Influence of thickness nonuniformity of piezoelectric zinc oxide layer on parameters of microelectronic BAW solidly mounted resonator

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Abstract. The paper presents the experimental results of a study of the influence of the thickness nonuniformity of a piezoelectric zinc oxide films on electrical equivalent parameters of microelectronic BAW resonators: the static and dynamic capacitances, dynamic inductance, and dynamic resistance. These parameters were determined using the experimental frequency dependences of resonator impedance and the Butterworth-van Dyke model. The resonators under investigation had an operating frequency of 2.8...3.0 GHz; the frequency spread about 500 MHz. The quality factor of the resonators was 250...350 and the relative width of the resonant bandwidth of the resonators were equal to 0.2...0.4%.

Keywords: bulk acoustic wave, solidly mounted resonator, magnetron sputtering, zinc oxide, electrical equivalent parameters

1. Introduction
The modern technology of mass production of microelectronic devices including magnetron deposition of multilayer thin-film structures involves the use of dielectric substrates 60x48 mm$^2$ or more and the dimensions of the devices are 1.5x1.5 mm$^2$. As a result, the electrophysical properties of thin films (for example, surface resistance, layer conductivity, etc.) may change [1-2].

Possible reasons for the occurrence of nonuniformity in the layers thickness include: the quality of the substrate material, the quality of the substrate washing before sputtering, the percent depletion of the target material, the design and technological possibilities of the magnetron sputtering installation (configuration and magnitude of the magnetic induction of the magnetron, the configuration of the correcting diaphragm, the distance from the target to the substrate, etc.). Such nonuniformity has a great influence on the operation of microelectronic devices working in the microwave range, in particular, thin-film resonators based on bulk acoustic waves (BAW). The nonuniformity in the film thickness leads to a change in the operating frequency of the device and in some cases to the impossibility of using resonators as part of a finished product [2-5].

The most sensitive to changes of the layers thickness is a microelectronic BAW resonator with a Bragg reflector called a solidly mounted resonator (SMR). The SMR is a multilayer structure and its design contains up to 15 thin-film layers. A change in the thickness of each layer of a Bragg reflector leads to a change in the conditions for the reflection of bulk acoustic waves in its structure [6-8]. Due to the wide bandwidth of the Bragg reflector, the shift of the resonant frequency has the weak effect on the performance of the reflector. However, additional difficulties arise when the thickness of the piezoelectric film changes. In this case the resonant frequencies of the BAW resonator are shifted. As a consequence, it is required to use the additional technological operations for controlling of the resonator frequencies and bringing them to the nominal value.
It is known that a change in the design parameters of the resonator leading to a shift in its operating frequency affects the dynamic parameters of the resonator. For particular problems, stringent requirements can be set for limiting the certain dynamic parameters of resonators, for example, for the dynamic inductance. Knowing the nature of the change in dynamic parameters, it is possible to optimize the thickness of the resonator layers. Until now, this issue has not been considered in detail. In this regard, the purpose of this work is to study the effect of the thickness of a piezoelectric zinc oxide film on the frequency characteristics and the equivalent electrical parameters of a microelectronic BAW SMR.

2. Method of experiment
To study the effect of nonuniformity thickness of a piezoelectric zinc oxide layer on the electrical characteristics of a microelectronic BAW SMR, the design of resonators with different areas of the upper electrode in the range from 0.01 mm² to 0.04 mm² was developed. The structure of the resonator is a CT-50-1 sitall substrate, on which layers of a Bragg reflector based on five pairs of layers of molybdenum and aluminium films and layers of a piezoelectric transducer based on zinc oxide films and aluminium electrodes are applied. Thin-film layers of the resonator were deposited by the magnetron method in a single technological cycle. The distance from the target to the substrate was 70 mm. The target had a size of 160x70 mm². The thickness of the thin-film layers was controlled by the resonance method with an accuracy of 0.1%. The thicknesses of the BAW resonator layers were calculated for an operating frequency of 2.9 GHz. After deposition of the multilayer structure of the resonator, the configuration of the upper electrode was formed using a photolithography operation.

The electrical parameters of the resonators were investigated using an E5071C vector network analyzer (Agilent Technologies) in the frequency range from 100 MHz to 8 GHz in the reflection mode (measured parameter S11). Before all measurements to eliminate the parasitic influences of the frequency characteristics of cables and microwave probes the measured parameters are corrected with a calibration board CSR-15 Cascade Microtech.

