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Academician B. P. Konstantinov, A. A. Grinberg, A. A. Kastalsky,

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Abstract

Full Text

Physics

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Generation of Ultrasound at a p-n Junction Made of a Nonpiezoelectric Material

The question of the possibility of using the space charge of a transition layer, one of whose materials possesses piezoelectric properties, was investigated theoretically and experimentally in work ([1]). A GaAs–metal contact was used as the transition layer; a frequency of 600 MHz was achieved on it. An alternating (sinusoidal) voltage was applied to the contact, connected in the reverse direction, and this voltage fell entirely across the space-charge region. Since GaAs is a piezoelectric, a change in the potential across the space-charge layer is accompanied by deformation of the lattice in the space-charge layer. If the frequency of the electrical signal coincides with the geometrical (natural) frequency of this region of the crystal, the excitation of ultrasound will take on a resonant character, and the space charge will operate similarly, for example, to a quartz plate of thickness L, equal to the thickness of the space-charge layer. The latter may reach values of several microns, so that the corresponding resonant frequency will be of the order of 10^3 MHz.

However, generation of ultrasound is also possible at an ordinary (p—n)-junction (and, in general, in any blocking layer) made of a material that does not possess a piezoelectric effect. The mechanism of ultrasound excitation in this case is due to the attraction of positively charged donors of the n-region and negatively charged acceptors of the p-region, which within the space charge of the p—n-junction are in an ionized state, and whose charge is not compensated by free current carriers. The application of an external potential difference to the p—n-junction leads to a change in the thickness of the space charge and thereby to a change in the force of their attraction. Since impurity atoms may be regarded as practically rigidly fixed in the lattice, this force determines the internal stresses of the crystal.

Let us pass to a quantitative description. We choose as the x-axis an axis directed perpendicular to the plane of contact of the p- and n-regions, with origin located in this same plane ($x > 0$ corresponds to the n-region).

The equation describing the deformation of the lattice is then written in the form

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Figure 1

Figure 1: Figure 1

Figure 1a

Figure 2: Figure 1a

$$\frac{1}{s^2}\frac{\partial^2 u}{\partial t^2} - \frac{\partial^2 u}{\partial x^2} = \frac{1}{\rho s^2}\frac{\partial T}{\partial x}, \tag{1}$$

where T is the stress tensor of the electric field, equal in the case under consideration to $\frac{\varepsilon}{8\pi}E^2$. Here ρ, ε are the density and dielectric constant of the material of the (p—n)-junction; s is the velocity of sound in it; E is the electric-field strength; u is the displacement of the lattice.

As a concrete example we shall consider a (p—n)-junction with a sharp boundary between the n- and p-regions. The electric field in the space-charge region of such an (n—p)-junction is written in the following analytic form:

$$E = -\frac{4\pi e}{\varepsilon}N_a(L_a + x)\big|_{-L_a<x<0}; \qquad E = -\frac{4\pi e}{\varepsilon}N_d(L_d - x)\big|_{0<x<L_d}. \tag{2}$$

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Fig. 1. Photographs of the glow of slot cells. Distance between electrodes:
a –0.4 mm, b –0.3 mm,
c –0.5 mm

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Fig. 1. a –signal from the piezoelectric transducer, $f_{\text{res}} = 500$ kHz, b –voltage at the p-n junction; the bias voltage V was applied in the form of a pulse of duration 120 μsec

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where L_a and L_d are the thicknesses of the space charge in the p- and n-regions, equal to

$$L_d = \left[\frac{\varepsilon V}{2\pi e N_d(1 + N_d/N_a)}\right]^{1/2}; \qquad L_a = \frac{L_{dN}d}{N_a}; \tag{3}$$

N_a, N_d are the concentrations of acceptor impurity in the p-region and donor impurity in the n-region, respectively,

$$V = \frac{2\pi e}{\varepsilon}N_{dL}d(L_d + L_a).$$

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To investigate the resonant operation of a $(p-n)$-junction, let us consider the case in which a large constant bias voltage in the reverse direction, V_0, is applied to the diode, while oscillations are excited by a small sinusoidal voltage $|\tilde{v}|$, such that the inequality

$$\tilde{v} \ll V = V_0 + V_k, \tag{4}$$

is satisfied, where V_k is the contact potential difference.

