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Some trends in microwave acoustoelectronics development

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1. Introduction

Progress in acoustoelectronics is associated with the development of subminiature devices intended for the formation, filtration, and analogue mathematical processing of signals. The feasibility and wisdom of such kinds of employment of acoustic waves arise from their low velocity in comparison with the speed of light. Converting an electromagnetic signal to an acoustic signal whose wavelength is 10^5 times shorter makes it possible not only to substantially reduce the dimensions of electronic devices which perform different operations on signals, but also to perform in some cases these operations in a simpler and more rational way. In this report we make a brief survey of the problem and exemplify some results of investigations obtained by the authors in the area of fabricating resonators and microwave filters that use bulk acoustic waves and developing acoustoelectronic sensors of physical quantities, which are built around such microwave resonators. Also described is an original technique of acoustic resonance spectroscopy of single crystals and thin films.

The current interest in research and development of frequency-driving and frequency-selective acoustoelectronic elements for the short-wavelength part of the microwave region stems from the increasing demand for these elements in order to modernize present-day and design radically new promising systems of global and cell communications, radar, navigational, search-and-rescue, and global space satellite systems, low-bulk atomic watches, and physical quantity sensors with wireless monitoring.

At the present time, the major part of the problems focusing on the processing and formation of signals at frequencies below 2 GHz is successfully being solved with the aid of acoustoelectronic components involving piezoelectric-based surface acoustic waves (SAWs). However, further advancement of such devices to the short-wavelength part of the microwave region is abruptly being terminated by contemporary technological capabilities of fabricating on the piezoelectric crystal surface a periodic submicron metallic electrode structure for exciting (receiving) SAWs. It turned out that for acoustoelectronic devices operating in the short-wavelength part of the microwave region it is more advantageous to employ bulk acoustic waves (BAWs) [1–3].

Modern research, including ours, in the area of developing acoustoelectronic BAW-based devices for the short-wavelength part of the microwave region is undertaken primarily along the following lines.

(1) Solution of the physical and technological problems related to the fabrication of microwave resonators for bulk acoustic waves and of composite filter structures on the basis of electrical or acoustic coupling of resonator elements.

Here, our main concern is with studying new operation principles of acoustic resonators and microwave filters, construction of the theory, analysis of the possible limiting parameters for these devices, development of their fabrication technology, and experimental verification of their working capacity. For making an impressive headway toward microwave range, of fundamental importance is the search for new low-absorption acoustic materials with a small temperature coefficient of acoustic wave delay.

(2) Development of acoustoelectronic microwave sensors of physical quantities on the basis of microwave resonators.

As our analysis suggested, it is possible to produce highly advanced sensors of physical quantities on the basis of thin-film microwave resonators. Temperature, pressure, and gas composition sensors that make use of BAW-based thin-film microwave resonators as the sensitive element have been proposed, fabricated, and experimentally investigated. These sensors exhibit a better responsivity to the factors being measured than SAW-based components. Furthermore, they are smaller in size and are compatible with microwave antennas, which makes them candidates for passive wireless sensors in systems for remote monitoring, including ecological monitoring.

(3) Development of original technological techniques required for the fabrication of acoustoelectronic microwave devices, first and foremost, the techniques for growing films and multilayer thin-film structures with prescribed acoustic and electrical properties.

(4) Development of methods for measuring acoustic parameters of thin films.

The acoustic properties of thin films of piezoelectrics and metals are, as a rule, different from the properties of bulk samples, which generates the need for their direct measurement. The widely used echo method becomes practically unsuitable in the case of thin material layers and films. A demand arose for the development of radically new methods for measuring the velocity and absorption of microwave acoustic waves in thin films and layers. We proposed and elaborated an original method of resonance microwave spectroscopy. The use of this method has also proved to be highly fruitful in the investigation of acoustic properties of several new piezoelectric materials which exhibit lower losses than the commonly used quartz and are capable of replacing it in operation at high frequencies.

Some possible solutions to the above problems are consecutively discussed below.

