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LARGE MULTIPLE ACOUSTOELECTRIC INTERACTION OF SURFACE ACOUSTIC WAVES IN SEMICONDUCTOR-PIEZOELECTRIC STRUCTURE

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Quasi-static and quasi-one dimensional method of calculation of acoustoelectric interaction of surface acoustic waves (SAW) in layered semiconductor-piezoelectric structures are developed. The method is based upon conceptions of the electron and hole quasi-Fermi levels and the surface electric impedance. Both the concentration and trap mechanisms of nonlinearity are taken into account. This permits to obtain a nonlinear solution in not only small signal approximation. The solution obtained is valid for finite and also large SAW amplitudes and takes into account special surface semiconductor properties of principle such as surface band bending and surface states. According to the method, nonlinear SAW attenuation and dispersion, convolution, transverse acoustoelectric voltage (TAV), acoustoelectric current and charge transport, and acoustoelectric bistability are calculated and analyzed. The theoretical results obtained are in agreement with many our and other experimental results and may be principles of calculation of the nonlinear acoustoelectric devices and investigation technique.

KEYWORDS : quasi-static, quasi-one dimensional, nonlinear acoustoelectric phenomena, transverse acoustoelectric voltage, acoutoelectric current, volume dielectric permitivity.

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Introduction

Nonlinear acoustoelectric phenomena [1, 2] in layered piezoelectric-semiconductor structures evoke scientist's and engineer's interest in their application to the design of date-processing and sensing devices, the new technique for nondestructive evaluation of basic electronic properties of materials, and wave modeling [3-5]. It is well-known nonlinear acoustoelectric devices such as convolvers, correlators, acoustic charge transport devices, and sensors. In the most cases the theory used for describing nonlinear acoustoelectric interaction of surface acoustic waves (SAW) is based on a small signal approximation [6-8]. This assumption is not enough for describing nonlinear acoustoelectric interaction of not small SAW amplitudes and do not permit us to make calculations in dynamics and understand nonlinear acoustoelectric phenomena discovered formerly such as bistability, multistability, self-sustained oscillation of acoustoelectric voltages and self-sustained modulation of SAW power [9-12].

A SAW interacts with the semiconductor by means of an accompanying alternating electric field that penetrates into the semiconductor and because of nonlinear semiconductor properties the SAW has nonlinear attenuation and dispersion and various nonlinear acoustoelectric voltages and currents arise. The main problem is how to find a solution of nonlinear SAW attenuation and dispersion and amplitudes of acoustoelectric voltages and currents that could be valid for finite and also large SAW amplitudes. It is especially necessary because a criterion of large SAW amplitudes in the layered piezoelectric-semiconductor structure is easy achieved for relatively small SAW power of several tens' watts. Surface principal properties of semiconductor in the layered structures such as surface band bending and trapping free charge carriers must also be taken into account. Their necessity of taking into consideration is another peculiarity of the nonlinear SAW acoustoelectric interaction and leads to mathematical difficulties.

In this paper, a new analytical method for calculation of nonlinear SAW acoustoelectric interaction that permits to obtain the nonlinear solution being valid for small signal and large SAW amplitudes and taking into account special surface semiconductor properties of principle such as surface states and band bending of the semiconductors. According to the method, nonlinear SAW attenuation and dispersion, convolution, transverse acoustoelectric voltage (TAV), acoustoelectric current and acoustic charge transport are calculated and analyzed.

AN APPROACH FOR SOLVING THE PROBLEM

Solving the problem of nonlinear SAW acoustoelectric interaction in the layered structures we will base on the quasi-static and quasi-one dimensional approach, the conceptions of surface electric impedance advanced [13-15], and the electron and hole quasi-Fermi levels known in semiconductor theory [16, 17]. Both concentrations and trapping mechanisms of nonlinearity will be included into consideration.

Let us assume that in a layered piezoelectric-semiconductor structure a SAW with a frequency ω and a wave number k propagates along the z direction.

