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PHYSICS AND APPLICATION OF SURFACE ACOUSTIC WAVES ON VARIOUS STRUCTURES OF GALLIUM ARSENIDE

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The present paper deals the fact that each orientation of GaAs may be best fitted to specific applications, depending on the properties of the SAW propagating .The results of experimental investigations of delay lines, transducers, resonators, layered structures, and ACT devices fabricated on different cuts of GaAs are also considered.

KEYWORDS : Transducer, Resonator, Piezoelectric moduli, Epitaxial Structures, Acoustic charge transfer, Interdigital Transducer.

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Introduction

GaAs is one of the most widely used A_3B_3 group semiconductors featuring significant intrinsic piezoelectric effect. The guides for its possible application as well as investigation are determined by both its piezoelectric and semiconducting properties. The application comprises both surface acoustic wave (SAW) devices as well as electronic components which may be fabricated on a single integrated circuit [1, 9]. The great variety of SAW phenomena include transducing, acoustic signal delay by the delay lines, filtering, resonance with high Q factors, acoustic signal mixing, and acoustic charge transfer (ACT). Therefore, it is obvious that the design of the devices employing any of the phenomena mentioned requires detailed knowledge of parameters of the SAW propagating on the crystal cuts intended for the device fabrication. Fortunately, those parameters can be computed with sufficient accuracy using the known acoustoelectric constants. Thus, first of all we present the calculated parameters of different modes of SAW propagating in the [1, –1, 0] direction over the usual (001) cut as well as the (11n) cuts with $n = 1 ... 3$. As the properties of SAW in the [1, –1, 0], (001) have been known before, coincidence of our results concerning this orientation with those obtained by other authors before confirms the correctness of our calculations.

Properties of SAW propagating in the [1, –1, 0] direction over different cuts of GaAs

First of all, we would like to give only some hints on the theory of acoustic wave propagation in piezoelectrically active media. Let's start with the equation describing the movement of the particles of a solid homogeneous body. Particle movement and electric potential in piezoelectric solids may be described by the following set of equations:

$$\rho \frac{\partial^2 u_i}{\partial t^2} = C_{ijkl} \frac{\partial^2 u_l}{\partial x_j \partial x_k} + e_{kij} \frac{\partial^2 \Phi}{\partial x_j \partial x_k}, \quad i = 1,2,3 \qquad \text{… (1a)}$$

and
$$e_{kij}\frac{\partial^2 u_l}{\partial x_j \partial x_k} - \varepsilon_{jk}\frac{\partial^2 \Phi}{\partial x_j \partial x_k} = 0, \qquad \ldots (1b)$$

where ρ is the material density, C_{ijkl} is the stiffness tensor, e_{kij} is the tensor of piezoelectric moduli, ε_{jk} is the dielectric susceptibility tensor, u_i is the displacement component, Φ is the electric potential, x_j is the coordinate. The Einstein convention on the summation over repeated indices from 1 to 3 is accepted here.

Consider a plane-wave solution of Eq. l. Let its have the wave vector lying in the x_1 x_2 plane and thus have uniform displacement and potential in the x_3 direction and propagation velocity in the x_1 direction v. Having substituted the solution into Eq. l we arrive at another set of four homogeneous equations known as the Cristoffel equations, which are linear with respect to the displacement and the potential. Those equations allow us to find the displacement vector and potential for any given value of v, provided the determinant of the coefficient matrix is zero. The determinant equation is an eighth degree polynomial with respect to the wave vector component in the direction x_2. It has eight roots n_2^r, and for each root, regarded as an eigenvalue, we can find the displacement-potential vector, regarded as an eigenvector. Note that the material constants are real quantities; therefore, if v is real too, all the polynomial coefficients are real. So, complex roots of the polynomial (if any) are conjugate pairs. On the other hand, we can take a fixed real value of n_2 and solve the equation with respect to v^2, which is of the third degree. If we choose zero for n_2, the three values of v^2 obtained are the squared velocities of the slow quasitransversal, fast quasitransversal and quasilongitudinal bulk waves (v_{T1}, v_{T2}, and v_L, correspondingly), propagating in the x_1 direction. The general solution of Eq. l is a superposition of the eight wave solutions with arbitrary weighting factors. We will call them the wave solutions which we combine into the general solution the partial waves.