2. Operating principle of acoustic microwave resonators and filters employing BAWs

To the resonance frequencies of BAW-based resonators operating in the short-wavelength part of the microwave region there correspond micro- and submicrometer values of piezoelectric layer thicknesses. Owing to the brittleness of thin layers and the difficulties encountered in fabricating the layers of desired thickness, the design and technological solutions employed in making the quartz BAW resonators are unsuited for their fabrication. The search for new principles of fabricating resonators and filters has led to the development of thin-film structures and progress in their fabrication technology. Several types of BAW-based composite microwave resonators are schematically depicted in Fig. 1.

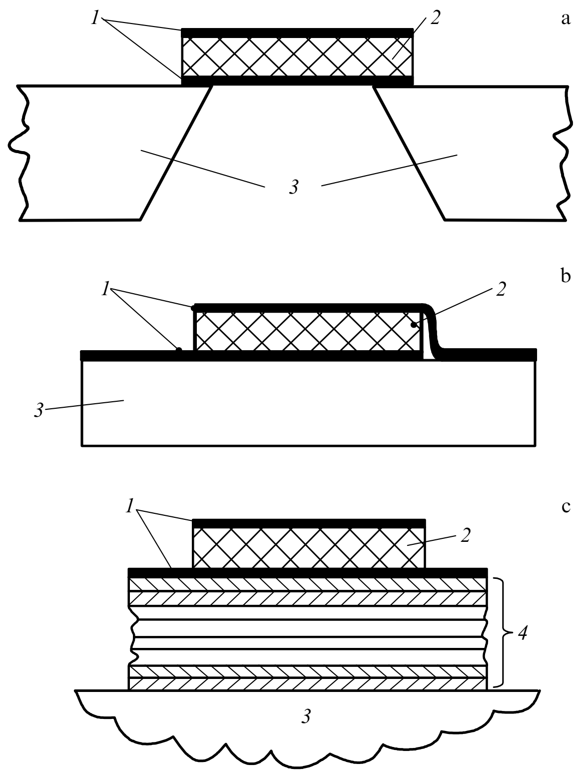

Figure 1. Different types of microwave resonators for bulk acoustic waves: (a) membrane-type resonators; (b) multifrequency resonators operating at high harmonics, and (c) resonators with acoustic insulation from the substrate. *1* — metallic electrodes, *2* — piezoelectric film, *3* — substrate, *4* — quarter-wave thin-film layered structure.

Microwave resonators of the membrane type. Figure 1a shows the structure of a thin-film resonator of the membrane type. In the English-language literature this type of resonator is referred to as the thin-film resonator (TFR). A membrane containing a thin piezoelectric film of zinc oxide or aluminium nitride is located between metallic film electrodes. Resonators of this type are fabricated on semiconductor substrates employing selective etching techniques which are widely used in silicon and gallium arsenide technologies. The virtues of this type of resonator are, first, operation on the fundamental harmonic of the piezoelectric transducer, which lies immediately in the microwave range and, second, the possibility of fabricating the resonators on a semiconductor (for instance, silicon) substrate and combining them with other electronic components fabricated on the same substrate.

The Q factor of membrane-type resonators is not high: below 1000 even at a frequency of 1 GHz. This is due to the relatively high acoustic absorption coefficients for materials on which to base membranes — silicon, gallium arsenide, zinc oxide films, or aluminium nitride.

Membrane resonators are the concern of a wealth of experimental works. In the investigation of these resonators, primary emphasis has been on the elucidation of the feasibility of making sensors of different physical quantities on their basis, for even minor external factors have a strong influence on resonator frequency owing to the small membrane thickness. On the basis of membrane structures it is possible to make impedance-type microwave filters, in which separate film resonators are used as their elements [4].

Multifrequency composite resonators. A high-overtone bulk acoustic wave resonator (HBAR) [1, 2, 5] is schematically depicted in Fig. 1b. It contains a substrate — a platelet several hundred micrometers thick, with a thin-film electroacoustic transducer on its surface. The transducer consists of a micrometer-thick piezoelectric film (ZnO or AlN) and metallic electrode films. The platelets are made of single crystals with a record-low acoustic absorption — sapphire, aluminium – magnesium spinel, lithium tantalite or niobate, or yttrium aluminium garnet (YAG) [4]. The optically polished face surfaces of the platelet are strictly plane-parallel (an error of several arc seconds is permissible). The piezoelectric film electrically links the whole resonator structure to an external circuit. In essence, these devices are high-Q acoustic analogues of Fabry – Perot resonators. This resonator is of a multifrequency type (up to several hundred harmonics of the fundamental frequency of the structure may be efficiently excited). Hundreds of acoustic half-waves are present between the plane-parallel surfaces which limit the resonator. With the aid of the piezoelectric film, the resonator can be excited at harmonics lying within a wide frequency band. The thickness of the piezoelectric film (and of the electrodes) is much smaller (several hundredfold) than that of the substrate platelet. The vibrational energy of the resonator accumulates primarily in the substrate platelet, and its Q factor is practically determined by acoustic losses in the substrate material. The substrates are made of materials

