CONFERENCES AND SYMPOSIA

PACS number: 01.10.Fv

Joint scientific session of the Physical Sciences Division of the Russian Academy of Sciences and the Joint Physical Society of the Russian Federation "Acoustoelectronics" (30 March 2005)

A joint scientific session of the Physical Sciences Division of the Russian Academy of Sciences (RAS) and the Joint Physical Society of the Russian Federation "Acoustoelectronics" was held in the Conference Hall of the P N Lebedev Physics Institute, RAS, on 30 March 2005. The following reports were presented at the session:

(1) **Gulyaev Yu V** (Institute of Radioengineering and Electronics, RAS, Moscow) "Acoustoelectronics (historical review)";

(2) **Alekseev S G, Gulyaev Yu V, Kotelyanskii I M, Mansfel'd G D** (Institute of Radioengineering and Electronics, RAS, Moscow) "Some trends in microwave acoustoelectronics development";

(3) **Anisimkin I V**, **Anisimkin V I** (Institute of Radioengineering and Electronics, RAS, Moscow) "Multimode acoustic sensors and systems".

An abridge version of the reports is given below.

PACS numbers: **01.65.+g**, **72.50.+b**, 73.50.Rb
DOI: 10.1070/PU2005v048n08ABEH002840

Acoustoelectronics (historical review)

Yu V Gulyaev

1. Introduction

High-frequency (above 20 kHz) acoustic (sound) waves (AWs) — 'ultrasound' — have long been used in different areas of science and technology. Two important properties of AWs — a relatively low velocity of propagation (10^5 times slower than the speed of light), as well as the simplicity and high efficiency of excitation in piezoelectric materials — underlie their use in radio engineering and electronics. Delay lines based on bulk acoustic waves (BAWs) have been employed in radio engineering for many dozens of years. Equally well known are other devices harnessing BAWs in piezoelectric materials — quartz-crystal resonators for frequency stabilization. Both of these devices provide widely known examples of the use of AWs (ultrasound) in radio-electronic systems for the processing and transfer of information signals.

Many scientists and engineers have made their contributions to this area (see monographs by A V Shubnikov [1], W Cady [2], W P Mason [3], B Auld [4], and some others). Enumerating all the concrete names would have occupied much space and, furthermore, there inevitably exists the likelihood of someone being omitted, which is always painful.

However, of special note is the outstanding contribution Soviet scientists made prior to the early 1960s, which is sometimes underestimated. And I will venture, with allowance for the aforesaid and the personal knowledge of the author, to enumerate several names. These are (in an arbitrary order): A V Shubnikov, I G Shaposhnikov, S A Sokolov, A G Sokolinskii, L M Brekhovskikh, L E Gurevich, S G Kalashnikov, I M Lifshits, L A Shuvalov, I G Mikhailov, V A Krasil'nikov, G K Ul'yanov, S S Karinskii, K N Kozlovskii, L K Zarembo, L D Rozenberg, S I Soluyan, A G Smagin, M I Yaroslavskii, V S Bondarenko, V I El'shits, A I Akhiezer, M I Kaganov, V A Shutilov, A I Smolenskii, K N Baranskii, I A Viktorov, V E Lyamov, and many others.[1]

Since the early 1960s, the term acoustoelectronics[2] in the narrow sense of the word has come to be used in reference to the investigation of effects related to the interaction of AWs with free electrons in solids.[3] What are these effects?

(1) 'Electronic' absorption of AWs.

(2) AW velocity variation due to the interaction with electron plasma in solids.

(3) 'Acoustoelectric' effect — electron-AW drag and, as a consequence, the emergence of direct-current voltage or direct electric current in the direction of AW propagation.

The first two effects were first investigated by Shaposhnikov [5] in 1941 and were later studied by many authors (see, for instance, reviews [6, 7]). The third effect was discovered by R H Parmenter [8] in 1953 and comprehensively investigated by H E Bömmel [9], A B Pippard [10], G Weinreich [11], and others (see the review [12]).

In 1956, K B Tolpygo and Z I Uritskii [13] and independently G Weinreich [14] came up with the idea of amplifying BAWs by a supersonic drift electron stream. This

Uspekhi Fizicheskikh Nauk **175** (8) 887 – 904 (2005)
Translated by E N Ragozin; edited by A Radzig

[1] Even in 1927, the 1st All-Union Conference on Piezoelectric Vibrations and Their Use for Frequency Stabilization, at which the leading scientists of our country from Moscow, Leningrad, Nizhnii Novgorod, and Khar'kov presented the results of investigations of the corresponding laboratories, was held in Leningrad.

[2] In all likelihood this term was officially accepted at the Symposium on Ultrasonics in Sendai (Japan) in 1966.

[3] Before long, the term acoustoelectronics in the broad sense of the word came to be used in reference to the area of science and technology which studies and harnesses the interaction of high-frequency acoustic waves with electric fields and electrons in solids.

effect was first discovered and experimentally investigated by A R Hutson, J H McFee, and D L White [15] in a piezoelectric semiconductor CdS in 1961. The resultant gain was quite high: for instance, it amounted to 54 dB cm^{-1} at a frequency of 45 MHz.

In view of the offered fundamental possibility of developing new types of semiconductor amplifiers and oscillators, this work lent impetus to widespread vigorous investigations into acoustoelectronic phenomena in solids.

