Transverse acoustoelectric effect of new type, produced by a surface acoustic wave in a semiconductor

Yu. V. Gulyaev, A. M. Kmita, A. V. Medved', V. P. Plesskiĭ, N. N. Shibanova, and V. N. Fedorets

Institute of Radio Engineering and Electronics, USSR Academy of Sciences

(Submitted January 31, 1975)
ZhETF Pis. Red. **21**, No. 6, 353–355 (March 20, 1975)

A new type of transverse acoustoelectric effect produced by acoustic surface waves in a semiconductor was observed and investigated. This phenomenon is attributed to nonlinear capture of electrons by surface traps under the influence of the transverse electric field of the wave.

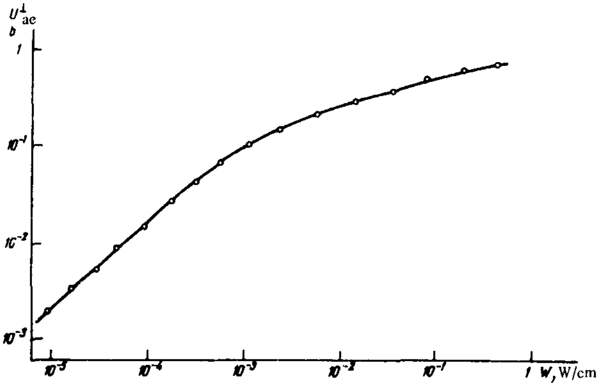
We have found that in many samples of n-Si in which the transverse acoustoelectric (AE) effect induced by surface acoustic waves (SAW) was observed, the sign of the effect was reserved after keeping the sample in air for a few days. The longitudinal AE effect remained of the same sign, i.e., no inversion layer was produced on the surface, and the majority carriers (electrons) were dragged by the SAW as before1).

The figure shows a plot of the emf $U_{ae}^{\perp}$ of this "inverted" transverse AE effect against the intensity W of the SAW, for an n-Si plate with $\rho = 560\ \Omega$-cm, clamped to the surface of a lithium niobate crystal (see[2,3]) along which an SAW propagated ($f = 100$ MHz). We see that in the initial section $U_{ae}^{\perp}$ is almost proportional to W, but later the proportionality becomes close to $W^{1/2}$.

It turned out that the onset of such an inverted transverse AE effect is accompanied by a strong acoustic conductivity—a change in the dc conductivity σ of the sample. The acoustoconductivity $\Delta\sigma/\sigma_{\perp}$ as a function of the SAW intensity exhibited approximately the same behavior as U_{ae}, and reached 50% at high intensities. This phenomenon was observed earlier in[5].

These results can be explained (at least qualitatively) on the basis of the nonlinear field effect in the transverse alternating field of the SAW in the presence of traps on the contact surface.

As first noted in[1], in contrast to volume acoustic waves, the SAW in a semiconductor is accompanied by a transverse (perpendicular to the surface) alternating electric field $E_{\sim}^{\perp}$, which is generally speaking of the same order of magnitude as the longitudinal electric field $E_{\sim}^{\parallel}$. The field $E_{\sim}^{\parallel}$ causes bunching of the electrons in the wave propagation direction. The $E_{\sim}^{\perp}$ causes bunching of the electrons in a direction perpendicular to the surface. It is easy to show, using the Poisson equation and the condition $\mathrm{curl}\ \mathbf{E}_{\sim} = 0$ that in the case $qr_D \ll 1$, which is typical of layered structures (q is the wave number of the SAW and r_D is the Debye radius) the ratio of the contributions of the fields $E_{\sim}^{\parallel}$ and $E_{\sim}^{\perp}$ to the formation of such a "two-dimensional" electron bunch turns out to be of the order of $q^2 r_D^2 \ll 1$. Thus, when considering the effect of the SAW on the electrons2) the bunching of the electrons by the longitudinal electric field of the SAW can be neglected, and the problem reduces essentially to the field effect in the transverse alternating electric field of the SAW.



Transverse acoustic emf vs. the sound intensity: n-Si sample, $\rho = 560\ \Omega$-cm, $f = 100$ MHz.

