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COMMENT ON WHITE'S ACOUSTOELECTRIC FORMULA VALIDITY

ЗАМЕЧАНИЕ ПО ПОВОДУ СПРАВЕДЛИВОСТИ ЭЛЕКТРОАКУСТИЧЕСКОЙ ФОРМУЛЫ ВАЙТА.

I. TUREK*, Žilina

According to White's theory [1] the electron contribution to ultrasound absorption in piezoelectric semiconductors with small electric conductivity shows an interesting feature: the field dependence of the sound absorption should have a sharp maximum of gain or a sharp maximum of absorption in fields slightly greater or smaller then the critical field E_0. (The critical field is the field for which the drift velocity of the electrons is equal to the sound velocity). However, the field dependences of the absorption, obtained from experiment do not confirm this result of White's theory [2, 3].

Discussing this disagreement Shapiro and Spector [4] pointed out that White's formula resulted from the first iterative step of solving the dispersion equation (1) and so it does not describe the problem in all its features. In order to discuss the question of accuracy of White's formula we carried out the second iterative step for solving the dispersion relation [4]:

$$\left[\left(\frac{\omega}{v_k}\right)^2 - k^2\right][\omega - kv_d - \mathrm{i}\,(\omega_c - \mathscr{D}k^2)] = -\mathrm{i}\left(\frac{v_0}{v_k}\right)^2 K^2\omega_c k^2 . \tag{1}$$

Here k and ω are the wave number and angular frequency of the sound, v_0 is its velocity without taking into account the piezoelectric effect, $v_k = v_0(1+K^2)^{1/2}$, K is the electromechanical coupling constant, σ and ε are the electric conductivity and permittivity, v_d and $\mathscr{D}$ are the drift velocity and the electron diffusion constant in the material.

When $K^2 \ll 1$ equation (1) may be rewritten in the form convenient for iteration:

$$k^{(i+1)} = \frac{\omega}{v_K} + F(k^{(i)}) , \tag{2a}$$

where $k^{(i)}$ is the result of the i-th step of the iterative procedure and

$$F(k) = i\,\frac{K^2}{2}\,\frac{\dfrac{v_0^2}{v_K}\,\dfrac{\omega_c}{\omega}\,k^2}{\omega - v_d k + \mathrm{i}(\omega_c + \mathscr{D}k^2)} . \tag{2b}$$

If we take $k^{(0)} = \omega/v_K$ as the zero-th approximation, we get the following relation for the difference between the first and the zero-th approximation (i.e. for $\delta_1 k = k^{(1)} - k^{(0)}$):

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* Department of Physics, Techn. Univ. of Transport and Comm. Engineering, CS-010 88 ŽILINA.

$$\delta_1 k = i \frac{\frac{K^2}{2} \frac{\omega_c}{v_K}}{\gamma + i\left(\frac{\omega_c}{\omega} + \frac{\omega}{\omega_D}\right)}, \tag{3}$$

where $\gamma = 1 - v_d/v_K$ and $\omega_D = v_K^2/\mathcal{D}$.

As $\delta_1 k$ is small in comparison with $k^{(0)}$, the second step of the iterative procedure can be expressed as follows:

$$k^{(2)} = k^{(1)} + \left(\frac{\partial F(k)}{\partial k}\right)_{k^{(0)}} \delta_1 k . \tag{4}$$

Expressing $F(k)$ in (4) according to (2b) one gets for $\delta_2 k = k^{(2)} - k^{(1)}$:

$$\delta_2 k = -i \frac{K^2}{2} \frac{\frac{\omega_c}{\omega}\left(1 + \gamma + 2i\frac{\omega_c}{\omega}\right)}{\left(\gamma + i\left(\frac{\omega_c}{\omega} + \frac{\omega}{\omega_D}\right)\right)} \delta_1 k . \tag{5}$$

It is seen from (4) that the correction (5) can be interpreted as a result of a shift of the function $F(k)$ in the k-space by $\delta_1 k$. When $\gamma = 0$ and $\omega \ll \omega_D$, $\delta_1 k$ is equal to the real value $\frac{K^2}{2} \cdot \frac{\omega}{v_K}$ and the shift by $\delta_1 k$ in the k-space is equivalent to the shift by $\delta_1 v = -\frac{K^2}{2} v_K$ in the v-space.

That is a resonable result as the sound absorption should be expected to vanish when the drift velocity is equal to the actual value of the sound velocity and not when it is equal to v_K, which is the zero-th step approximation only.

The obtained value

$$(v_d)_{\alpha=0} = \left(1 - \frac{K^2}{2}\right) v_K \doteq v_0$$

indicates that the actual value of the sound velocity at $\gamma = 0$ is v_0. It corresponds to the fact that the piezoelectric field of the wave is compensated by the field of the free charge when $\gamma = 0$.

The value $\delta_1 k$ by which the function should be shifted is not constant. In spite of it the shape of the absorption field dependence following from the second step approximation is like that following from the first step approximation, as the value $\delta_1 k$ does not change very fast in the investigated region (for extremal α : $\gamma_1 = -\omega_c/\omega$ and $\gamma_2 = +\omega_c/\omega$). Thus, the sharp maxima of gain or absorption in fields close to the field E_0 are not a result of approximations made in the derivation of White's formula. Thus the disagreement between the theory and the experiments must be caused by non-fulfilling the assumptions of the theory.

The dispersion relation (1) describes the problem accurately only in the case of a long life-time of the carriers in the material. The life-time has to be longer than the period of the acoustic wave, not to prevent creation of the space-charge which compensates the electric field of the acoustic wave. However, the time of the formation of this charge is limited by the sound period observed in the coordinate system moving together with the space-charge. When the charge drifts with the velocity approaching the sound velocity, the effective period (according to the Doppler effect) becomes very large and so the period will exceed the carrier life-time very probably. In such a situation the relation (1) is not valid longer. The disagreement of experiments with White's theory is expected to appear in the fields where $v_d \cong v_K$ when the effective period becomes very large (i.e. in the region of the discussed maxima). At the same time, White's formula may remain valid for the other fields. We suppose that this is the very reason why the frequency dependence of the sound attenuation without the applied field corresponds well to White's formula, while the field dependence of the sound absorption in the same material does not correspond to White's theory in the same frequency range [3].

The present explanation is implicitly contained in the relations describing the sound absorption in the case of a short electron life-time, which leads to its good agreement with the experiment [5].

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