In 1962, virtually simultaneously and independently many theorists constructed the linear theory of electronic absorption and amplification of sound in semiconductors of various types, namely, piezoelectric, nonpiezoelectric, multivalley, with 'hot' electrons, magnetic, etc. These are the works of D L White [16], H N Spector [17], M E Gertsenshtein and V I Pustovoit [18], V L Gurevich [19, 20], N Mikoshiba [21], R F Kazarinov and V G Skobov [22], Hutson and White [23], Gurevich and V D Kagan [24], V L Bonch-Bruevich and Yu V Gulyaev [25], and some others (see reviews [6, 7, 26]).

The AW amplification mechanism in the 'low-frequency' case, $kl \ll 1$, where k is the wavenumber of the AW, and l is the electron mean free path, was shown to be similar to the amplification mechanism in a traveling-wave tube (TWT). The piezoelectric field of the AW assembles electrons in bunches which, when traveling with the wave, find themselves either on the trailing slope (Fig. 1a) or the front slope (Fig. 1b) of potential wells produced by the AW, depending on the electron drift velocity V_d. In the former case (Fig. 1a), $V_d < V_{AW}$, the AW is absorbed and attenuated; in the latter case (Fig. 1b), $V_d > V_{AW}$, it is amplified[4] (V_{AW} is the AW velocity).

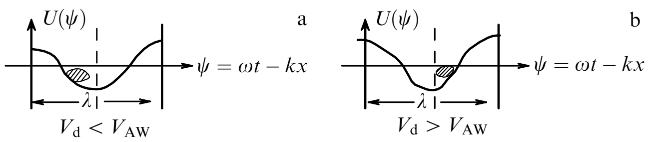

Figure 1. Amplification of acoustic waves in semiconductors by a supersonic electron drift: (a) $V_d < V_{AW}$ — 'electronic' absorption, and (b) $V_d > V_{AW}$ — 'electronic' amplification.

In the 'high-frequency' case, $kl \gg 1$, the amplification mechanism of an AW (which may be treated as a flux of coherent phonons) is the collective Cherenkov emission of phonons by supersonic electrons (see, for instance, Ref. [17]).

2. Acoustoelectronic phenomena involving surface acoustic waves

However, before long it became clear that the aforementioned elegant effect of bulk AW amplification by a drift electron flux in a piezoelectric semiconductor is hard to put to practical use. The point is that the electron mobility in good piezoelectric semiconductors (like CdS, CdSe, etc.) is quite small (~ 200 cm^2 V^{-1} s^{-1}), and attaining an electron drift velocity on the order of the speed of sound ($\sim 3 \times 10^5$ cm s^{-1}) requires applying a voltage on the order of several kilovolts.

[4] The amplification condition is represented as $V_d > V_{AW}$ only in the simplest case. Generally, it is of the form

$$r \frac{\mathbf{V}_d \mathbf{k}}{k} > V_{AW} ,$$

where the factor r may be either greater or smaller than unity or even negative (see, for instance, Refs [27, 28]).

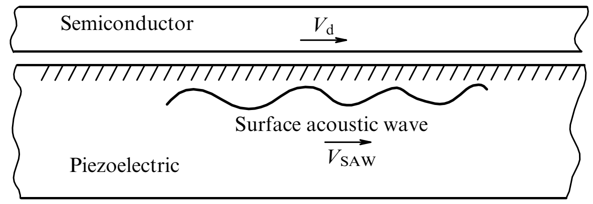

Figure 2. SAW amplification by a supersonic electron drift in a layered piezoelectric – semiconductor structure. The SAW amplification condition is fulfilled for $V_d > V_{SAW}$.

Owing to the Joule overheat, this amplifier can operate only in a pulsed mode.

In 1964, Gulyaev and V I Pustovoit [29] proposed the employment of surface acoustic waves (SAWs) in a layered piezoelectric – semiconductor structure (Fig. 2). Three types of SAWs are known that can propagate over a smooth free surface of a solid (Fig. 3; see, for instance, Ref. [4]). Owing to the electric field which accompanies an SAW in a piezoelectric and which extends beyond the surface, the SAW can interact with electrons in the adjacent semiconductor. And vice versa, the electric fields in the semiconductor can act on the SAW via a piezoelectric effect. In particular, when the electron drift velocity in the semiconductor exceeds the SAW velocity, the SAW will be amplified — virtually in close correspondence with the amplification mechanism realized in a TWT. The difference is that in this case it possible to employ a strong piezoelectric without regard for its conductivity, and a semiconductor with a high electron mobility, even though it may be a nonpiezoelectric type.

In essence, the main conclusion of the work [29] was that an SAW in a piezoelectric dielectric can interact with the electric fields and electrons in the neighboring conducting medium (which is adjacent to the surface) along the whole length of its propagation.

This idea was further elaborated in 1965 by R M White and F W Voltmer [30] who proposed to electrically excite SAWs with the aid of a periodic structure of combs comprised of metal electrodes and embedded in one another on the piezoelectric surface (Fig. 4) — the so-called interdigital transducer (IDT). The structure period is equal to the wavelength, and an alternating voltage with a period also equal to the wave period is applied to the combs. This structure makes it possible to convert the electric signal to an SAW with high efficiency (the losses are lower than 1 dB).

