AMPLIFICATION OF HYPERSONIC BY GaAs CRYSTALS

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The paper analyzes two basic mechanisms of amplification of acoustic-electromagnetic waves. The first mechanism is similar to the principle of operation of a traveling wave tube due to the piezoeffect, deformation potential, and electrostriction in different materials. The second mechanism is related to the Gunn effect and the negative differential mobility of charge carriers in GaAs. The possible realistic constructions of filters, delays lines, etc. that can be used in communication and control systems are demonstrated. The second mechanism of amplification of hypersound due to the Gunn effect (negative mobility in GaAs) is analyzed in detail. It is shown that this mechanism is more efficient and very promising for designing active filters and delay lines.

1. Introduction

The amplification of acoustic waves is the very well studied problem (see, e.g., [1—3]). The experimental investigations of the amplification have shown that it is possible [2], but its application was very complicated, because hypersound possesses high losses at microwave frequencies. On the other hand, the use of hypersound ($f > 10$ GHz) is very important for the application in the communication and the control systems. In this article, we give the analysis of the basic mechanisms of the amplification including the survey of our previous results mentioned in [4]. Additionally, we show a possibility of the strong amplification due to such mechanism of resonance excitation and amplification of sound as the space charge hybrid mode in n-GaAs films. As an example of the second mechanism, we demonstrate the amplification using the piezoeffect only, but it is clear that the amplification at frequencies $f > 30$ GHz is possible when utilizing the deformation potential in CaAs and another materials.

2. Basic Mechanisms of Classical Amplification of Hypersound, Structures, and Analytical Calculations of Amplification

We use the simplest models of crystals with the piezoeffect, deformation potential, and electrostriction. In the case of the piezoeffect and electrostriction, we use the example of GaAs placed on the substrate with a large value of the electromechanical coefficient of the piezoeffect $K^2 = \beta^2/\varepsilon C$, where the coefficient β is the piezoelectric modulus, and the coefficient C is the the elastic modulus. Really, we have all moduli as tensors. The coefficient $\beta_{i,jk}$ is the piezoelectric tensor of the third rank, and C_{ijkl} is the elastic tensor of the fourth rank. In the simplest case, we use only a single component of the elastic modulus C and the piezoelectric modulus β. Below, ρ is the material density, ε_0 and ε are the dielectric constant of vacuum and the relative dielectric permittivity of the material, respectively, U is the mechanical displacement. Also, V_0 is the constant of the deformation potential, and a_0 is the constant of electrostriction (the ceramics with a very high value of the electrostriction are the materials like $Sr(Ba)TiO_3$ at room temperature [4]). It is possible to make it conductive by means of a new technology.

We consider the simplest case of the passage of a longitudinal acoustic — electromagnetic mode (hybrid mode) in the direction of the axis Z. The equations of elasticity theory are as follows:

$$\rho\frac{\partial^2 U}{\partial t^2} = C\frac{\partial^2 U}{\partial z^2} + \beta\frac{\partial E}{\partial z}, \tag{1a}$$

$$D = \varepsilon_0\varepsilon E - \beta\frac{\partial U}{\partial z} = 0 \tag{1b}$$

in the case of the piezoeffect [4];

$$\rho\frac{\partial^2 U}{\partial t^2} = C\frac{\partial^2 U}{\partial z^2} - V_0\varepsilon_0\varepsilon\frac{\partial E}{\partial z}, \tag{2a}$$

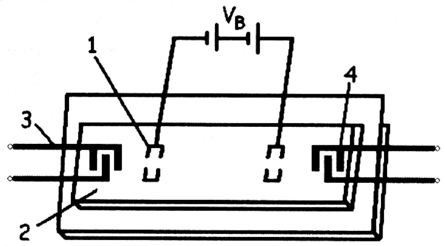


Fig. 1. Contact *1* serves for creating the electron beam, the input and output antennas consist of contacts *2* and *3*, which are ohmic and Schottky, so as we use a hybrid signal which is acoustic and a space charge wave, *4* is the output antenna