Before solving the problem it is interesting to take into consideration that in the limit case of a metal film instead of the semiconductor in the layered structure, on the surface of the film there is a zero longitudinal component of electric displacement, a zero surface electric potential φ_s, and a non zero normal component of electric displacement $D_s = D_{s0} + D_0 \cos(\omega t - kz)$, where D_{s0} and D_0 are the electric displacement in the cases without SAW and an amplitude of the tern created by the SAW, respectively. The value D_0 is proportional to a SAW amplitude and will characterize one. In the case of a semiconductor in the layered structure when the SAW frequency ω is much less than the conductivity frequency ω_c and the screen length ω is much less than the wavelength, the value D_s is approximately the same and the value φ_s differs from zero that we have to find. (Note that in the general case the screen length w does not equal to the Debye length). Taking the surface electric impedance or surface effective dielectric permitivity and, consequently, by means of impedance method we can calculate SAW attenuation and dispersion [13-15]. Taking harmonics of the surface potential

φ_s with zero wave number k permits us to obtain amplitudes of convolution and transverse acoustoelectric voltage. Taking into consideration longitudinal current gives acoutoelectric current.

In the semiconductor we will take solutions for electron n and hole p concentration in terms of

$$n = n_0 \exp\left(\frac{(q\varphi + x_n)}{T}\right), ...p = p_0 \exp\left(-\frac{(q\varphi + x_p)}{T}\right), \quad \dots (1)$$

where, respectively, n_0 and p_0 are the electron and hole concentration beyond the screen region; q is the electron charge, φ is the electric potential; T is temperature in energetic unit; χ_p and χ_n are the electron and hole quasi-Fermi levels with a deviation of semiconductor condition from the thermodynamic equilibrium. We will consider n–type semiconductor with and without inversion p-layer.

Using eq. (1) in assumption of constantancy of the χ_p and χ_n with depth in the screen region, the Poisson equation is integrated and with boundary conditions the surface potential can be presented in the following form:

$$\varphi = G(D_s) + A_n\chi_n + A_p\chi_p \quad \dots (2)$$

where $A_n = -1/q$, $A_p = 0$ for depletion-accumulation and $A_n = 0$, $A_p = -1/q$ for inversion, respectively; $G(D_s)$ is the function in the case of homogeneous thermodynamic equilibrium, and in semiconductors surface physics its inverse function $F(\varphi_s)$ is well known and expressed analytically [16, 17] :

$$F(\varphi_s) = -\text{sign}(\varphi_s)\sqrt{\sqrt{P_0/n_0}(e^{-\varphi_s/T} + \varphi_s/T - 1) + \sqrt{n_0/p_0}(e^{\varphi_s/T} - \varphi_s/T + 1)}$$

Then the equations of continuity for the electron and hole currents give equations for the χ_n and χ_p values. For example, in the case of inversion and depletion-accumulation we have, respectively,

$$\chi_p = iT\frac{\omega_{Dp}}{\omega}.\frac{1}{P(z)}\left\langle\frac{1}{P(z)}\right\rangle, \; \chi_n = i\frac{\omega}{\omega_c}.\frac{q}{\varepsilon_s k}D_S(z) \quad \dots (3)$$

where $P(z)$ is the layered surface hole concentration in the surface space charge region that is modulated by the SAW electric displacement $D_s(z)$, depends on the coordinate z, and changes in time with the frequency ω; $\omega_{Dp} = \omega^2/k^2D_p$ is the hole diffusion frequency; D_p is the hole diffusion coefficient; ε_s is the volume dielectric permitivity of the semiconductor.

THEORETICAL RESULTS

Separating out the harmonic with ω and k for the $G(D_s)$ function and χ_p and χ_n according to eqs. (2) and (3) we can calculate the harmonics of the surface electric potential φ_s and the surface effective permitivity of the semiconductor and SAW attenuation and dispersion for various SAW amplitudes in the layered structures. We will separate those SAW amplitudes $D_0 > D_{s0,}$ when in the inversion case the inversion layer is destroyed by the SAW electric field. Finally, we will present some theoretical results obtained.