The amplification of SAWs by electric current in layered piezoelectric – semiconductor structures was first examined experimentally by K Ioshida and M Yamanichi [31], C F Quate, J H Collins, K M Lakin, H M Gerard, and H J Shaw [32], C Fischler and S Yando [33], Gulyaev, A M Kmita, I M Kotelyanskii, A V Medved', Sh S Tursunov [34], and some others (Fig. 5). A detailed theory of SAW absorption and amplification, as well as of the acoustoelectric effect in piezoelectric semiconductors and layered piezoelectric – semiconductor structures, was presented in Ref. [35].

The employment of SAWs for information signal processing was first proposed by Gulyaev and Pustovoit [29] and White and Voltmer [30]. The surface acoustic wave propagates along the surface of a solid with a relatively low velocity and is accessible at any point along its way. Therefore, a signal in the form of an SAW can be contacted, affected, transformed, or amplified, part of its energy can be

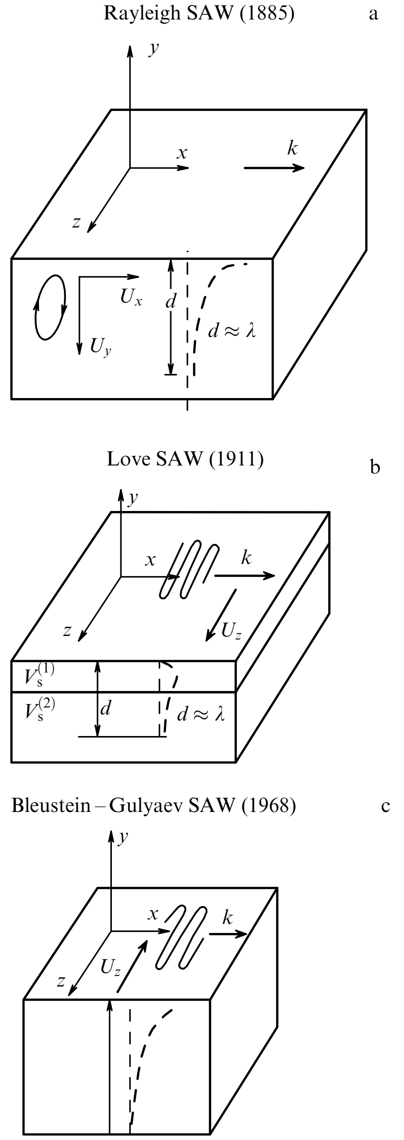

Figure 3. Surface acoustic waves: (a) Rayleigh wave — fundamentally required is the existence of two components of mechanical displacement to satisfy the boundary conditions at the free surface; (b) Love wave — fundamentally required is the existence of a layer rigidly bound to the substrate and transmitting a shear acoustic wave with the velocity $V_s^{(1)}$ lower than the shear AW velocity $V_s^{(2)}$ in the substrate: $V_s^{(1)} < V_s^{(2)}$; (c) Bleustein – Gulyaev wave — fundamentally required is the existence of the piezoeffect to satisfy the boundary conditions at the free surface, $d \approx \lambda/\eta$, where η is the electromechanical coupling constant.

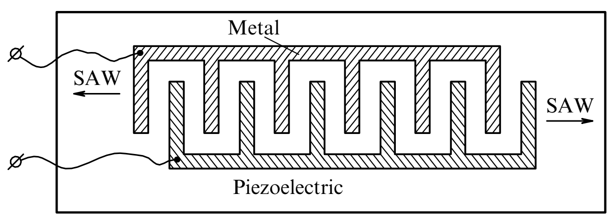

Figure 4. Simplest design of an interdigital transducer.

removed, and so forth. Since the SAW wavelength is approximately 10^5 times shorter than that of an electromagnetic wave with the same frequency, the complete processing of a signal in the form of an SAW takes place over a distance

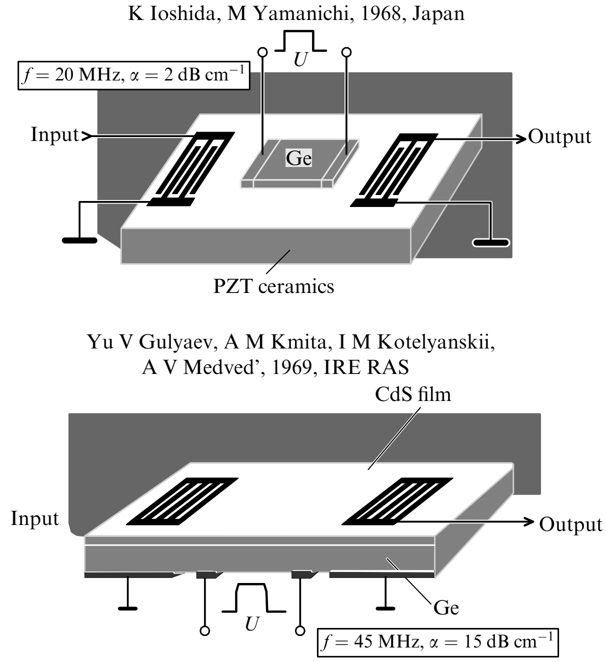

Figure 5. Experimentally examined SAW amplification in a layered structure.