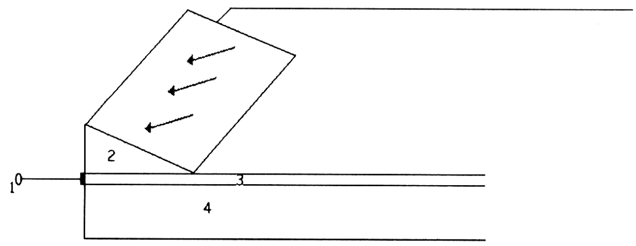


Fig. 2. Ohmic contact 1 is used to form the electron flux. The input and output antennas are like cuneiform element *2* made of i-GaAs. Thin film *3* of $n-$GaAs is on the substrate made of i-GaAs *4*. It is possible to put a signal through cuneiform contact *1*

$$D = \varepsilon_0 \varepsilon E - V_0 \varepsilon_0 \varepsilon \frac{\partial^2 U}{\partial z^2} = 0 \tag{2b}$$

in the case of the deformation potential [4], and

$$\rho \frac{\partial^2 U}{\partial t^2} = C \frac{\partial^2 U}{\partial z^2} - 2a_0 E_0 \frac{\partial E}{\partial z}, \tag{3a}$$

$$D = \varepsilon_0 \varepsilon E + \frac{1}{2} a_0 E_0 E = 0 \tag{3b}$$

in the case of the electrostriction. All values without the index 0 are variable. We have the longitudinal electric constant and a variable electric field in the direction of the axis Z.

The models of realistic structures for the filter and the delay line are shown in Figs. 1, 2.

We use the equations describing the dynamics of carriers and the electric field as well:

$$\frac{\partial D}{\partial z} = en, \tag{4a}$$

$$e \frac{\partial n}{\partial t} + \frac{\partial}{\partial z}(j_z) = 0, \tag{4b}$$

$$j_z = env_z, \tag{4c}$$

$$v = v_z \approx \mu_{diff} E + D_{diff} \frac{\partial n}{\partial z}, \tag{4d}$$

$$D = \varepsilon_0 \varepsilon E. \tag{4e}$$

We use the following equation for the analysis of space charges waves in the simplest model of the space charge wave $\sim \exp(i(\omega t - kz))$ [5—7]:

$$\frac{\partial E}{\partial t} + v_0 \frac{\partial E}{\partial z} + 2iD_{\mathrm{diff}} k \frac{\partial^2 E}{\partial z^2} +$$

$$+(\omega_{\mathrm{M}} + D_{\mathrm{diff}} k^2) E - D_{\mathrm{diff}} \frac{\partial^2 E}{\partial z^2} = 0. \tag{5}$$

Here, the influence of sound is neglected, and we take into account the differential mobility μ_{diff} which is negative in the case of a bias electric field exceeding the critical value for GaAs, v_0 is the constant velocity of electrons forming the current density j_z, n_0 is the electron concentration in the material, D_{diff} is the diffusion coefficient, and $\omega_{\mathrm{M}} = \sigma_{\mathrm{diff}}/(\varepsilon_0 \varepsilon)$ is the Maxwellian relaxation frequency with differential negative conductivity $\sigma_{\mathrm{diff}} < 0$. The first scientist who has used the effect of the amplification of electromagnetic waves was Prof. Anatoliy Barybin (see, e.g., [5]). We use the equations, which are given below, in the analytical calculations and the simulation. The analytical calculations are presented for two types of the amplification. The first mechanism of the amplification works like in a traveling wave tube; in the second one, we use the Gunn effect and the negative differential mobility.

3. Analysis of the Amplification with the Traveling Wave Mechanism

In the case of the piezoeffect, we use the system of equations (1a), (1b), and (4a)—(4e) and describe the hybrid wave like $\sim \exp(i(\omega t - kz))$. The dispersion equation looks as

$$k^2 = \frac{\omega^2}{s^2} - K^2 k^2 \frac{\omega - kv_0 - ik^2 D_{\mathrm{diff}}}{\omega - kv_0 - i(k^2 D_{\mathrm{diff}} + \omega_m)}, \tag{6}$$

where s is the sound velocity, $\omega_{\mathrm{M}} = \sigma_0/(\varepsilon_0 \varepsilon)$ is the Maxwellian relaxation frequency. In this case, it is positive, so as we take into account only the positive case of mobility and conductivity μ_0, σ_0. Taking into account that $k = k_0 + \Delta k \times K^2$ and $\Delta k = \Delta k' + i\Delta k''$, we find the solution for amplification $\Delta k''$ like the first approximation in $K^2 < 1$:

$$\Delta k'' = -\frac{1}{2}\frac{\omega_\mathrm{M}}{s}K^2\frac{1 - v_0/s}{(1 - \frac{v_0}{s})^2 + (\frac{\omega^2}{\omega_D} + \omega_\mathrm{M})^2}, \tag{7}$$

where $\omega_D = v_0^2/D_\mathrm{diff}$ is the diffusion frequency. We have the classical traveling wave amplification in the case of small values of $(s - v_0)/s = \delta < 1$ like that in a traveling wave tube (the Cherenkov effect). Experimental investigations have confirmed this result [2].