2.1 Static quasi one-dimensional approximation ($\chi_p \cdot \chi_n = 0$)

Small values of χ_p and χ_n is enough for calculation of transverse acoustoelectric effects such as SAW convolution and TAV. In static quasi-one dimensional approximation, when the χ_p and χ_n values and SAW attenuation are equal to zero, calculation of small signal convolution has been given in [18] and then a convolution and TAV of finite SAW amplitudes have been given in [17, 20]. For this paper it is necessary to note that strong nonlinearity for low SAW power is not strong for large SAW power. Devices with low losses have not a wide dynamic range. We have to choose the low losses or wide dynamic range. There is an optimal condition between both of them. Amplitudes of different nonlinear effects as convolution V_c (D_0), *TAV* V_a (D_0), and others can be expressed in terms of the function G (φ_s) and each other with the relations:

$$V_c(D_0) = \frac{1}{2\pi}\int_{-\pi}^{\pi} v_a(2D_0\cos\alpha)\ \cos(2\alpha)\ d\alpha,.$$

$$V_c(D_0) = \frac{1}{2\pi}\int_{-\pi}^{\pi} G(D_{s0} + D_0\cos\alpha)\ d\alpha - \varphi_{s0}.$$

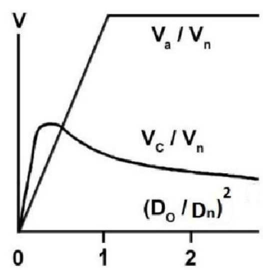

Fig. 1. The normalized convolution amplitude V_c/V_n and normalized TAV amplitude V_a/V_n verses the normalized SAW amplitude squared $(D_0/D_n)^2$.

In some cases the TAV reverses a sign with increasing the SAW amplitude and changing the band bending potential φ_s. Its limit magnitude $V_{\underline{a}}$ is equal to the saturation value $V_n = (T/2q)\ \ln\ (p_0/n_0) - \varphi_s$ that increases with increasing the concentration n_0. The convolution decreases under increasing the SAW amplitude. A typical dependence of the normalized convolution amplitude V_c/V_n with the normalized SAW amplitude squared $(D_0/D_n)^2$ is shown in Figure 1 when the TAV amplitude V_a has a saturation shape, Here, D_0 is the SAW amplitude when the TAV saturation achieved and approximately equal to $D_n = s_sTn_0$. The value $(D_0/D_n)^2$ is proportional to the SAW power.

2.2 Quasi-static, quasi-one dimensional approximation ($\chi_p \cdot \chi_n \neq 0$)

In quasi-static approximation, when the χ_p and χ_n values are not equal to zero but small, for calculation of the SAW attenuation, dispersion, and acoustoelectric current one should take into consideration their non zero values in (2).

The SAW attenuation is given by the following expression for its coefficient:

$$\alpha = \frac{\Delta V_s}{V_s} k(B_n\alpha_n + B_p\alpha_p),$$

where $$B_n = \frac{\varepsilon_p}{\varepsilon_s}\frac{\omega}{\omega_c},\ B_p = \frac{T\varepsilon_p \omega_{Dp}}{q^2 V_s}\frac{1}{p(D_{s0})},$$

$\Delta V_s/V_s$ is the relative deviation of the SAW velocity $V_s = \omega/k$ under metallization of the piezoelectric with the dielectric permitivity ε_p in the layered structure. Normalized coefficients α_n and α_p are :

$$\alpha_n = 0,\ 1,\ 1 + \frac{\sin(2\pi / D_{On})}{2\pi} - \frac{1}{D_{On}};$$

$$\alpha_p = \frac{2(1-\sqrt{1-D_{0n}^2})}{D_{0n}^2}, 0, \frac{\sin[\pi(1-1/D_{0n})]}{\pi(1-1/D_{0n})};$$

for the cases :

(1) with inversion for the not destroyed SAW amplitudes $D_0 < qP\ (D_{s0})$,

(2) without inversion layer for the depletion-accumulation, and

(3) with inversion for the destroyed SAW amplitudes $D_0 > qP\ (D_{s0})$, respectively. Here, $D_{0n} = qP\ (D_{s0})$ is the normalized SAW amplitudes.

