Measurement of the conductivity of semiconductors in the high-frequency field effect

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It is shown that action of a high-frequency external electric field can greatly alter the dc component of the conductivity of a semiconductor because surface levels participate in the electron exchange. A possible connection between this effect and certain acousto-electronic phenomena is indicated.

When an external electric field acts on the surface of a semiconductor, the electric conductivity of the semiconductor is altered (field effect[1]). In an alternating field $E_1 \exp(i\omega t)$, the induced charge per unit surface is $Q_1 \exp(i\omega t)$ and the electric conductivity acquires a component $\Delta G(\omega t)$ which is indeed the one usually investigated in the study of the HF field effect.[2,3] The "effective mobility" is $\mu_{\text{eff}} < \mu_n + \mu_p$, where μ_n and μ_p are the mobilities of the electrons and holes.

However, a dc component $\Delta\overline{G}$ can also appear in the change of the conductivity of the sample. This component can also vary in time, but aperiodically and much more slowly, and can exceed $\Delta G(\omega t)$ by several orders of magnitude. This circumstance, to our knowledge, was never considered in studies of the HF field effect[1)]. Accordingly, the effective mobility, which we define in this case as $\overline{\mu}_{\text{eff}} = \Delta\overline{G}/Q_1$, can exceed $\mu_n + \mu_p$.

The experiments were performed at room temperature on Si with intrinsic illumination (dark resistance 10^3–10^4 Ω-cm) and intrinsic Ge without illumination ($N_D + N_A < 10^{12}$ cm^{-3}), of thickness $d = 0.3 - 0.8$ mm (d much larger than the Debye length; d approximately equal to the diffusion length L). The duration of the high-frequency pulse was 10^{-3}–10^{-2} sec. At each instant of time, the two surfaces of the semiconductor were oppositely charged (Fig. 1). The grounding of the output coil of the HF generator was chosen such that the minimum HF current flowed through the sample contacts. If the two surfaces of the electrodes are identical and the amplitudes of the HF field are equal, then $\Delta G(\omega t)$ should equal to zero.

Experiments have shown that $\Delta\overline{G}$ always corresponds to a decrease of the sample conductivity, and $\Delta\overline{G}/G_0$ reaches 70–80% (Fig. 2). The maximum values of $\overline{\mu}_{\text{eff}}$

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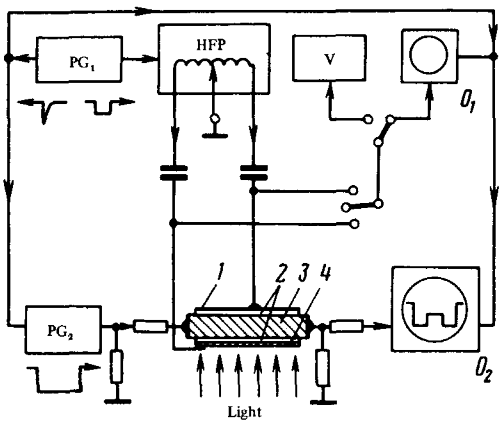

FIG. 1. Block diagram of setup: 1—opaque electrode, 2—mica, 3—sample, 4—transparent electrode, PG_1, PG_2—pulsed generators, O_1, O_2—oscilloscope, HFO—high frequency oscillator, V—voltmeter.

were 1.8×10^5 cm²/V-sec for Ge and 7.5×10^3 cm²/V-sec for Si. These values greatly exceed $\mu_n+\mu_p$. The effect was not connected with rectification of the HF signal that penetrated in the contacts: $\Delta\bar{G}/G_0$ was independent of the current pulse and did not change when the penetrating HF signal was increased by tens of times.

We explain the observed effect in the following manner: For the effect to occur it is essential to have $\tau_M<T<\tau_s$, where τ_M is the maxwellian time, $T=2\pi/\omega$, and τ_s is the time of relaxation of the surface levels (SL). At $T<\tau_s$, the occupation of the surface levels within the time T does not manage to change, and the HF field is weakly screened by the SL. Owing to the nonlinear dependence of the carrier density at the surface on the external field, their mean values $\langle n_s\rangle$ and $\langle p_s\rangle$ per period, differ from their values n_{s0} and p_{s0} in the absence of a field. This leads, first, to a slow (in comparison with T) change in the filling of the SL and the surface charge, and consequently also of the average conductivity of the space-charge layer (SCL). Second, it leads to a change in the rate of surface recombination, ΔR_s, which causes a change in the conductivity also in the quasineutral region (at a depth $\sim L$ much larger than the SCL thickness).