Similar calculations in the case of the deformation potential yield the coefficient

$$\Delta k'' = -\frac{1}{2}\omega_\mathrm{M}N^2\frac{\omega^6}{s^6}\frac{1 - \frac{v_0}{s}}{\omega^2(1 - \frac{v_0}{s})^2 + (\omega_\mathrm{M} - \frac{\omega^2}{\omega_D})^2}, \tag{8}$$

where $N^2 = (V_0/e)^2(\varepsilon_0\varepsilon/C)$ is the coefficient (dimensional, [cm$^2\times$s^2]) which is analogous to the parameter $K^2 = \beta^2/(\varepsilon C)$ (dimensionless). The difference in the amplification in the case of the deformation potential is the following. The amplification decreases with frequency so as $\mathrm{Im}(k)_\mathrm{def}/\mathrm{Im}(k)_\mathrm{piezo} = (N^2\omega^4/K^2s^2)$. At frequencies $\omega > (Ks/N)^{1/2}$, the mechanism due to the deformation potential is dominating (this takes place approximately at the frequency $\omega \sim 2 \times 10^{11}$ s^{-1}). In the case of GaAs, this is the millimeter range, so hypersound has classical amplification in the case of the deformation potential. In the case of ceramics with the great values of the coefficients of electrostriction and conductivity, we get analogously

$$\Delta k'' = -\frac{1}{2}\omega_\mathrm{M}M^2\frac{\omega^2}{s}\frac{1 - \frac{v_0}{s}}{\omega^2(1 - \frac{v_0}{s})^2 + (\omega_\mathrm{M} + \frac{\omega^2}{\omega_D})^2}, \tag{9}$$

where the coefficient $M^2 = a_0^2E_0^2/(2\varepsilon_0\varepsilon C)$ is dimensionless and is similar to $K^2 = \beta^2/(\varepsilon C)$. We have a possibility to change (to control) this mechanism of amplification by means of changing the electric constant field E_0. It is very promising, because, in this case, we have a possibility to use a new technology very important for optoelectronics.

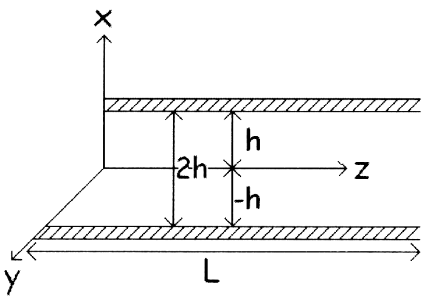


Fig. 3. Geometry of the simplest model for simulation

4. The Simplest Model of Amplification of Hypersound due to the Gunn Effect

For analysis, we use the simplest case of a thin film of n-GaAs placed between two media, one of which is a substrate made of the same material, and the transverse wave passes along the axis Z like that in the structure of Figs. 1, 2 but without acoustic contact with the environment. The component of a mechanical displacement U is directed along the axis Y. The film includes a 2D gas with a high negative differential mobility. The length of the element is L (along the axis Z), and the thickness of the film $2h$ (see the simplest model of simulation in Fig. 3).

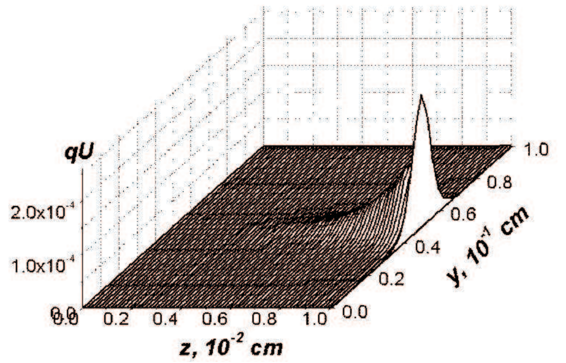
This film has the substrate with depth $d$with the same material. The hybrid wave decreases in the substrate, and all its energy is in the very thin film with a 2D electron beam, so the resonance condition is described by the effective parameter $H = d/2 + h$ (see below).