Table 1.

Material	Q factor	Frequency, GHz
Sapphire	6.5×10^3	7.6
YAG (110)	5×10^4	3.8
$LiNbO_3$ (001)	2.5×10^3	5.6

with very low acoustic absorption coefficients, and therefore this type of BAW-based microwave resonator possesses an extremely high Q factor. The typical Q factors attained for the multifrequency resonator are given in Table 1.

In an electric circuit, the resonator can be excited at one of the higher harmonics selected. A small frequency tuning is possible by changing the capacitance connected in series with the resonator-containing circuit, which opens up the ways to compensating for frequency departures, fine tuning, and microwave oscillator frequency locking [6]. Therefore, multifrequency resonators are candidates for microwave frequency synthesizers with electronic oscillation frequency switching and for low-noise locked microwave oscillators operating directly at frequencies in the decimeter and centimeter ranges.

In developing the microwave resonators it is important to know the real values of the absorption coefficient and the velocity of sound in crystal platelets and thin (micro- and submicrometer-thick) films of piezoelectrics, metals, and dielectrics that make up the resonator. It is well known that the acoustic properties of such thin films and single crystals are different. This arises from the dependence of acoustic properties on the deposition conditions and film thickness, as well as on the substrate material. The conventional echo method commonly used for measuring the absorption coefficient and the velocity of sound in various materials is unfortunately inapplicable to thin plates and the more so to films owing, in particular, to the radio engineering difficulties associated with the generation and recording of ultrashort radio pulses. It turned out that the extremely high Q factor of multifrequency microwave oscillators is virtually coincident with the acoustic Q factor of the substrate material (for thicknesses above 300 μm). This led us to come up and advance a new method of acoustic absorption measurements in thin substrate platelets of different materials, which has come to be known as the acoustic resonance spectroscopy technique [7].

The heart of the technique consists in the measurement of resonance peak widths and the calculation, using these data as the base, of the absorption coefficient for acoustic waves, as well as in the determination of their velocity from the frequency difference between the neighboring peaks. The convenience of this technique lies in the possibility to directly measure the frequency dependences of the absorption coefficient, because the resonance peaks are observed simultaneously over a wide frequency range, for instance, from 500 MHz to 4 GHz, with one resonator. The use and further improvement of this method permitted us to develop the methods of measuring the absorption and velocity of sound not only in platelets, but also in films deposited on the rear side of the substrate plate, where the data on acoustic absorption in the films are derived by comparing the measurement data obtained with and without the film. The information content of the proposed technique arises from the employment of short-wavelength acoustic microwaves comparable with the film thickness.

With the aid of this technique we were able to measure for the first time the acoustic losses in the microwave region for new quartz-like materials like gallium orthophosphate, langasite [8], and langatate [9] (intended to replace quartz in frequency stabilization and control systems). For langatate, it has been possible to measure the entire set of viscous stress tensor components.

The resonance acoustic spectroscopy technique was applied to measuring the losses in thin films of ZnO and AlN piezoelectrics, several dielectrics, and a series of metals — aluminium, tungsten, titanium, and molybdenum [10]. It turned out that refractory metals, especially tungsten, possess very small acoustic absorption coefficients, which are comparable with or smaller than the absorption coefficient for piezoelectric films employed in thin-film resonators (ZnO, AlN). Tungsten, molybdenum, and titanium can therefore serve as a basis for the fabrication of Bragg acoustic mirrors with relatively low losses. We also used this method for the first time to measure the absorption coefficients in Langmuir – Blodgett films and the modulus of elasticity in carbon nanotubes [11].