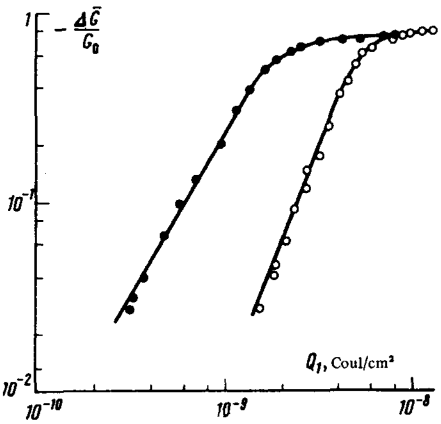

FIG. 2. Plot of $\Delta\bar{G}/G_0$ against the amplitude Q_1 of the induced charge: •—Si, $G_0=2.5\times10^{-5}\ \Omega^{-1}$, $f=10.5$ MHz; ○—Ge, $G_0=1.65\times10^{-3}\ \Omega^{-1}$, $f=16.5$ MHz.

It follows from the foregoing that $\Delta\bar{G}/G_0$ should increase on going from low frequencies ($\omega\tau_s<1$) to high frequencies ($\omega\tau_s>1$). This was indeed observed in experiment (Fig. 3). The magnitude of the effect depended on the surface finish (which changes the SL and the initial bending of the band) and the illumination (which changes the initial densities of the free carriers and the occupation of the SL).

A quantitative calculation using the Bogolyubov averaging method has confirmed the considered qualitative model. It has shown that the relative role of the SCL and of the quasineutrality region in the change of the conductivity depends on the sample parameters. Thus, if the electron and hole densities in the volume do not differ greatly, then the influence of ΔR_s can be decisive. The large value of ΔR_s can then be due a) to the increase of $\langle n_s\rangle$ and $\langle p_s\rangle$, and b) to charge exchange of SL of various types. The change of the occupation of different SL can be large, even if the total charge of the surface has changed little. In this case a large $\Delta\bar{G}/G_0$ is possible even in thick samples ($d\sim L$), and $\bar{\mu}_{eff}$ can be larger than $(\mu_n+\mu_p)$. This is precisely what we had in mind in our experiments. Calculation shows also that owing to accumulation of the charge on the SL, the type of conductivity of the surface layer can be reversed under the influence of the HF field.

On the other hand, if the density of the minority carriers in the volume is small, then $\Delta\bar{G}/G_0$ is due principally to a change of the SCL conductivity. In this case a large $\Delta\bar{G}/G_0$ is possible only in thin sample (d on the order of the SCL thickness), and in the absence of an inversion layer $\bar{\mu}_{eff}$ is smaller than μ of the majority carriers. In the absence of an inversion layer, the latter can vanish under the influence of the HF field.

The indicated singularities of the HF field effect can become manifest in several acoustelectronic phenomena. Thus, the change of the conductivity of silicon plates under the influence of a surfaces sound wave (SSW) in a layered piezodielectric-silicon structure, observed in[4,5], may be due to the HF field effect, owing to the presence of an electric-field component normal to the surface.[4] The value of $\bar{\mu}_{eff}$ calculated by us from the data of[4] turned out to be $\sim10^2$ cm²/V-sec, which is much less than μ_n. This corresponds to the case of the thin impurity samples used in[4]. Next, a reversal of

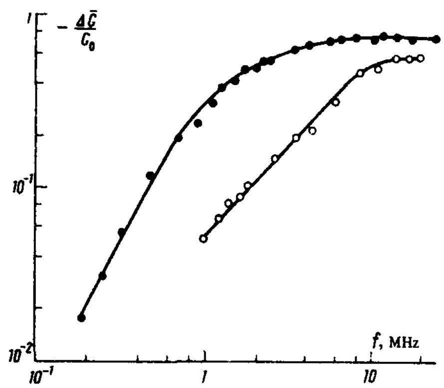

FIG. 3. Frequency dependence of $\Delta\bar{G}/G_0$: •—Si, $G_0=2.5\times10^{-1}\ \Omega^{-1}$, $Q_1=3.8\times10^{-9}$ C/cm²; ○—Ge, $G_0=1.65\times10^{-3}\ \Omega^{-1}$, $Q_1=6.5\times10^{-9}$ C/cm².

the sign of the longitudinal acoustoelectric effect in a layered $LiNbO_3$-Si structure was observed in[6] with increasing power of the SSW. The model considered above shows that this reversal of sign can be due not only to the innate inversion layer,[6] but also to its creation of annihilation under the influence of the HF electric field of the SSW.

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[1]We emphasize that the effect considered here differs from the so-called "accumulation effect" observed in a constant field or at low frequency.[1] The magnitude of the latter is smaller by several orders of magnitude, and its establishment time is longer by several orders.

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