The input and output antennas are similar to ones presented in Figs. 1, 2, and the sizes are explained in the simulation part of the article below. The other sizes are considered as infinite. We analyze the simplest transverse acoustic mode using the equations of elasticity theory in the presence of the piezoeffect. We use the variable electric field $E = -\partial\varphi/\partial z$ (in the direction of the axis Z) [8, 9] determined by the potential φ:

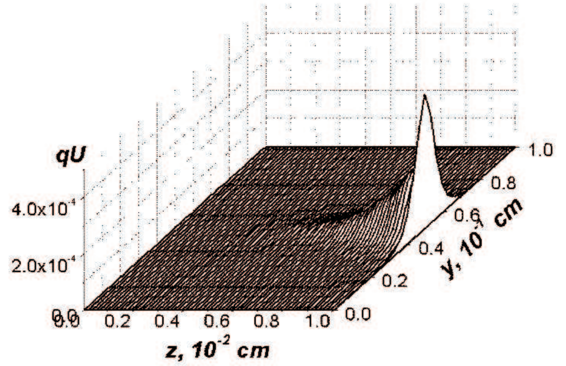
$$\frac{1}{s^2}\frac{\partial^2 u}{\partial t^2} = \Delta u + \Gamma\Delta\frac{\partial u}{\partial t} - \frac{2\beta}{\rho s^2}\frac{\partial^2\varphi}{\partial x\partial z}, \tag{10a}$$

$$-\Delta\varphi + \frac{\beta}{\varepsilon_0\varepsilon}\frac{\partial^2\varphi}{\partial x\partial y} = 0, \tag{10b}$$

$$\left[\frac{\partial u}{\partial x} + -\frac{\beta}{\rho s^2}\frac{\partial\varphi}{\partial z}|x = +, -h/2\right] = 0, \tag{10c}$$



a



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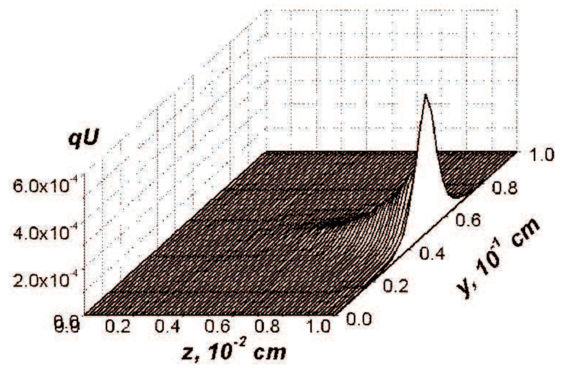

c

Fig. 4. Distribution of the amplitude of the acoustic deformation along the film at the time moments of 3, 4, 5 ns (parts *a, b,* and *c*, correspondingly). The resonant frequency is $\omega = 10^{11}$ s^{-1}. The parameter H is 0.4 μm. The input electric signal (at the input antenna) is $E^{\sim}(z, y, t) = E_{10} \times \exp(-((z - z_1)/z_0)^2 - ((y - y_1)/y_0)^2) \times \sin(\omega t) \times \exp(-((t - t_1)/t_0)^2)$, $z_1 = 0.001$ cm, $z_0 = 2.5 \times 10^{-5}$ cm, $y_1 = 0.05$ cm, $y_0 = 0.005$ cm, $t_1 = 2.5$ ns, $t_0 = 1.25$ ns, and $E_{10} = 25$ V/cm. The 2D concentration of the electron gas is $n_{20} = 10^{11}$ cm^{-2}. The bias electric field is $E_0 = 4.56$ kV/cm. Here, q is the transverse wave number of the acoustic mode (the corresponding mode index is quite large, $m \sim 5$)

where we have the boundary condition (10c) in the case of a free very thin film $2h \ll d$, and we take into account the viscosity coefficient Γ for the simulation of the real situation. In the presence of the electric current, the wave process in this element has the amplification if the synchronism is satisfied between the sound transverse mode and the space charge wave