For these three cases the electron and hole acoustoelectric currents are given by the following relations,

$$I_{na} = 0, -\frac{\mu_n}{2\varepsilon_s}\frac{\omega}{\omega_c}D_0^2, -\frac{\mu_n}{2\varepsilon_s}\frac{\omega}{\omega_c}\left[1 + \frac{\sin 2\pi / D_{0n}}{2\pi} - \frac{1}{D_{0n}}\right]D_0^2,$$

$$I_{pa} = qP(D_{so})\ V_s(1-\sqrt{1-D_{0n}^2}), 0, qP(D_{s0})\ V_s;$$

where μ_n and μ_p are the electron and hole mobility. It is necessary to note that in first and second cases as mentioned above, acoustoelectric currents and attenuation coefficient are related with the Weinreich'a relation that is well-known for bulk acoustic waves [21]:

$$I_{na} / \alpha = 2\mu_n P_{SAW} / V_s, I_{pa} / \alpha = 2\mu_p P_{SAW} / V_s,$$

where P_{SAW} is the SAW power. This is in accordance with the experimental paper [22] and a basis of the acoustoelectric technique of measurement of surface mobility [23]. The third case mentioned above corresponds to the case of charge transport when all the holes of the inversion layer are captured and transported by the SAW with velocity V_s.

For the layered structure with *n*-type semiconductor with surface *p*-type inversion some calculated dependencies are demonstrated in Figures 2-5. Normalized attenuation coefficients α_p and α_n versus normalized SAW amplitude D_{0n} are shown in Figure 2. Normalized to $qP\ (D_{so})\ Vs$ the hole and electron acoustoelectric currents, I_{pa} and I_{na}, depending with the normalized SAW amplitude D_{0n} are shown in Figure 3.

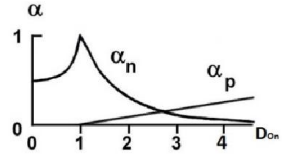

Fig. 2. The normalized attenuation coefficients α_p and α_n versus the normalized SAW amplitude D_{0n}.

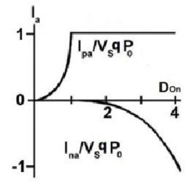

Fig. 3. The normalized hole and electron acoustoelectric currents, I_{pa}/qP_0V_s and I_{na}/qP_0V_s, versus the normalized SAW amplitude D_{0n}.

Figures 4 and 5 demonstrate a peculiarity in a stationary state when the surface layered hole concentration P_0 differs from one $P_{00} = qP\ (D_{s0})$ in the case without SAW. In this stationary case hole acoustoelectric current I_{pa} is equal to the diffusion current $I_D = \beta\cdot(P_{00} - p_0)$ that is proportional to $(P_{00} - P_0)$ with the coefficient of proportionality β depending on the hole diffusion coefficient and structure geometry. In the other words, acoustoelectric and diffusion currents make circular currents along the surface in the semiconductor inversion layer. Figure 4 shows dependence of the normalized hole acoustoelectric current I_{pa}/V_sD_0, solid curve, and the diffusion current I_D for various coefficients β, dashed curves, versus the normalized stationary surface hole concentration qP_0D_0. These dependencies give a solution for P_0 in the stationary state. In the crossing solid and dashed curves in Fig. 4 there are situations with two stationary states as in experimental papers [7, 8]. The third state is not stationary. An example of dependence of the normalized stationary surface hole concentration P_0/P_{00} versus the normalized SAW amplitude D_0/qP_{00} obtaining from Figure 4 are shown in Figure 5 and demonstrate bistability with changing the SAW amplitude

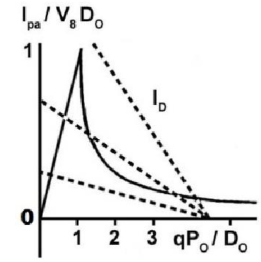

Fig. 4. The normalized hole acoustoelectric current I_{pa}/V_sD_0, solid curve, and the diffusion current $I_D = \beta\cdot(P_{00} - P_0)$ for various coefficients β, dashed curves, versus the normalized stationary surface hole concentration qP_0/D_0.