Microwave resonators with acoustic insulation of the piezoelectric transducer from the substrate. The structure of the thin-film BAW-based microwave resonator with acoustic insulation of the piezoelectric transducer from the substrate [solidly mounted resonator (SMR)] [1, 3] is represented in Fig. 1c. It consists of a substrate (normally silicon), as well as of a multilayer Bragg reflective structure and a piezoelectric resonator sequentially located on the substrate surface. The resonator is acoustically loaded to a very low acoustic impedance, which is almost equivalent to the existence of a free resonator boundary. At the same time, the thick substrate assures mechanical strength of the structure. The resonator is formed by a piezoelectric film (ZnO or AlN) with metallic film electrodes. The Bragg reflective structure involves alternating thin-film quarter-wave layers made of acoustic materials with a strong relative contrast between their acoustic impedances. The multilayer Bragg structure (in actual practice, 6 – 8 layers would quite often suffice, for instance, SiO_2 – AlN) affords an almost total reflection of the acoustic waves. In this case, the losses through the energy removal to the substrate are much lower than the losses in the resonator material itself.

These resonators operate by the fundamental harmonic of the piezoelectric transducer, which lies directly in the microwave range. They can be fabricated on a semiconductor substrate and combined with other electronic components fabricated on the same substrate.

As with membrane resonators, to obtain a high Q factor requires selecting piezoelectric materials with low acoustic losses. Lithium niobate is known to be one such material. It was shown that by virtue of using a material with low acoustic losses one is capable of achieving rather high Q factors, $Q = 5.2 \times 10^4$ and $Q = 1.7 \times 10^4$, respectively, at the fundamental resonance frequency (2.995 GHz) and near the third harmonic of this frequency (9 GHz). However, the quarter-wave structure contains many heteroepitaxial layers, and the fabrication of this resonator is a major technological problem.

Filters on the basis of thin-film microwave resonators. A filter containing two resonators is schematically depicted in Fig. 2a. This is the so-called stacked filter. The amplitude – frequency characteristics of such filters are exemplified in Figs 2b and 2c. The Bragg mirror contains six quarter-wave layers (SiO_2 – W – SiO_2 – W – SiO_2 – W). The resonator itself comprises a zinc oxide film of thickness close to half the