So far we have considered only infinite substrates with no boundaries. Now, we shall consider a semi-infinite substrate having a surface perpendicular to the x_2 axis. The mechanical condition of the free boundary implies that it is stress-free; the electrical condition implies that the normal component of the electric induction in the crystal is equal to that in vacuum at the boundary as there is no free charge on it. For the boundary covered with an infinitesimally thin metal layer, the electrical condition becomes simply $\Phi = 0$ at $x_2 = 0$. Generally, the boundary conditions are expressed by four homogeneous linear equations with respect to the weighting factors. Once again, those have a solution if the determinant of the appropriate coefficient matrix vanishes.

Now, let's choose a sufficiently small value of v such that all the eight n_2's are complex-conjugate pairs. Half of them correspond to the waves exponentially decaying with increasing x_2, *i.e.*, with getting deeper into the substrate. Whereas the others exponentially increase. We combine four decaying solutions having physical sense as always being finite and then substitute them into the four boundary condition equations. Then we calculate the boundary conditions determinant, and by iteration procedures try to find a value of v which drives the determinant (generally it is complex) to zero. In the most cases, it is possible to find a value of v, satisfying the boundary conditions, and less than that of the slow quasitransverse bulk wave. Such waves are called the Rayleigh, or normal surface acoustic waves (NSAW). Their Poynting vector $\boldsymbol{P}$, defining their energy flow, is parallel to the surface. Their displacements and potential become negligible at the depth of a few wavelengths.

Metallization of the surface slightly slows a SAW down. The degree of this slow-down determines the strength of electromechanical coupling for the wave. (An acoustoelectrically inactive surface wave doesn't “feel” the metallization at all, as it tends to short out electric field which is absent in this case.) As usual, the electromechanical coupling coefficient is defined as $K^2 = 2(v - v_0)/v$. Here v_0 is the phase velocity of the wave propagating on the metallized surface. K^2 of the wave determines the possibility of its electrical transduction.

Further on, let's choose a larger value of v such that one pair of n_2's is real. This solution describes a bulk wave, propagating either in the x_1 direction or somewhere between x_1 and x_2. (It is the case when we reach a so called transonic state [2].) No matter which one of the two solutions describing the bulk partial wave we include in the general solution, we fail to satisfy the boundary conditions. To satisfy them, we introduce an imaginary part of the velocity, and further it is complex. Now, all the roots of the polynomial are complex again although not conjugate. Unfortunately, to satisfy the boundary conditions, out of the pair of the formerly bulk partial waves we must include the one with growing amplitude when getting deeper into the crystal. We will call it a leaky partial wave, whereas the whole wave solution, satisfying the boundary conditions, will be known as the leaky surface acoustic wave (LSAW). The imaginary part of v results in the attenuation of the LSAW in the direction of propagation. Such a wave conserves its energy, however, its energy flow is parallel to the surface only at the surface. Going deeper into the crystal, it becomes tilted down and in the limit the angle between the Poynting vector and the surface becomes constant and determined solely by the leaky partial wave. In the strict sense, LSAW cannot exist in crystals having the second surface perpendicular to the x_2 axis because the energy cannot “escape” through the second boundary to the vacuum. Thus, the results about the LSAW should be treated with some care. Probably, the obtained parameters of the LSAW reflect the actual behaviour of the wave in the case when the second boundary absorbs the acoustic energy well. Otherwise the leaky partial wave is reflected by the second boundary and is transformed into waves which are of the form different from that discussed here. On the other hand, if there were no the second boundary, the displacements of the leaky partial wave would become infinitely large with increasing x_2. Therefore, the energy transmitted by the LSAW would become infinite.

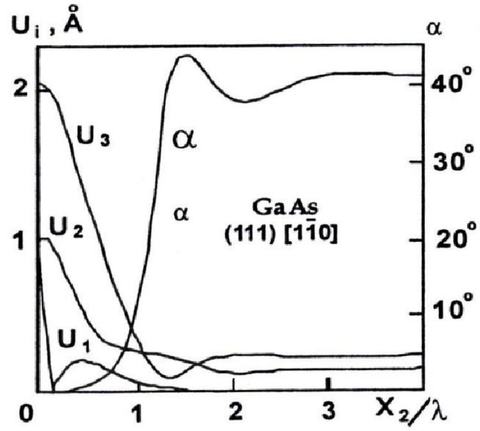

Fig. 1. Particle displacement components and angle between the surface and the energy flow versus the depth into the crystal for the LSAW in the (111), [1, –1, 0] orientation

The main theoretical results (the main parameters of SAW propagating on different cuts of GaAs in the [l, –l, 0] direction) are revealed in Table l.