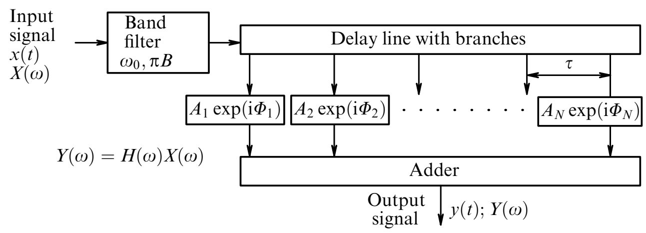

Figure 6. Transversal Kalman filter. Amplitude – frequency characteristic is given by

$$H(\omega) = \sum_{n=1}^{N} A_n \exp(i\Phi_n) \exp(-i\omega n\tau) \quad \text{for} \quad |\omega - \omega_0| \leqslant \frac{\pi B}{2} ,$$

$$H(\omega) = 0 \quad \text{for} \quad |\omega - \omega_0| > \frac{\pi B}{2} ,$$

where B is the frequency band.

of several centimeters or even millimeters. These are precisely the SAW characteristics that permit realization of the model of a so-called transversal filter, which was proposed by H E Kalman as far back as 1940 (Fig. 6). By proper selection of the amplitudes and phases of the branched signals, it is basically possible to construct a filter with an arbitrary amplitude – frequency characteristic (AFC).

The first efficient design of an SAW-based transversal filter involving an IDT was independently proposed by A V Kovalev and I B Yakovkin [36], and R H Tancrell and M G Holland [37] in 1971. To form the requisite filter AFC, they came up with the idea of varying the comb electrode overlap length in the IDT, the so-called 'apodization'. In the ideal case, the AFC of such an IDT is the Fourier transform of the electrode overlapping as a function of the coordinate along the SAW traveling direction (Fig. 7).

However, this 'ideal' case does not take into account the real physical processes occurring when an SAW travels along

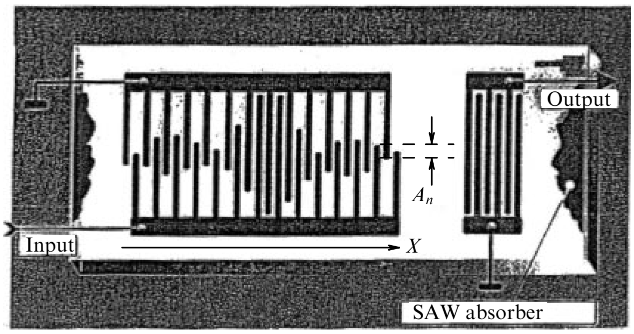

Figure 7. SAW-based transversal filter. The amplitude – frequency characteristic $H(\omega) = F[f(x)]$, where $F[\ldots]$ denotes the Fourier transform, and $f(x)$ is the electrode overlap function. In the case depicted in the drawing, $f(x) = (\sin x)/x$. The AFC is $H(\omega) = 1$ when $|\omega - \omega_0| \leqslant \pi B/2$, otherwise $H(\omega) = 0$.

the piezoelectric surface with metallic electrodes on it. These 'secondary' effects, which strongly alter the characteristics of this filter, are as follows:

(1) in-IDT SAW reflections from both the input and output IDTs;

(2) the electrode mass and conduction effects;

(3) SAW diffraction (especially in the regions where the electrode overlapping is small);

(4) the generation of parasitic bulk acoustic waves;

(5) source – load impedance mismatch;

(6) 'direct' permeation of the electromagnetic signal.

To suppress these parasitic 'secondary' effects, several design solutions were proposed, some of which are of a fundamental nature.

In 1973, in particular, E G S Paige and his colleagues [38] advanced the so-called multistrip directional coupler. With the aid of metallic strips on the surface of this coupler, the electric potentials of an SAW are transmitted to another surface region and generate the SAW in a parallel channel. This makes it possible to smooth the wave front and alleviate some of the above-listed 'secondary' effects.

To eliminate the first three, which are the most unfavorable of the above 'secondary' parasitic effects, Gulyaev, A M Kmita, and A S Bagdasaryan [39] and, independently, D C Malocha and B J Hunsinger [40] proposed the so-called capacitive weighting of the electrodes in an IDT.

In this design, the main SAW-emitting comb structure with a *uniform* electrode overlapping is coupled to additional electrode combs with *apodization* through the utilization of capacitive couplings (Fig. 8). Apart from a reduction in the main 'secondary' parasitic effects, furnished by this design, it turns out to be much more versatile as regards the formation of various AFCs, because in this case such a formation may be effected in several places and in both IDTs — the input IDT, and the output one.

Calculating the performance characteristics, designing and fabricating these SAW-based filters is only slightly more complicated than for filters with a simple apodization. Figure 9 portrays the AFC of a typical SAW-based filter for a D/K- and B/G-standard television set developed at the IRE RAS (Moscow) and introduced into mass production. Figure 10 shows the AFC of an intermediate-frequency filter for a GSM-standard cell radio-telephone also elaborated at the IRE RAS. One can see that these filters ideally comply with specification requirements. Today, such filters are employed in virtually all radio-electronic devices.

In particular, in radar, radio navigation, and friend-or-foe identification systems wide use is made of SAW-based dispersion filters for signal compression, for encoding and decoding signals, and so forth (for more details, see monographs [41 – 48]).

The outstanding characteristics of these filters, their simplicity, reliability, smallness, and immunity to different actions have motivated their mass production throughout the world up to several billion annually.

The characteristics of SAW-based band transversal filters presently produced by the industry are collected in Table 1.

During the 40 years that have passed since the pioneering works [29, 30] concerning the use of SAWs in radioelectronics, a wealth of research has been performed on the physics and technology of SAWs around the world. The number of publications ranges into the thousands, and several monographs have also been published (see the aforementioned books [41 – 48], as well as Ref. [49]). Apart from the accomplishments outlined in the foregoing, I will therefore indicate a few most fundamental, in my view, scientific achievements.