It can be proposed that during the time of its oxidation in air the surface of the silicon acquires capture centers—traps. If their surface density is equal to N_t, then they capture electrons at a rate $dn_t/dt = C_n[(N_t - n_t)n_s - n_1 n_t]$, where n_t is the density of the electrons on the traps, C_n is the corresponding trapping coefficient, n_s is the electron concentration near the surface, and n_1 is a known quantity that characterizes the rate of the reverse thermal rejection of the electrons from the traps. This expression is nonlinear in the amplitude of the external field $E_{\sim}^{\perp}$. At small amplitudes we have $n_s \sim E_{\sim}^{\perp}$ and $n_t \sim E_{\sim}^{\perp}$, and the expression for dn_t/dt acquires in general a dc component proportional to $\overline{n_t n_s} \sim \overline{E_{\sim}^{\perp 2}} \sim W$ (the superior bar will denote from now on averaging over the period of the wave). Under stationary conditions, $dn_t/dt = 0$, we obtain for the time-constant change in the number of the electrons in the traps $\Delta n_t = \bar{n}_t - n_{t_0} = -\overline{n_t n_s}/n_1 \sim W$. This leads in turn to the onset of the constant electric field of the transverse AE effect, $E^{\perp} \approx 4\pi e \Delta n_t \sim W$ and to an acoustoconductivity $\Delta\sigma/\sigma \approx \Delta n_t/dn_0 \sim W$ (d is the thickness of the semiconductor plate and n_0 is the equilibrium electron concentration in the volume).

In the case of large amplitudes, $E_{\sim}^{\perp} \gg 4\pi e n_0 r_D$, it is necessary to solve the nonlinear problem of the field effect in the presence of traps. At large field amplitude, the electron concentration that can be produced in one half cycle near the surface is very high, $n \gg n_0$, while during the second half-cycle the near-surface layer can at best be only depleted. As follows from the expression presented for the capture rate, the average charge of the traps will then increase from period to period. Under the following conditions: (a) the number of the traps is very large, $N_t \gg E_{\sim}^{\perp}/4\pi e$, (b) the degree of their filling is always small, $n_t \ll N_t$ and changes little over one cycle of the wave, $|T(dn_t/dt)| \ll |n_t|$, (c), the free electrons actually adapt themselves instantaneously to the change of the electric field, $T \gg \tau_M$ (τ_M is the Maxwellian relaxation time), and (d) the external field varies sinusoidally, $N(t) = E_{\sim}^{\perp}/4\pi e = N\cos\omega t$, we obtain $\bar{n}_t \to N$. If $N \gg n_t$, then the produced field of the transverse AE effect $E^{\perp}$ tends to the maximum value of the external alternating field $E_{\sim}^{\perp}$, i.e., $E^{\perp} \sim W^{1/2}$, and the corresponding acoustoconductivity $\Delta\sigma/\sigma \to -N/dn_0 \sim W^{1/2}$. Since the traps become filled, the contact surface becomes negatively charged, i.e., the sign of the produced "trap-induced" transverse AE effect is opposite to the sign of the effect previously investigated (see[2,3]). The numerical experimental value of $E^{\perp}$ (see the figure) near high SAW intensities is close to the maximum value of $E_{\sim}^{\perp}$, in accord with the theory.

We note in conclusion that the depletion of the surface layer of a semiconductor as a result of capture of electrons by traps at a large value of the field $E_{\sim}^{\perp}$ can lead to inversion of the type of conductivity of this layer. This can explain qualitatively the change of the sign of the longitudinal AE effect at high SAW intensity, as observed for the first time in[6].

1) Etching the silicon surface restored the initial sign and magnitude of the transverse AE effect.

2) But not at all when the reaction of the electrons on the SAW is considered!

---

[1] Yu. V. Gulyaev, (Paper at Gordon Conference on Acoustoelectronics), Andover, New Hampshire, USA, July 1970; Yu. V. Gulyaev, A. Yu. Karabanov, A. M. Kmita, A. V. Medved', and Sh. S. Tursunov, Fiz. Tverd. Tela **12**, 2595 (1970) [Sov. Phys.-Solid State **12**, 2085 (1971)].

[2] A. M. Kmita and A. V. Medved', ZhETF Pis. Red. **12**, 455 (1971) [JETP Lett. 12, 317 (1971)].

[3] A. M. Kmita and A. V. Medved, J. Appl. Phys. **44**, 3034 (1973).

[4] N. J. Moll, O. W. Otto, and C. F. Quate, J. de Phys. **C6**, **33**, 231 (1972).

[5] C. Fishler, J. Zucker, and E. M. Conwell, Appl. Phys. Lett. **17**, 252 (1970).

[6] S. G. Kalashnikov, A. I. Morozov, and M. A. Zemlyanitsyn, ZhETF Pis. Red. **16**, 170 (1973) [JETP Lett. **16**, 118 (1973)].