Table l. The main theoretical results

Cut	SAW Type	Velocity (m/s)	$K^2 10^6$	Attenuation (dB/λ)
(111)	NSAW	2425.9	1.8	0
(112)	NSAW	2451.4	7	0
(113)	NSAW	2462.9	7	0
(001)	LSAW	2862.5	784	0
(111)	LSAW	3239.2	972	$7.49 \cdot 10^{-2}$
(112)	LSAW	3047.4	930	$4.94 \cdot 10^{-5}$
(113)	LSAW	2959.5	865	$2.6 \cdot 10^{-3}$

It is seen that all the normal waves propagating on the given cuts are almost acoustoelectrically inactive and, therefore, difficult to excite. The NSAW will not concern us further. Note that the LSAW propagates on the (001) cut unattenuated. This is a degenerate LSAW with zero amplitude of the leaky partial wave. The LSAW propagating on the (111) surface is of the highest acoustoelectrical activity. Its extremely high attenuation is related to the large angle of its energy flow vector (Fig. 1) [4]. This orientation may be employed in sensors which use the opposite crystal side as a sensing surface, as will be detailed later. Whereas the LSAW propagating on the (112) cut has the highest electromechanical coupling coefficient out of all the waves so far known in GaAs (except for the wave just mentioned above). Its attenuation is infinitesimal and cannot be seen during experiments. This cut may be successfully used for filters, delay lines, ACT devices.

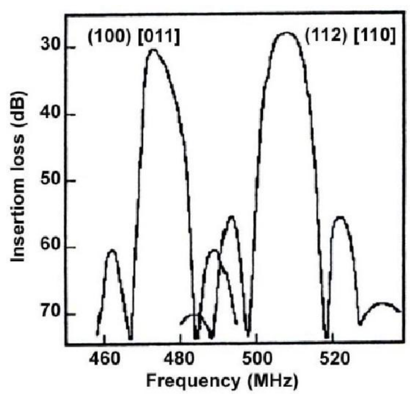

Fig. 2 : Frequency responses of type II delay lines, fabricated on the (100) and (112) cuts of GaAs [3]

Operation of SAW filters fabricated on the two cuts of GaAs

Two types of experimental SAW filters were fabricated on the (112) cut GaAs plates of 0.3 mm thickness. The conductivity of GaAs crystals was lower than 10^{-7} W^{-1} cm^{-1}. Interdigital transducers (IDTs) for the LSAW excitation and reception were made of 1500-2000 Å thick aluminium film and oriented for the LSAW propagation in the [110] direction. The IDT of type I SAW filters had 100 pairs of fingers with the period of 24 μm and overlap of 1.4 mm. The distance between the centers of the IDTs was 6 mm. The IDT of type II SAW filters had 50 pairs of fingers with the period of 6 μm and overlap of 150 mm. The distance between the IDTs was 8 mm. For the comparison of the LSAW characteristics to ones of the SAW propagating in the [011] direction on the (100) cut, additional experimental SAW filters of both types were fabricated on the (100) cut GaAs plates.

Frequency responses of type II SAW filters are presented in Fig. 2. It is seen that the response of the filter fabricated on the (112) cut is more symmetric than that of the filter fabricated on the (100) cut.

Operation of SAW resonators fabricated on the two cuts of GaAs

A simple SAW resonator consists of an interdigital transducers (IDT) and two periodic grating structures reflecting SAW, situated at either side of the IDT. We have investigated experimentally the parameters of SAW resonators, fabricated on GaAs of both (100) [011] ir (112) [1, –1, 0] orientations, with reflection gratings of two types.