In 1967, E A Ash [50] came up with the idea of so-called 'topographic' SAW waveguides — geometrical structures which are engraved on the surface and are capable of guiding SAWs due to the modification of the elastic properties of the material. Also in 1967, D L White [51] proposed 'strip' waveguides wherein the SAW-guiding capacity arises either from a lower sound velocity in the strip of a different material laid on the surface or from the short-circuiting of piezoelectric fields in the case of a metallic strip. The waveguides are

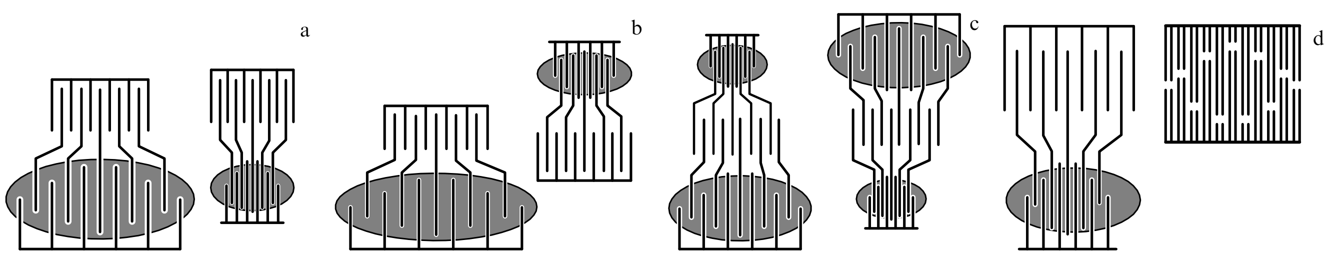

Figure 8. SAW-based filters with capacitive electrode weighting (Yu V Gulyaev et al.) (schematic topology): (a) USSR Author's Certificate No. 726648; (b) US Patent No. 4162415; (c) France Patent No. 7821723; (d) Germany Patent No. 2831584. All these filters exhibit a high selectivity and furnish the possibility of forming the AFC in both IDTs. An additional advantage of the scheme in Fig. 8d is the simplicity of realization of an intermediate-frequency filter for television.

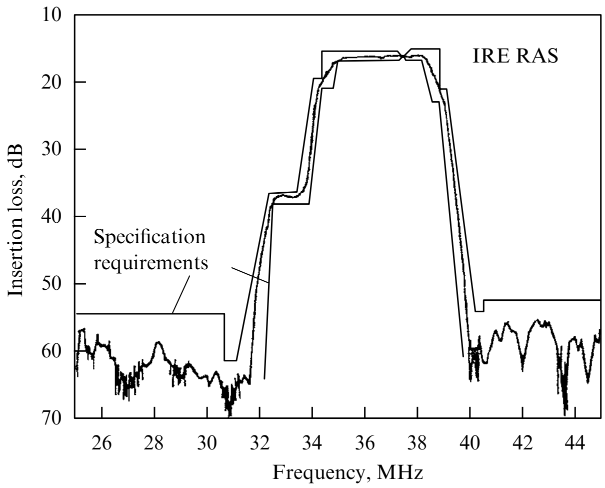

Figure 9. Measured AFC of the intermediate-frequency filter for BG-CCIR- and D/K-OIRT-standard television sets. The insertion loss is equal to 16 dB. The crystal measures 10 × 2 × 0.2 mm. Material: $LiNbO_3$, 127.86° *Y*-cut.

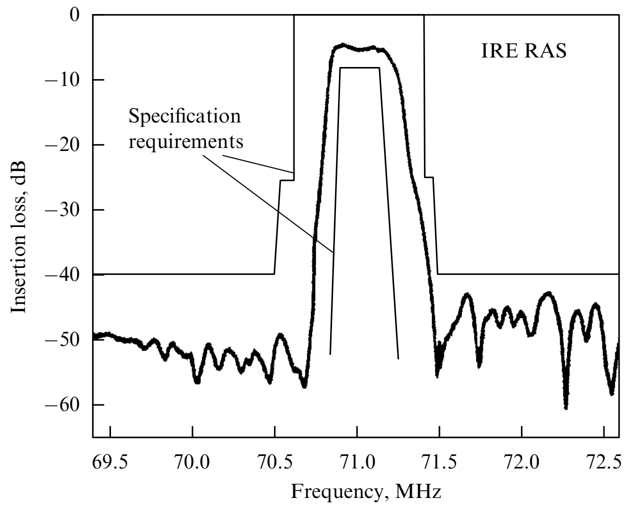

Figure 10. Amplitude–frequency characteristic of the intermediate-frequency filter (71 MHz) for a GSM-standard radio-telephone. The in-bandwidth insertion loss is equal to 4.8 dB in a 910-Ω path. The group delay time is 0.6 μs.

Table 1. Parameters of SAW-based band transversal filters.

Parameter	Central frequency, mHz	Relative bandwidth at a 3 dB level, %			Insertion loss, dB	Amplitude irregularity over the band, dB	Phase irregularity, deg	Rectangularity coefficient (ratio between the 3- and 40-dB level bandwidths)	Side lobe suppression, dB	Longest delay, μs
		Lithium niobate	Lithium tantalite	Quartz						
Best value	2500	3–50	1.5–20	0.1–10	10	0.2	1.5	< 1.1	60	10

employed to concentrate the SAW energy along specific paths when making the acoustic analogues of the well-known microwave devices — directional couplers, power dividers, circulators, etc.