To accuracy linear in $\tilde{v}$, equation (1) is rewritten in the form

$$\frac{1}{s^2}\frac{\partial^2 u}{\partial t^2} - \frac{\partial^2 u}{\partial x^2} = F_a \quad \text{for } -L_a \le x \le 0; \qquad \frac{1}{s^2}\frac{\partial^2 u}{\partial t^2} - \frac{\partial^2 u}{\partial x^2} = -F_d \quad \text{for } 0 \le x \le L_d, \tag{5}$$

where

$$F_a = \frac{\varepsilon L_a}{8\pi\rho s^2}\left(\frac{4\pi e N_a}{\varepsilon}\right)^2 \frac{|\tilde{v}|}{V} e^{i\omega t}; \qquad F_d = \frac{\varepsilon L_d}{8\pi\rho s^2}\left(\frac{4\pi e N_d}{\varepsilon}\right)^2 \frac{|\tilde{v}|}{V} e^{i\omega t}.$$

We shall first consider the case in which the diode is loaded (in the acoustic sense), on the side of the n-region, by an infinitely extended medium of the same composition as the material of the $(p-n)$-junction, while on the side of the p-region it borders on vacuum. In this case, the solution of equations (5) in the space-charge region and outside it, with allowance for the boundary conditions corresponding to the case under consideration, gives for the amplitude of the generated ultrasonic wave in the region $x > L_d$ the expression*:

$$|u| = \frac{F_{as}^2}{\omega^2}\left[\left(1 + \frac{N_d}{N_a}\right)\sin kL_a - \frac{N_d}{N_a}\sin k(L_a + L_d)\right], \tag{6}$$

where ω is the frequency and k is the wave number of the sound wave.

In the case of a strongly asymmetric $(p-n)$-junction, namely for $N_d \ll N_a$, $kL_a \ll 1$, it follows from (6) that

$$|u| = \frac{F_{dL_{ds}}}{\omega}\left(1 - \frac{\sin kL_d}{kL_d}\right). \tag{7}$$

The resonance is determined by the condition $k_{nL}d = 2\pi(n + 3/4)$, where $n = 0, 1, 2, ...$, and the power of the acoustic energy at resonance is equal to

$$W_n = \frac{\rho s^3 (F_{dL} d)^2}{2}\left[1 + \frac{1}{2\pi(n + 3/4)}\right]^2. \tag{8}$$

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An estimate of W_n for Ge ($s = 5 \cdot 10^5$ cm/sec; $\rho = 5.4$ g/cm^3; $\varepsilon = 16$) at $N_d = 10^{17}$ cm$^{-3} \ll N_a$, $V = 30$ V, $|\tilde{v}| = 3$ V gives the value $W_n = 5 \cdot 10^{-3}$ W/cm^3 at $\omega_n = 3 \cdot 10^{10}$ sec^{-1}.

Of great interest is the case in which the diode p- and n-regions adjoining the space-charge region are finite, and the radiation occurs into an ambient medium with an acoustic impedance $\rho_0 s_0$ different from that of the material of the $(p-n)$-junction.

* In solving equation (5) we did not take into account changes in the boundaries of the space-charge region, which is permissible under the condition

$$k(L_a + L_d)\frac{|\tilde{v}|}{2V} \ll 1,$$

which means that the change in $L_a + L_d$ upon application of the voltage $\tilde{v}$ is small compared with the wavelength of sound (see (1)).

Let us denote by d_1 and d_2, respectively, the thicknesses of the n- and p-regions of the $(p—n)$-junction. If such a $(p—n)$-junction is placed in a medium with acoustic resistance $\rho_0 s_0$, then for the amplitude of the ultrasonic wave radiated into this medium we obtain the following relations.

For $x \geqslant d_1$

$$|u| = \frac{F_a s^2}{\omega^2}\Big\{\left[y \sin k(d_2 + L_d) + \sin k(d_2 - L_a) - (1+y)\sin kd_2\right]^2 +$$

$$+\xi^2\left[\cos k(d_2 - L_a) + y\cos k(L_d + d_2) - (1+y)\cos kd_2\right]^2\Big\}^{1/2} \times$$

$$\times\Big\{(1+\xi^2)^2 \sin^2 k(d_1 + d_2) + 4\xi^2 \cos^2 k(d_1 + d_2)\Big\}^{-1/2}.$$

For $x \leqslant -d_2$

$$|u| = \frac{F_a s^2}{\omega^2}\Big\{\left[\sin k(d_1 + L_a) + y\sin k(d_1 - L_d) - (1+y)\sin kd_1\right]^2 + \qquad (9)$$

$$+\xi^2\left[\cos k(d_1 + L_a) + y\cos k(d_1 - L_d) - (1+y)\cos kd_1\right]^2\Big\}^{1/2} \times$$

$$\times\Big\{(1+\xi^2)^2 \sin^2 k(d_1 + d_2) + 4\xi^2 \cos^2 k(d_1 + d_2)\Big\}^{-1/2},$$

where $y = N_d/N_a$, $\xi = \rho_0 s_0/\rho s$.

Let us now consider a number of limiting cases following from (9).