The dynamic parameters of the resonator were determined according to the Butterworth-van Dyke model with using the algorithm described by the authors in [9]. In conformity with the Butterworth-van Dyke model, the equivalent electrical circuit of the BAW resonator includes static (C₀) and dynamic (Cₑ) capacitances, dynamic inductance (Lₑ) and dynamic resistance (Rₑ). The static capacitance of the resonators was measured using an E5071C network analyzer according to the Wolpert-Smith diagram at a frequency of about 100 MHz. The quality factor of the resonators was determined from the frequency dependence of the active conductivity of the BAW SMR. Measurement of the upper electrode dimensions was carried out with a KN-8700 high-resolution video microscope.

3. Results and their discussion
On the basis of the developed design and technology, the prototypes of resonators were made. These resonators operated at frequency of 2.6...3.1 GHz and had a quality factor of 250...350. Their resonant bandwidth was 8...14 MHz. The external view of the cross section of microelectronic BAW SMR is shown in Fig. 1.

After fabrication of the resonators the substrate was divided into modules. Each module contained 8 resonators with a different area of the upper electrode (Sₑ). In this work, 30 modules with resonators fabricated in one technological cycle were investigated.

Figure 2 shows typical frequency dependences of the active conductivity (G) and the modulus of electrical impedance (|Z|) of a resonator based on a piezoelectric zinc oxide film. The series resonance frequency of this resonator is 2.803 GHz, the resonant bandwidth of the SMR is 11.3 MHz and the Q factor is 332. The maximum value of the active conductance corresponds to the frequency of series resonance and is equal to 8.43 mS. The modulus of electrical impedance at the frequencies of series and parallel resonances is 44.3 ohms and 64.1 ohms, respectively.
Figure 1. Topology (a) and cross section (b) of microelectronic BAW SMRs having a different area of the upper electrode.

Figure 2. Frequency dependences of active conductivity (a) and modulus of electrical impedance (b) of a microelectronic BAW SMR based on zinc oxide films.

After recording all the electrical characteristics of the BAW resonators, the experimental results were processed according to the algorithm presented by the authors in [9]. The thickness of the zinc oxide film was determined from the serial resonance frequency of BAW SMRs. Based on the data obtained, the dependences of the equivalent electrical parameters of the resonator on the thickness of the piezoelectric zinc oxide film were plotted, Fig. 3.

Figs. 3a and 3b show that with increasing the thickness of the zinc oxide film by 1.2 times, the values of static and dynamic capacities decrease by 1.23 times and 1.6 times, respectively. With increasing the thickness of the zinc oxide film by 1.2 times, the increase of the values of the dynamic resistance and inductance by a factor of 2 is observed. The general nature of the change in the static capacitance and dynamic inductance remains at different values of the area of the upper electrode of the BAW SMR. However, for resonators with an upper electrode area less than 0.0225 mm², we observe a smaller change in the values of the dynamic capacitance, in contrast to resonators with an upper electrode area from 0.0256 mm² to 0.04 mm². For dynamic resistance, we observe the opposite picture. Accordingly, for resonators with an area of less than 0.0225 mm², we have a greater change in
the dynamic resistance values, in contrast to resonators with an upper electrode area from 0.0256 mm\(^2\) to 0.04 mm\(^2\).

**Figure 3.** Dependence of the static capacitance (a), dynamic capacitance (b), dynamic resistance (c) and dynamic inductance (d) of the BAW SMR on the thickness of the piezoelectric layer with different values of the upper electrode area (1 – \(S_{el} = 0.010\) mm\(^2\); 2 – \(S_{el} = 0.0144\)mm\(^2\); 3 – \(S_{el} = 0.0169\)mm\(^2\); 4 – \(S_{el} = 0.0225\)mm\(^2\); 5 – \(S_{el} = 0.0256\)mm\(^2\); 6 – \(S_{el} = 0.0324\) mm\(^2\); 7 – \(S_{el} = 0.0361\)mm\(^2\); 8 – \(S_{el} = 0.040\) mm\(^2\)).

Thus, in the development and manufacture of microelectronic BAW SMRs based on zinc oxide films, it is necessary to take into account the technological capabilities of thin-film deposition and the possible variation of the equivalent electrical parameters of resonators.
4. Conclusion
This paper presents the results of the experimental studies of the electrical parameters of microelectronic BAW SMR from the nonuniformity thickness of a piezoelectric zinc oxide film. The obtained resonators operate at a frequency from 2.6 GHz to 3.1 GHz, the bandwidth of the resonator is 8...14 MHz, and the Q factor is 250...350.

It is shown that the increase of the thickness of the zinc oxide film by a factor of 1.2 leads to the decrease of the values of the static and dynamic capacitances by a factor of 1.23 and 1.6 times, respectively, and the increase of the values of dynamic resistance and dynamic inductance in 2 times.

The results obtained will be useful for developers of microwave frequency selection and signal generation devices, sensors and biosensors, as well as developers of other devices based on microelectronic BAW SMR.

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