In 1968, J L Bleustein [52] and Gulyaev [53] independently[5] came up with a new type of SAW — purely shear SAWs in piezoelectric materials. These waves, which are referred to as 'Bleustein–Gulyaev waves', or BG waves, came to be the third type of surface acoustic waves [along with the well-known Rayleigh (1885) and Love (1911) waves, see above] that can exist on the smooth free surface of a solid. Here, the boundary conditions for the absence of mechanical stress at the free surface are satisfied due to the exact on-surface compensation for the stresses arising from mechanical displacement and the piezoelectric effect. The surface nature of the wave is related to a decrease in the crystal elastic modulus 'stiffened' by the piezoelectric effect nearby the surface and thereby to a lowering of the velocity of the shear acoustic waves in the near-surface layer (see Ref. [54]). In 1972, G Koerber and R Vogel [55] considered the general existence problem of purely shear SAWs in piezoelectric crystals and showed in which crystals and for which cuts the BG waves can exist as eigenmodes.[6] BG waves were first discovered in experiment by C Maerfeld, F Gires, and P Tournois [57] and independently by A I Morozov and M A Zemlyanitsyn [58] in 1970 and have been much studied over the years. In particular, BG-type SAWs were investigated at the interface between two piezoelectrics, in crystals with a strong electrostriction, in ferromagnetic and antiferromagnetic crystals, as were studied 'leaky' SAWs possessing the properties of BG waves (see the review [54]). As regards practical implementation in acoustoelectronic devices, BG waves offer an advantage over Rayleigh waves in the high-frequency case (above 2 GHz). They penetrate into a crystal more deeply than Rayleigh waves, and are therefore less affected by irregularities emerging during surface treatment.

B Auld, J Gagnepain, and M Tan [59], as well as Gulyaev and V P Plesskii [60] showed that purely shear SAWs can exist on the periodically irregular surface of any solid, too — similarly to slow electromagnetic waves in a slow-wave comb structure. Physically, the surface nature of these waves is related to a decrease in the near-surface stiffness of a solid due to the existence of grooves. The velocity of a shear wave in the near-surface region decreases because it is as if the wave 'travels around' the surface asperities and thereby traverses a longer path. Today, these waves are employed to lower the losses in delay lines involving near-surface BAWs, as well as to augment the Q factor of SAW-based resonators.

In 1969, K A Ingebrigtsen [61] came up with a phenomenological technique for calculating the characteristics of SAW-based devices via the so-called effective permittivity and for measuring the velocity of SAWs on free and metallized (i.e., when the piezoelectric fields are short-circuited) piezoelectric surfaces. Ingebrigtsen's technique is

[5] Bleustein's paper was issued in December 1968, and Gulyaev's paper in January 1969, but it had been submitted to publication 20 days earlier than Bleustein's paper. That is, clearly both works had been performed simultaneously and independently.

[6] It is pertinent to note that purely shear SAWs whose surface nature is related to the piezoelectric effect had earlier been considered by M I Kaganov and S Shklovskaya [56]; however, in the case of crystals with a cubic symmetry, they were interested in, these waves cannot exist.

widely used in the calculation and design of SAW-based devices even in complex cases.

In 1970, E A Ash [62] advanced the schemes of resonators and resonator filters for SAWs, which now are widely used in SAW-based devices (for more details, see Ref. [45]).

L O Svaasand [63], as well as M Luukkala and G S Kino [64] were the first to realize devices for the convolution and correlation of signals using SAWs in a piezodielectric, which relied on nonlinear 'lattice' effects involving SAWs (see, for instance, Ref. [65]). A substantial efficiency improvement in the convolution and correlation of SAW signals was achieved by Kmita and Medved' [66] in 1971 and by P Das, M N Araghi, and W C Wang [67] in 1972 through the use of electronic nonlinearity in a layered piezoelectric – semiconductor structure. An SAW-based convolver is a unique acoustoelectronic device which enjoys wide application, in particular, in new-generation cell phones (see, for instance, Refs [68, 69]).

Extensive investigations of the physical effects related to the interaction of SAWs with electric fields and electrons in piezoelectric dielectrics and semiconductors, as well as in layered piezoelectric – semiconductor structures were later carried out in the 1970s – 1990s in Europe, USA, USSR, Japan, and other countries. This resulted in intensive elaboration of acoustoelectronic devices and their use in different radioelectronic information processing and communication systems (see, for instance, an excellent review by D Morgan [70]). In 1974, five European scientists, Ash, Collins, Gulyaev, Ingebrigtsen, and Paige, were awarded the Hewlett – Packard Prize of the European Physical Society for developing the physical principles of SAW-based devices.

The present-day nomenclature of SAW-based acoustoelectronic components manufactured around the world is rather broad. It includes:

— band filters;
— dispersion filters;
— delay lines;
— dispersive delay lines;
— resonators and oscillators;
— devices for encoding and decoding signals;
— fast Fourier transform devices;
— digital Nyquist filters;
— frequency synthesizers;
— devices for signal convolution and correlation;
— sensors, etc.