Amplitude-frequency characteristics of the resonators are given in Figs. 3 and 4. The characteristics of resonators fabricated on the (100) [011] orientation crystals are remarkable. Generally, those fabricated with reflection gratings filled with aluminium have better characteristics than those with hollow grooves. The quality of some samples pertaining to this group is as high as 6500 units. Whereas the characteristics of the resonators of the (112) [1, –1, 0] orientation have a few resonant maxima. When investigating the samples with different size of their resonant cavities (the distances between the two reflection gratings), we have noticed that the frequency interval between the minor resonances is almost independent on the size of the resonant cavity. While the main resonance is sensitive to this magnitude and is well pronounced only if the positions of the IDT electrodes coincide with those of the maxima of the standing wave confined by the refloctors. The minor resonances are probably caused by the interaction between the LSAW and quasitransverse bulk waves. Due to its leaky nature, the SAW, propagating on the (112) cut, penetrates deeper into the crystal than the SAW propagating on the (100) cut, which, as mentioned before, has no leaky component. On the other hand, the SAW, propagating on the (112) cut, has large displacement component in the x_3 direction, perpendicular to the sagittal plane. Those conditions stimulate the transformation of the LSAW, propagating on the (112) cut into a transverse bulk wave.

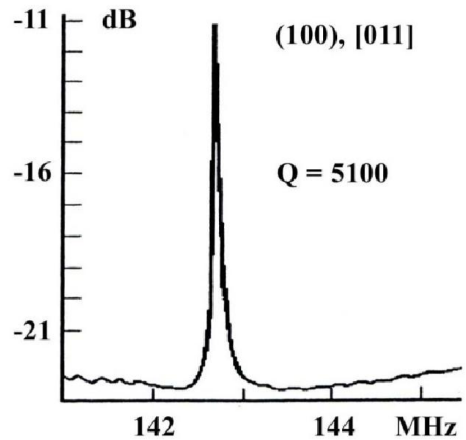

Fig. 3. Frequency-amplitude response of a resonator in the (100), [011] orientation.

The results obtained imply that the (112) [1, –1, 0] orientation is not perspective for the design of SAW resonators. The traditional (001) [1 10] is much better for that purpose.

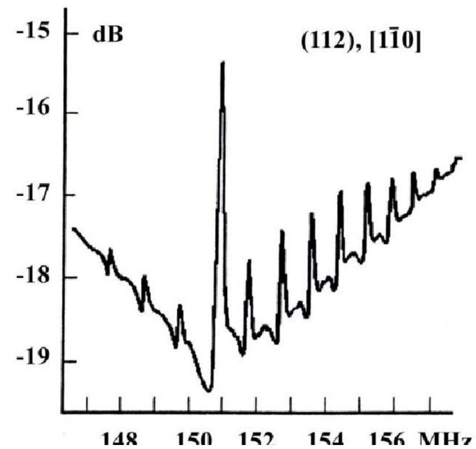

Fig. 4 : Frequency-amplitude response of a resonator in the (112), [0, –1, 1] orientation.

Acoustic charge transport in GaAs

The operation of ACT devices is based on dragging of free charge carriers under the action of electric fields accompanying SAW in piezoelectric and at the same time semiconducting water. These devices are made of GaAs epitaxial structures which are among the best of those suitable for integration of acoustoelectric and semiconducting units in a single crystal [6].

We have fabricated experimental ACT devices from homoepitaxial *i*-GaAs/*n*-GaAs wafers with the 3-3, 5 μm thickness of *n*-GaAs layer having the concentration of free electrons of about 2.10^{15} cm^{-3} and charge carrier mobility higher than $1{,}2\cdot 10^{5}$ $cm^{2}/(V\cdot s)$ at 77K.

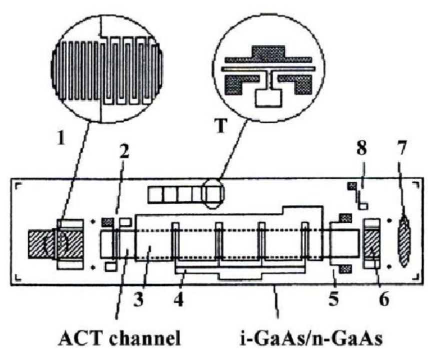

Fig. 5. The scheme of the investigated ACT.