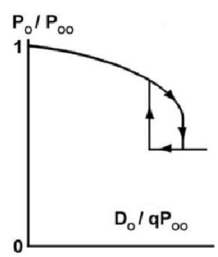

Fig. 5. The normalized stationary surface hole concentration P_0/P_{00} versus the normalized SAW amplitude D_0/qP_{00}.

2.3 Influence of semiconductor surface states on SAW acoustoelectric interaction

Surface semiconductor trapping free charge carriers may be added in results presented above.

As for high frequency processes, it is enough to compare surface frequency depended admittance connecting with surface states Y_{ss} and free charge carriers near the semiconductor surface Y_n. Then the condition of neglecting surface semiconductor trapping free charge carriers may be written in the form:

$$\left|Y_n\right| >> \left|Y_{ss}\right|$$

or with results of the paper [24] for Y_n and Y_{ss} for continuous distribution of surface states with density N_{ss} in the following form:

$$\left| i\omega \frac{q^2}{T} R_D\, n_0 \frac{1-\exp(q\varphi_s/T)}{F(\varphi_s)} \right| \gg \left| \frac{qN_{ss}}{2\tau} \ln(1+\omega^2\ \tau^2) + i\frac{qN_{ss}}{\tau} \quad \arctan\,(\omega\tau) \right|$$

where R_D is the Debye radius and τ is the relaxation time of charge on the surface states. It is necessary to note that the criterion of neglecting surface states needs the parameter $\omega\tau/N_{ss}$ is depending on semiconductor parameters $\omega\tau >> 1$. Real semiconductor surfaces is valid and we are not obliged to take into account surface states in high frequency processes. In nonlinear processes when harmonics $\omega = 0$ exist, the criterion mentioned above is not completely valid. In this situation there is a nonlinear high frequency field effect [25, 26] and under action of high frequency electric field of SAW there is an accumulation of charge carriers on surface states in semiconductors. That is why a trapping TAV exists.

The amplitude of the trapping TAV is

$$v_{at} = -\frac{T}{q}\frac{d_1}{1+\dfrac{n_0 R_D}{a_1 T N_{ss}}} D^2{}_{on}\left(1-\frac{d_1}{2}D_{0n}^2\right)$$

where a_1 and d_1 are some coefficients depending on semiconductor parameters and surface potential. It is especially necessary to note that the amplitude of the trapping TAV is proportional to the surface state density N_{ss} in the case of small values of N_{ss} and does not depend on N_{ss} if the surface state density N_{ss} is more then the value of n_0R_D/a_1T *i.e.*, $\approx 10^{10} - 10^{11}$ cm^{-2} and easy reaches for Si/SiO_2 interface. Moreover, the trapping TAV is larger than the TAV in the case of concentration mechanism of nonlinearity. These results are in a good agreement with experimental ones [27].

Conclusion

Proposed analytical method of calculation of nonlinear SAW acoustoelectric interaction is able to obtain the nonlinear solution for not only small signal approximation but including large amplitudes and takes into account surface semiconductor properties. Nonlinear SAW attenuation and dispersion, convolution, transverse acoustoelectric voltage (TAV), acoustoelectric current, acoustic charge transport and acoustoelectric bistability are calculated, analyzed, and compared with experiments. Optimal losses, dynamic range of nonlinear acoustoelectric devices and strong nonlinear acoustoelectric phenomena in the layered structures are described. Both concentration and trapping mechanisms of nonlinearity are included into consideration. Results obtained are in agreement with many our and other experimental results and may be principles of the calculation of the nonlinear acoustoelectric devices and investigation technique.