Band filters for television, stereo broadcasting, car radio, video tape recorders, CD and DVD players, and, in recent years, cell phones account for 90% of the market for SAW-based products. Among the main enterprises which manufacture acoustoelectronic products are such well-known companies as Murata, Kyoto Ceramics, Fujitsu, Hitachi, NEC, Samsung, Sawteck, Thompson, Vectron, Motorola, and Siemens, to name but a few. In the territory of the former Soviet Union, acoustoelectronic components are produced by Morion, Avangard (St.-Petersburg), Butis-M, Angstrem, Fonon (Moscow), and ONIIP (Omsk), as well as by companies in Cherkassy (Ukraine) and Minsk (Belarus').

3. Physical research on acoustoelectronics

Along with research on the physics and technology of SAW-based devices, the 1960s and the 1970s saw comprehensive investigations into the propagation of bulk and surface acoustic waves through conducting materials — semiconductors and metals — as well as of the AW interaction with free electrons. Many new effects were exposed and new methods for material studies were elaborated.

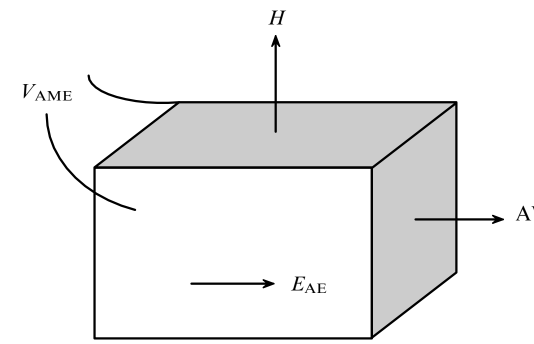

Figure 11. Acousto-magnetoelectric effect in semiconductors.

Among the most significant accomplishments in this area I would highlight the new techniques for characterizing materials, their mechanical, electrical, magnetic, thermal, and other properties, with the aid of acoustic waves. In this connection mention should be made of the works of F S Hickernell and his co-workers [71 – 74], A Slobodnik (see monograph [75]), S N Ivanov and his colleagues [76], A I Morozov and his colleagues [77], G D Mansfel'd and his co-workers [78], and many others.

Another major scientific achievement is the theoretical prediction and description, as well as experimental investigation, of a new class of kinetic effects in solids related to entrainment of electrons by acoustic waves (electron-AW drag). One of these effects has been discussed in the foregoing — the acoustoelectric effect discovered by Parmenter [8] in 1953. Another representative of this class of effects is the acousto-magnetoelectric (AME) effect. It works on the principle that an acoustic wave generates in a sample placed in a magnetic field perpendicular to the direction of AW propagation an electric current or voltage (when the sample is open) perpendicular both to the magnetic field and the direction of AW propagation (Fig. 11).

In the case of a bipolar semiconductor, the AME effect, which was discovered by A A Grinberg and N I Kramer [79] in 1964, is explained by the AW drag of both electrons and holes and the resulting oppositely directed Hall electron and hole flows. The AME effect in a monopolar semiconductor was theoretically predicted by E M Epshtein and Gulyaev [80] in 1967 and experimentally examined by A Korolyuk and N Roi [81] in 1972. In the monopolar case (say, for a sample open in all directions), the AME effect is explained as follows.

Electrons are entrained by an AW, and a compensating acoustoelectric field E_{AE} forms in the sample. But electrons show some (say, Maxwellian) energy distribution. In a natural way, the AW entrains primarily 'cold' electrons (because they reside deeper in the potential wells of the wave), and the field E_{AE} acts in the opposite direction equally on all electrons. That is why, although the total current at each point of the sample is equal to zero (the sample is open!), in the direction of AW propagation there exist oppositely directed 'partial' currents equal in magnitude: 'cold' electrons in one direction, and 'any' electrons in the other. The difference in the Hall effects for these currents yields the voltage of the AME effect. From the theory of the Hall effect it is known that this difference will be nonzero only when the electron momentum relaxation time τ depends on the electron energy ε. Indeed, both theory and experiment reveal that

$V_{\rm AME} \sim {\rm d}\tau(\varepsilon)/{\rm d}\varepsilon$. Therefore, the AME effect in a monopolar semiconductor constitutes a subtle method of investigating electron momentum and energy relaxation mechanisms.

Owing to electron-AW drag other transfer phenomena also emerge: the acoustothermal effect [82], the acousto-magnetothermal effect [83], and 'acoustic' (i.e., involving acoustoelectric current) Ettingshausen and Peltier effects [84]. All these effects have important distinguishing features arising from the bunching of electrons entrained by the AW. In particular, in the case of the ordinary Peltier effect there is no way of obtaining very low temperatures, because the Peltier coefficient $\Pi \sim (kT/\varepsilon_{\rm F})^2 \to 0$ as the temperature $T \to 0$, where $\varepsilon_{\rm F}$ is the Fermi energy. In the case of the 'acoustic' Peltier effect, $\Pi_{\rm AE} \to$ const as $T \to 0$, which opens up, at least from this standpoint, the possibility of obtaining low temperatures.

Predicted theoretically by Gulyaev et al. [35] in 1970 and discovered experimentally by Kmita and Medved' [66] in 1971, a transverse acoustoelectric effect provides the basis for making efficient acoustoelectronic convolvers and correlators [67].

In 1976–1979, Gulyaev and R A Gasparyan [85] considered the SAW interaction with a two-dimensional electron gas in the near-surface layers of semiconductors and in thin films. They showed that the SAW absorption (and gain) coefficient, the SAW velocity, and the voltage of the acoustoelectric effect exhibit quantum oscillations due to dimensional quantization.