$$k_0 \approx \sqrt{\frac{\omega_0}{s^2} - \frac{(2m+1)^2\pi^2}{4H^2}} = \frac{\omega_0}{v_0}, \tag{11}$$

where k_0 and ω_0 are the longitudinal wave number and the frequency, respectively, s and v_0 are the velocities of sound and a space charge wave, the parameter $H = d/2 + h$, and the index $m(1, 2, 3...) \gg 1$. The resonance condition $\cos gH \cong 0$ must hold true. The parameters g, ω_0 are given by the formulas

$$g = \frac{\omega_{\mathrm{cr}}}{s} = \frac{(2m+1)\pi}{2H}, \quad \omega_{\mathrm{cr}}^2 = \frac{\pi^2 s^2}{4H^2}\,(2m+1)^2\,.$$

These conditions for the amplification are more optimal for the symmetric modes like

$$u_n \sim B \sin gx \cdot e^{i(\omega t - kz)}, \quad \phi_n \sim \frac{ik\pi}{g} B \cos gx \cdot e^{i(\omega t - kz)}.$$

The boundary condition in the case of the absence of the acoustic contact of the film with the environment has a view (10c). In the simulation, we use Eqs. (5) and (10) and the resonance condition (11). We take into account the 2D electron gas of the $n-$GaAs thin film and the equations for the slowly changing amplitudes of an acoustic-electromagnetic hybrid wave with potential φ. The electric field is directed along the axis Z, and the transverse displacement U is in the direction of the axis Y.

5. Parameters and Simulation of the Amplification of Hypersound due to the Gunn Effect

The numerical simulations have demonstrated the effective amplification of hypersound in the presence of the negative differential mobility (conductivity). The following parameters have been chosen: the concentration of electrons in the film is $n_0 \approx 10^{15}$ cm^{-3}, the velocity of electrons is $v_0 \approx 2 \times 10^7$ cm/s, the length of the film is $L < 0.1$ cm, and the parameter $H \leq 1$ μm. The intensity of the acoustic mode can reach 1 $\mathrm{W/cm}^2$ at microwave frequencies $\omega = 5 \cdot 10^{10} - 2 \cdot 10^{11}$ s^{-1}. In Fig. 4, we demonstrate the amplification of hypersound (a hybrid wave).

6. Conclusions

We have discussed two mechanisms of the amplification of hypersound, namely the traveling wave mechanism and the mechanism connected with the Gunn effect (the negative differential mobility), and the possible realistic structures for applications like active filters and delay lines.

The traveling wave mechanism has been demonstrated in three cases: piezoeffect, deformation potential, and electrostriction. We demonstrate the strong effect of the amplification of hypersound (a hybrid wave) in the case of the piezoeffect. The mechanism due to the deformation potential can be used at high microwave frequencies (hypersound), it dominates at frequencies $\omega > 2{\cdot}10^{11}$ s^{-1}. The mechanism due to the electrostriction is characterized by the possibility to change (to control) the level of the amplification due to the use of a bias electric field.

The excitation of coupled space charge — acoustic waves (a hybrid wave) in thin n-GaAs films is realized due to the synchronism of the sound mode and the space charge wave. A thin film is placed between two media without an acoustic contact. This film includes a 2D electron gas with high negative differential conductivity. In the presence of a current, the amplification of a space charge wave takes place due to the negative differential conductivity. This wave can excite the acoustic modes of the film due to the piezoeffect. It has been shown that the inverse influence of the excited sound on the space charge wave is unessential. The numerical simulations have demonstrated the effective excitation of hypersound there.

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ПІДСИЛЕННЯ ГІПЕРЗВУКУ КРИСТАЛАМИ GaAs

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Р е з ю м е

Розглянуто два основні механізми підсилення акустоелектромагнітних хвиль. Перший механізм аналогічний принципу дії лампи біжучої хвилі з використанням різних матеріалів завдяки п'єзоефекту, деформаційному потенціалу та електрострикції. Другий механізм пов'язаний з ефектом Ганна та від'ємною диференціальною рухливістю носіїв заряду в GaAs. Запропоновано реальні схеми фільтрів, ліній затримки, і т.п. в комунікаційних системах та системах контролю, що використовують вищезазначені механізми. Другий механізм підсилення гіперзвуку за допомогою ефекту Ганна досліджено детально. Показано, що цей механізм підсилення ефективніший для побудови активних фільтрів та ліній затримки.