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1. A completely symmetric system: $d_1 = d_2 = d;\ N_d = N_a;\ d > L_a;$

$$|u|_{|x|\geq d} = \frac{4F_a s^2}{\omega^2 \xi}\ \sin^2 \frac{kL_a}{2} \sqrt{\frac{\sin^2 kd + \xi^2 \cos^2 kd}{(1+\xi^2)^2 \sin^2 2kd + 4\xi^2 \cos^2 2kd}}. \tag{10}$$

The maximum amplitude (resonance) is attained, if $\xi \ll 1$, for k satisfying the condition

$$k_n d = (2n+1)\frac{\pi}{2}, \qquad n = 0, 1, 2, ... \tag{11}$$

It is then equal to

$$|u^{\text{res}}| = \frac{2F_a}{\xi k_n^2} \sin^2 \frac{k_{nL} a}{2}.$$

If $d \gg L_a,\ k_{nL} a \ll 1$, then

$$|u^{\text{res}}| = \frac{F_{aL} a^2}{2\xi},$$

and the power of the ultrasonic energy radiated to one side is

$$W_n = \frac{1}{2}\rho s \omega_n^2 \left(\frac{F_{aL} a^2}{2\xi}\right)^2. \tag{12}$$

2. $L_a \ll L_d \ll d_1 = d_2 = d; \quad kL_d \ll 1.$

This case is easily realized experimentally. The amplitude has the form (for $|x| > d$)

$$u = \frac{F_{aL_{aL}} d}{2} \left\{ \frac{\sin^2 kd + \xi^2 \cos^2 kd}{(1+\xi^2)^2 \sin^2 2kd + 4\xi^2 \cos^2 2kd} \right\}^{1/2}. \tag{13}$$

In the case under consideration, for $\xi \ll 1$, resonance, as in case 1, occurs under condition (11), but the amplitude turns out to be L_d/L_a times larger than in case 1:

$$u^{\text{res}} = \frac{F_{aL_{aL}} d}{4\xi} = \frac{F_{dL} d^2}{4\xi}. \tag{14}$$

3. $L_a \ll L_d \ll d_2 \ll d_1,\ kd_2 \ll 1$. The variant considered is applicable to the majority of industrial diodes. The resonance is determined by the condition

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$$k_n(d_1 + d_2) = n\pi, \qquad n = 1, 2, \dots, \tag{15}$$

and the resonant amplitude is equal to

$$u^{\text{res}}_{|x|>d_1} = \frac{F_a k_n L_a L_d d_2}{4\xi} \sqrt{1 + \frac{\xi^2}{(k_{nd}2)^2}}. \tag{16}$$

The ratio of this amplitude to the amplitude in case 1 is equal to $\frac{L_d d_2 k_n^2}{2L_a}$. This quantity may be either greater than unity or less than unity, depending on the relation between d_1 and d_2.

Thus, from both the theoretical and the experimental point of view, the most favorable is case 2, considered in formula (14). Estimates show that for this case, as applied to germanium $(p-n)$ junctions placed in air ($\xi = 10^{-5}$) with $N_d = 10^{17}$ cm$^{-3} \ll N_a$, $|\tilde{v}| = 3$ V, $V = 30$ V, $d_1 + d_2 = 0.5$ cm, when operating at the first resonant harmonic, the pressures arising in the sample are of the order of 3 kg/cm^2, and the radiated power is

$$W = \frac{\rho s \omega_n^2}{32} \frac{(F_d L_d^2)^2}{\xi} \simeq 0.4 \cdot 10^{-5}(2n+1)^2 \ \frac{\text{W}}{\text{cm}^2}. \tag{17}$$

Let us note in conclusion that in piezoelectric semiconductors, to order of magnitude, the ratio of the force of electrostatic interaction of ions to the piezoelectric force is equal to E_m/η, where E_m is the maximum electric field in the space-charge layer, and η is the piezoelectric constant. For known piezoelectric semiconductors this ratio is less than 0.1, so that piezoelectric semiconductors are a more efficient material from the point of view of ultrasound generation. However, in physical investigations using ultrasound, the method considered above can be used for contactless introduction and reception of ultrasound in a wide class of nonpiezoelectric semiconductors.

An experimental verification of the calculation set forth above was carried out for a germanium $p-n$ junction ($N_a \gg N_d \simeq 10^{16}$ cm^{-3}) with adjoining p- and n-regions ($d_1 = d_2 = d = 0.5$ cm; to eliminate electrical pickup between the n-region and the piezoelectric transducer, a quartz buffer of length $2d$ was placed).

The oscillation amplitude (see Fig. 1, inset, p. 44) proved proportional to $|\tilde{v}|$, and at $V = 15$ V and $\tilde{v} = 3$ V the relative displacement $\partial u/\partial x$ reached a value of the order of 10^{-3}, which corresponded to loads of the order of 10^3 dyn/cm^2.

Because of internal losses, the width of the resonance band, equal in our case to 10 kHz ($\Delta\omega/\omega_0 \simeq 2 \cdot 10^{-2}$), considerably exceeded the theoretical one ($\Delta\omega/\omega_0 \simeq 10^{-5}$), and as a consequence the oscillation amplitude proved to be three orders of magnitude lower than the calculated value.

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In conclusion, we note that, simultaneously, the mechanism of ultrasound generation set forth above was independently considered theoretically by V. L. Gurevich and G. E. Pikus (private communication) for the case of a $p-n$ junction loaded on both sides by an infinite medium of the same acoustic impedance as the $p-n$ junction.

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Note: Figure translations are in progress. See original paper for figures.

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