein detection and investigation of in vitro bacterial S-layer formation, Sensors and Actuators A: Physical, In Press