The configuration of experimental ACT device is presented in Fig. 5. The SAW exciting unit (1) consists of an inter digital transducer and SAW reflecting grating [5]. IDT contains 150 pairs of undoubled aluminum electrodes with the 300 μm overlap and 8 μm period. We have studied the ACT devices with SAW reflection gratings realized either as grooves or as aluminum electrodes. In both cases, a reflection grating contained 200 periods. The electrode, which formed a charge transport channel, as well as electrodes of a non-destructive charge testing were made of a 100 nm thick aluminum film. The charge input and output diodes ((3) in Fig. 5) involved an ohmic contact forming electrode made of the Au-Ge-Ni alloy and an aluminum electrode forming a Schottky contact. The width of each electrode and the spacing between them was 2 μm. We have placed a protective aluminum electrode, 2 μm wide, between the input diode and the electrode of the charge transport channel. The width of the transport channel was 240 µm, its length, i.e. the distance between input and output diodes, was 5 mm. Behind the output diode, we have fabricated an IDT to record the SAW level at the charge transport channel output.

We have examined electrical characteristics of our ACT samples by operating them as pulsed signal delay lines. The oscillograms of signals at the output diode for various powers of SAW with the frequency 355.3 MHz are presented in Fig. 6.

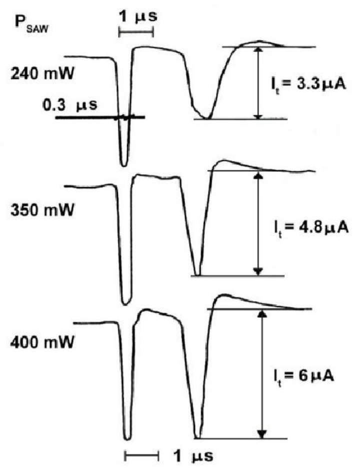

Fig. 6. The oscillograms of signals detected by the output diode for various SAW powers the output diode for various powers of SAW.

SAW devices on GaAs as sensors

SAW devices are widely used as gas and liquid sensors. Their operation is based on the fact that surface loading, entailed by liquid or gas, causes the SAW, propagating over the surface, to slow down. However, it isn't convenient to have the sensing area of the sensor on the same surface as the SAW is generated and detected. It is why SAW which do not penetrate deep into the crystal are not well suited for that purpose [4].

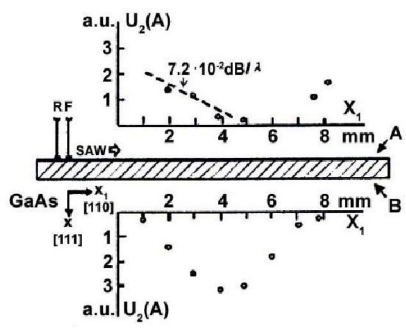

Fig.7 : The measured amplitude of the excitation on the surface B of the sample versus the horizontal distance from the exciting IDT. The geometry of the experiment is such that the LSAW is generated in the direction [1, –1, 0].

Consider now Fig. 7, illustrating the measured amplitude of the excitation on the opposite surface B of the sample. The geometry of the experiment is such that the LSAW is generated in the direction [l, -l, 0] on the cut (111) of GaAs. Due to a large energy flow angle (see Fig. 1), at some short distance from the exciting transducer the LSAW reaches the lower surface of the crystal and then reflects from it back. Therefore, the lower surface of the crystal of this orientation may be conveniently used as a sensing area of a sensor.

Conclusion

Surface acoustic waves (both degenerate and non-degenerate), as being acoustoelectrically active, may be successfully used in semiconductor electronics.

The SAW in the traditional [1, –1, 0] (001) orientation, as being degenerate leaky with no energy flow down into the crystal is best suited for resonators.

The SAW in [1, –1, 0] (112) orientation, as being even more acoustoelectrically active, can be used for SAW filters which yield more symmetric frequency response than those in the [1, –1, 0] (001) orientation. However, due to large displacement component in the x_3 direction and pronounced leaky nature of the wave, its use for SAW resonators is not desirable.

The LSAW in [1, –1, 0] (111) orientation, is of the highest acoustoelectrical activity out of all the SAW known to us in GaAs. Its being extremely "leaky", with large energy flow angle, rules out any possibility of its use for SAW resonators. However, it can be successfully used for sensors with sensing area situated on the crystal boundary opposite to that on which the LSAW is generated and received.

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