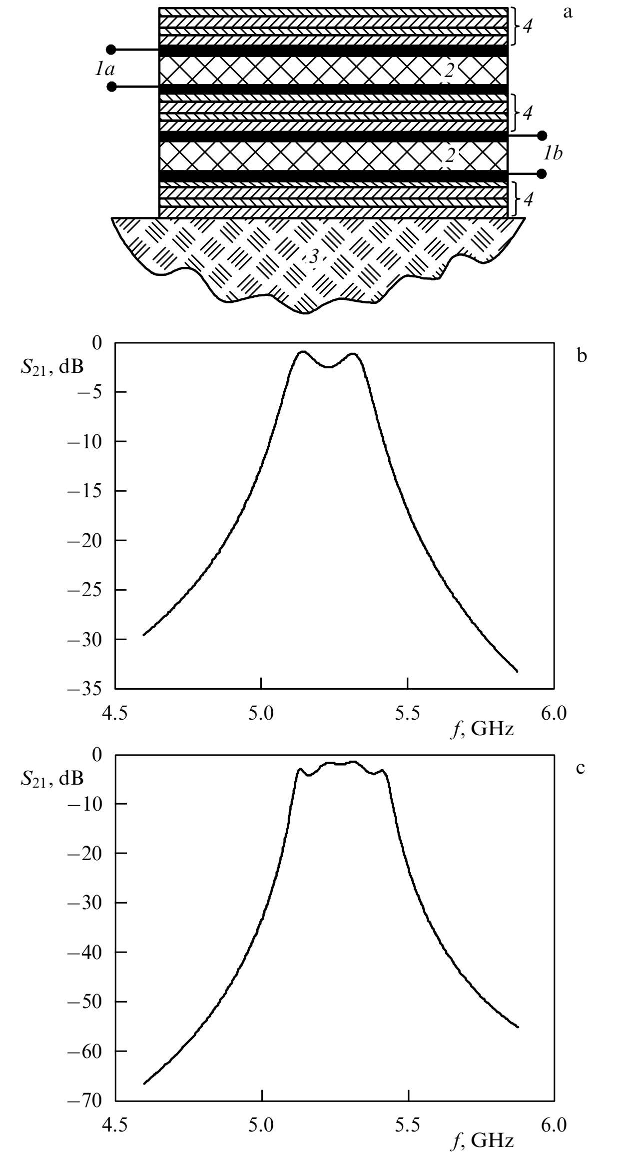

Figure 2. (a) Structure of a stacked filter with acoustic insulation of the resonant elements from the substrate, with intermediate layers and a protective quarter-wave structure: *1a* — input metallic electrodes, *1b* — output metallic electrodes, *2* — piezoelectric film, *3* — substrate, *4* — quarter-wave thin-film layer structure. (b) Example of the frequency response for a structure containing three intermediate coupling layers ($SiO_2 - W - SiO_2$), and (c) the same as in Fig. 2b in the case of two additional resonance layers.

wavelength, with aluminium film electrodes. The band is formed by setting the requisite acoustic coupling between separate half-wave resonator films with the aid of a system of thin layers limiting the acoustic coupling between them, thus transforming the unified oscillatory system into a system of coupled resonators. An example of the frequency response of a structure containing three intermediate layers ($SiO_2 - W - SiO_2$) coupling the resonators is provided in Fig. 2b. The conducting W layer in this structure simultaneously fulfils the function of an electrode. One can see that the resonance curve becomes double-peaked, corresponding to the system of two coupled vibrational contours. The nonuniformity of the frequency response can be weakened by varying the layer thicknesses. When the W layer thickness is decreased by 30% and the SiO_2 layer thicknesses are increased by 30% relative to the quarter-wave thickness, the curve exhibits a rather flat peak, as is seen in Fig. 2b. Another way of defining the shape of the frequency response consists in the inclusion of additional resonance half-wave layers in the system of intermediate layers. An example of the frequency response in the case of two additional resonance ZnO layers (the intermediate layer structure looks as follows: $SiO_2 - W - SiO_2 - ZnO - SiO_2 - W - SiO_2 - ZnO - SiO_2 - W - SiO_2 -$) is provided in Fig. 2c.

The parameters of composite multilayer structures and their characteristics are amenable to a rather rigorous and precise quantitative description, in particular, with the aid of a matrix technique elaborated at the IRE RAS. This technique permits the input and output electrical filter characteristics to be related between themselves taking into account the acoustic (elastic and viscous) and piezoelectric properties of all layers that make up the structure.

In comparison with similar microwave devices utilizing surface acoustic waves, BAW-based microwave resonators with acoustic insulation of the piezoelectric resonator from the substrate offer several advantages: fabricating them does not require submicron electron lithography; the fabrication technology of the BAW-based microwave resonators with acoustic insulation is planar and reasonably well adaptive, and the requirements on substrate surface quality are slackened. Crumpled layers and defects do not affect the operation of the resonance structure, because it turns out to be acoustically insulated from the thin piezoelectric film which makes up the resonator itself. Furthermore, the substrate material is by no means a critical factor for the Bragg structure and can be selected for technological convenience: for a micro- or submicrometer thickness of the resonator itself, the resultant devices measure about several hundred micrometers. Their weight amounts to fractions of one gram. At the same time, the electric characteristics of BAW-based resonators and filters meet the requirements imposed on them by several promising microwave systems — the electric strength of these devices is several times greater than for SAW devices.

Sensors on the basis of thin-film microwave resonators. For BAW-based microwave resonators employed as sensors, recording a physical quantity relies on direct measurements of the resonator frequency changes that arise from external action. An analysis showed that BAW-based microwave sensors may operate at higher frequencies and possess a better sensitivity in the measurements of temperature and pressure, and in doing so be smaller in size than similar SAW-based devices [12]. Oscillations in the resonators can be remotely excited and registered with the aid of microwave antennas. This makes microwave resonator-based sensors indispensable for employment in passive wireless sensors which may be used, for instance, in systems intended for remote ecological monitoring.