References

1. Singh, B.K., Kumar, M. and Alok, U., *Orissa J. of Physics*, **18**, 227-236 (2011).
2. Alok, Ujjwal, Kumar, Manoj, Singh, B.K., and Kumar, Praveen, *Bibechana*, **8 BMHSS**, 67-72 (2012).
3. Kino, G. S., *Proc. IEEE*, Vol. **64**, No. **5**, pp. 724-748 (May 1976).
4. Vyun, V.A., Rzhanov, A.V. and Yakovkin, I.B., *Novosibirsk: Institute of Semiconductor Physics*, (1987) (in Russian).
5. Balalrirev, M. K., *World Scientific Publ*., 191-232 (1985).
6. Otto, O. W., *J. Appl. Phys*., **45**, 10, 4373-4383 (1974).
7. Morita, S., Tsuboochi, K. and Mikoshiba, N., *Japan. J. Appl. Phys*., **15**, 6, 1019-1028 (1976).
8. Vyun, V.A. and Levin, M.D., *Fiz. Tverd. Tela*, **23**, 3, 838-845 (1981) (*Sov. Phys. Solid. State*, Vol. **23**, No. **3**, pp. 838-845, March 1981).
9. Vyun, V.A., Ghiner, A.V., Surdutovich, G.I. and Yakovkm, I.B., *DAN SSSR*, **296**, **3**, 583-587 (1987).
10. Vyun, V.A. and Yakovkm, I.B., *Int. J. Engng. Set*, **29**, 3, 411-418 (1991).
11. Vyun, V.A., *Proc. 1992 IEEE Ultrason. Symp., Tucson, Arizona*, 987-989 (October 1992).
12. Vyun, V.A., *Proc. 1993 IEEE Intern. Frequency Control Symp., Salt Lake City, UT*, 509-513 (June 1993).
13. Ingebrigtsen, K.A., *J. Appl. Phys*., **40**, **9**, pp. 2681-2686 (July 1969).
14. Greebe, C.A.A.J., van Dalkn, P.A., Swanenburg, T.J.B. and Wolter, J., *Phys. Repts*., **1**, 5, 236-268 (May 1971).
15. Vyun, V.A., *Akust, Zh.*, **31**, **4**, 459-463 (Jury-August 1985) (*Sov. Phys Acoust*, **31**, 4, 272-275 Jury-August 1985).
16. Garrett, C.G.B. and Brattain, W.H., *Phys. Rev*., **99**, 2, 376-387 (February 1955).
17. Many, A., Goldstein, Y. and Grover, N.B., *Semiconductor Surface*, New York: John Willy and Sons (1965).
18. Kino, O.S. and Gauuer, H., *J. Appl. Phys*., **44**, **12**, 5219-5221 (December 1977).
19. Vyun, V.A. and Xevin, M.D., *Fiz. Tverd. Tela*, **22**, **1**, 792-795 (January 1985) (*Sov. Phys. Solid State*, **22**, 1, 40-41 January (1980).
20. Vyun, V.A.; Pnev, V.V. and Yakovirin, L.B., *Radiotekhnika i elektronika*, **31**, 9, 1886-1887 (September 1986).
21. Weiareich, G. and White, H.G., *Phys. Rev*., **106**, **5**, 1104-1106 (May 1957).
22. Ingebrigtsen, K. A., *J. Appl. Phys*., **41**, 2, 454-459.
23. Bers, A.J., Cafarella, J. and Burke, B., *Appl. Phys. Lett*., **22**, **8**, 399-341 (August 1973).
24. Gotsberger, A. and Sze, S.M., *Applied Solid State Science, Advances in Materials and Device Research*, New York and London : Academic Press, **I**, 153-238 (1969).
25. Gulyaev, Yu.V. and Others, *Fiz. Tverd. Tela.,* **17**, 12, 3505-3515 (December 1975).
26. Gi Caiashnikov, S. and Fedosov, V.I., *Fiz. i Tekh. Poluprov*., **9**, **11**, 2161-2170 (October 1975).
27. Vyun, V.A., Pnev, V.V. and Yakovkin, I.B., *Fiz. Tverd. Tela*., **28**, **5**, 1538-1540 (May 1986).

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