The nonlinear theory of the interaction between AWs and electrons in semiconductors was developed late in the 1960s. Gurevich and B D Laikhtman [86] constructed the nonlinear theory of propagation and interaction with electrons for low-amplitude AWs with the inclusion of 'electronic nonlinearity'. In the works by Y Abe [87], J R A Beale [88], and P E Zil'berman [89], a study was made of high-amplitude stationary AWs related to the nonlinearity of the medium. The nonlinear effects of high-amplitude AW–electron interaction in semiconductors were numerically calculated by P K Tien [90]. The analytical nonlinear theory of high-amplitude AW–electron interaction in semiconductors in the classical hydrodynamic case $kl \ll 1$ was constructed by Gulyaev [91] in 1970. The analytical nonlinear theory of AW propagation in the high-frequency case $kl \gg 1$ (with the inclusion of the so-called 'pulsed' nonlinearity) was elaborated by Zil'berman [92] in 1971 and was experimentally borne out by the work of Ivanov, Kotelyanskii, Mansfel'd, and E N Khazanov [93] in the same year. A detailed experimental investigation of different acoustoelectronic nonlinearity mechanisms was carried out employing the original idea of multitransit generation and amplification of high-amplitude AWs, proposed by A S Bugaev, Gulyaev, and Mansfel'd [94] in 1978.

4. Conclusions: some prospects

Acoustoelectronics continues to successfully advance as a scientific and technical area. International conferences on ultrasonics, piezoelectrics, and frequency control, which bring together about a thousand participants, are held annually under the aegis of the American Institute of Electrical and Electronics Engineers (IEEE). The stream of publications and patents does not subside. Not even pretending to predict the main areas of acoustoelectronics development, I will nevertheless run the risk of specifying some of the avenues that have already taken shape.

• First and foremost is improving and broadening the field of application of matched SAW-based filters which are presently employed for coded signal intelligence. We believe that such filters will enjoy wide applications as markers for the remote identification of any objects — ranging from consumer goods to airplanes, rockets, trains, and automobiles — including personal identification.

• Next is the use of bulk very-high-frequency (above 3 GHz) acoustic waves in acoustoelectronic devices, where the use of SAWs is hampered by strong absorption in surface layers. These devices will be represented by high-frequency filters based on BAWs for wide use in wristwatches, telecommunication and telephony, navigation (GPS systems), instrumentation, and rocket and space technologies (see Ref. [95]).

• Development of SAW-based sensor devices will also be important. Today, such sensors are already being used for identifying gases, vapors, and liquids. In recent years, many new SAW-based sensor designs have been proposed, which possess improved sensitivity and selectivity, including those which make use of new types of AWs (see Refs [96–98]). This opens up new areas of application, including identification of toxins and drugs.

• The fourth area of acoustoelectronics progress in the following years will, in my opinion, be related to the employment of piezoelectric semiconductors or layered piezoelectric–semiconductor structures, as proposed in Ref. [29]. It is possible to point out at least six promising SAW-based devices built around layered piezoelectric–semiconductor structures.

(1) An SAW amplifier using supersonic electron drift of the TWT type (see Refs [29–35, 99]). The best result [99] (a central frequency of 280 MHz, 50 dB amplification, noise factor < 7, broad bandwidth) is comparable with transistor characteristics and suggests that this amplifier will find its niche, the more so as it offers several advantages like the complete electric insulation of the input from the output.

(2) The so-called acousto-injection transistor (AIT) [100] wherein the signal amplification is achieved due to conductivity modulation in the region between collector electrodes, which results from electron bunching by the acoustic wave generated by the input signal. The first experimental data have confirmed the promise of this device.

(3) Acoustic-wave charge transfer devices [101, 104].

(4) Convolvers and correlators which harness the transverse acoustoelectric effect with the participation of an SAW (see Refs [67–69]). The emergence of new efficient designs of these devices gives promise that they will find wide use in signal intelligence and other information processing.

(5) A device for image sensing with the aid of short acoustic pulses which propagate through a layered piezoelectric–photosensitive semiconductor structure and produce a local transverse acoustoelectric effect. In a sense, this device is an analogue of a vidicon, with the difference that an acoustic pulse is employed instead of an electron beam.

(6) Memory devices relying on the capture effect with secondary electrons, which are knocked out by an external pulsed electron beam, in the surface layer of a piezoelectric in accordance with potential distribution in a traveling AW [105, 106]. The situation appears as if the SAW 'stopped' for some time (for hours or days, depending on the residual conductivity of the piezodielectric). The 'stored' information is read out by directing to the surface another electron-beam short pulse, which closes the piezoelectric fields. The existing

voltages relax and excite the same SAW which can be recorded by the output transducer.

We are reminded of the recently published reports about the experimental examination of light 'stopping' in some gases [107]. I believe that there is a certain analogy with the above effect of SAW 'stopping' [105, 106].

To summarize, it is valid to say that studying the propagation of acoustic waves through different solids and their interactions with electric and magnetic fields and elementary excitations in such systems will undoubtedly lead to new and interesting effects which in turn will underlie new breakthroughs in the development of high-technology instruments and devices.

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PACS numbers: 07.07.Df, **72.50.+b**, 77.65.Dq
DOI: 10.1070/PU2005v048n08ABEH002841

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.