3. Conclusions

At present, progress in microwave acoustoelectronics is related to the development of piezoelectric microwave componentry utilizing bulk acoustic waves. This is due to the advancement of modern systems of communications, radar, and navigation to the higher-frequency working range of 3 – 10 GHz. Acoustoelectronic microwave devices utilizing BAWs offer several aforementioned potential advantages over similar microwave devices reliant on other principles.

Further progress in acoustoelectronic componentry utilizing BAWs and its adoption require the continuation of the search for solutions to the following basic problems:

— development of a new design philosophy of high-Q thin-film acoustic resonators and microwave filters, as well as elaboration of a theory describing their operation;

— the search for new acoustic materials and structures characterized by low losses in the propagation of acoustic microwave waves for resonators and filters;

— development of the physical principles of acoustoelectronic methods of generating acoustic and electromagnetic microwave oscillations in piezoelectric semiconductor films, and, in particular, investigation into acoustoelectronic nonlinearity and determination of the conditions for narrow spectral line generation in resonators on the basis of thin semiconductor films;

— elaboration of the growth technologies of piezoelectric, dielectric, and metallic films with specified electrophysical and acoustic properties, and

— elaboration and employment of new techniques of investigating the physical properties of thin layers and films along with development of the methods for controlling the acoustic parameters of thin layers and films.

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Multimode acoustic sensors and systems

I V Anisimkin[1], V I Anisimkin

1. Introduction

Heightened terrorist threats, environmental contamination, and the spread of new diseases have set new urgent tasks before the developers of electronic sensors. One of them consists in creating miniature devices intended for the detection of hazardous substances which may be present at low concentration in gaseous and liquid mixtures. The solution to this complicated and multidisciplinary problem is being pursued along several alternative directions in many laboratories all the world over.

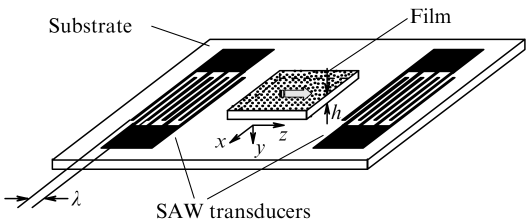

Figure 1. Schematic of a one-channel gas sensor utilizing surface acoustic waves.

Among acoustic sensors, devices which utilize Rayleigh surface acoustic waves (SAWs) have gained the widest acceptance (Fig. 1). A small localization depth (~ 10 μm) makes these waves especially sensitive to the mass load of the surface. That is why a variation in the properties of film that lies in the path of a wave is responsible for variations in its velocity v, phase φ, and amplitude A, which are recorded at the device output as frequency or voltage variations. The frequency response of acoustic sensors advantageously sets them apart from devices of other types because it furnishes a high measurement accuracy and simple compatibility with digital information processing systems. However, none of the present-day sensors alone, including acoustic ones, is capable of ensuring selective detection of a given gas because attempts to make a chemical coating that reacts to a single gas component and not to all the rest have not met with success.

The solution to this problem was found by producing 'electronic nose' and 'electronic tongue' instruments similar to the olfactory and gustatory organs of animals and humans [1–3].

The main constituent of these devices is the so-called sensor array — a set of several elements with differing sensitivity to the same gas components. The sensors are made different by combining devices of different types into the array (for instance, electrical resistors, capacitors, field-effect transistors, quartz microbalances, SAW-based devices) and using a specific chemical coating for each sensor. The set of responses read out from the sensors is subjected to special mathematical processing which enables determination of the entire composition of the mixture being tested or its correspondence to one of those belonging to the database. Under this approach, the sensor array becomes the key element of the entire instrument, which determines its accuracy, resolving power, and stability. In this case, there emerges a fundamental contradiction: on the one hand, the greater the number of sensors contained in the array and the greater their diversity, the more perfect the operation of the electronic nose as a whole; on the other hand, the greater the number of sensors and hence the number of gas-sensitive coatings, the less stable the operation of the instrument as a whole due to the aging of the films. This contradiction brings up the question: Is it possible to develop arrays containing a large number of different sensors and, at the same time, a small number of chemical coatings for them?

Pursuing this line of inquiry, the staff members of the IRE RAS (Moscow) proposed and elaborated a new, purely acoustic approach. Its key idea consists in harnessing, instead

[1] Perished tragically in the terrorist attack in the center of Moscow on 9 December 2003.