Direct experimental observation of electron waves excited by a sound wave in a semiconductor in an alternating electric field

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Experiments have been carried out to observe stimulated electron waves excited by a sound wave in a semiconductor film in an alternating electric field produced by a periodic array of ohmic contacts. The spectrum and the features of the field dependence of the changes in the signals at the sum and difference frequencies lead to the conclusion that stimulated electron waves were actually observed in these experiments.

It was predicted in Refs. 1–3 that stimulated electron waves might arise in an electron plasma in a semiconductor crystal subjected simultaneously to an alternating piezoelectric field accompanying a sound wave of frequency ω_s and a spatially uniform alternating electric field of frequency Ω. The spatial period of these waves would be the length of the sound wave, while their frequencies would satisfy the condition $\omega_k = \omega_s \pm k\Omega$, where $k = 0,1,2,\ldots$. Indirect evidence of the existence of such electron waves came from the experimental observation of some interesting physical phenomena which were predicted in Refs. 1–3: huge oscillations of the sound absorption coefficient,[4] a plasma-drift resonance, and the excitation of backward sound waves in an alternating electric field.[5]

In the present experiments we have been able to directly observe the electric field associated with stimulated electron waves by making use of surface acoustic waves in a layered structure consisting of a piezoelectric dielectric and a semiconductor film. The layer and structure is shown in Fig. 1. A surface acoustic wave of frequency $\omega_s/2\pi = 56$ MHz is excited in a piezoelectric $LiNbO_3$ plate 1, by electroacoustic transducer 2. The alternating electric field which arises from the piezoelectric effect and which has the spatial and temporal periods of the sound wave penetrates into a photosensitive semiconductor (CdSe) film 3, 2 μm thick, which has been deposited on the surface of the piezoelectric. The conductivity of the film can be adjusted by adjusting the illumination level. A periodic array of ohmic contacts 4 with a spatial period twice the length of the sound wave is deposited on the surface of the film by photolithography. This array of contacts is connected electrically to a load resistance R_L and an alternating voltage source of frequency Ω. Alternating electric fields of frequency Ω are thus produced in the semiconductor film in the gaps between the electrodes. When the field of frequency Ω and the alternating electric field of the sound wave act simultaneously, stimulated electron waves can be excited in the semiconductor film, along with electric fields of frequencies ω_k, which are related to the electron waves and which are distributed periodically over space. If they exist, these fields should give rise to currents of frequencies ω_k which can be detected with a spectrum analyzer.

Figure 2 shows a representative spectrum of the output signal for the case in which the frequency of the alternating electric field is $\Omega/2\pi = 100$ kHz. At 56 MHz we see a spectral component corresponding to the sound wave. In symmetric positions on either side of this component are components with frequencies $\omega_s \pm k\Omega$, where $k = 1,3,5$ (i.e., k is odd).

The change in the level of the signal at the difference frequency ($\omega_s - \Omega$) depends in an interesting way on the amplitude (U_Ω) of the alternating voltage applied to the array of ohmic contacts. Figure 3 shows some results for various frequencies of the alternating voltage. In the case $\Omega/2\pi = 10$ MHz (curve 1) we see that the linear dependence at low voltages ($U_\Omega < 1.5$ V) gives way to a steeper, nearly quadratic, dependence. For other relations between the frequencies of the sound wave and of the alternating voltage the dependence may be different. For example, curve 2 in Fig. 3, obtained at $\Omega/2\pi = 224$ MHz, corresponds to a strictly linear behavior. A change in the conductivity of the semiconductor film also changes the dependence of the level of the difference frequency on the alternating voltage. In particular, the dependence becomes almost strictly linear with increasing film conductivity.

To interpret the results we calculated the resultant current i_k of frequency ω_k produced in the load circuit by the

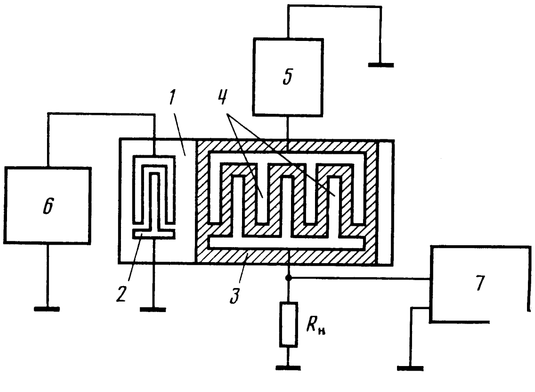

FIG. 1. The experimental layout. 1—Piezoelectric dielectric plate; 2—electroacoustic transducer; 3—film; 4—ohmic contacts; 5—U_Ω generator; 6—U_ω generator; 7—spectrum analyzer.

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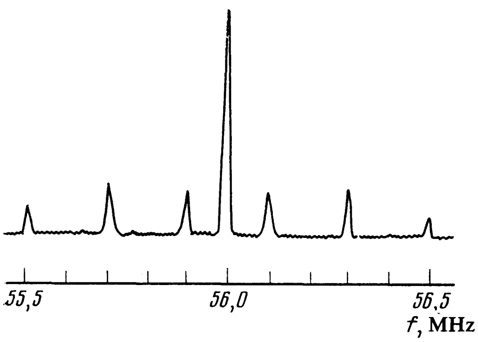

FIG. 2. Spectrum of the electric signal detected when the frequency of the external electric field is $\Omega/2\pi = 100$ kHz.

electric fields of the stimulated electron waves excited in the gaps between the electrodes. In these calculations we used the formalism of Ref. 2 and took into account the circumstance that the fields in adjacent gaps were excited and detected out of phase. We found

$$i_k \approx \left(\frac{P_{ak}K^2}{\omega_s(\varepsilon_0+\varepsilon_p)W}\right)^{1/2} \frac{2S_k}{R_0+R_\text{н}}(1-\cos(\pi k+2qL))^{1/2}\cos\omega_k t,$$

$$S_k = \left|\sum_{l=-\infty}^{\infty} \frac{J_l(\xi)J_{l+k}(\xi)}{i\omega_s\tau(1+l\Omega/\omega_s)+1}\right|, \qquad \tau=\tau_M\frac{\varepsilon_0+\varepsilon_p}{\operatorname{th} qd}. \quad (1)$$

Here R_0 is the dc resistance of the semiconductor film, P_{ak} is the power of the sound wave, K is the effective electromechanical coupling coefficient, ε_0 is the permittivity of free space, ε_p is the dielectric constant of the piezoelectric, W is the aperture of the acoustoelectric transducer, q is the wave vector of the sound wave, L is the distance between electrodes, τ_M is the Maxwellian relaxation time, d is the thickness of the semiconductor film, $J_l(\xi)$ is the Bessel function of integer index l and argument

$$\xi = \frac{\omega_s}{\Omega}\frac{\mu E_\Omega}{V_s},$$

μ is the electron mobility, $E_\Omega = U_\Omega/L$ is the amplitude of the alternating electric field, and V_s is the velocity of the sound wave in the piezoelectric.

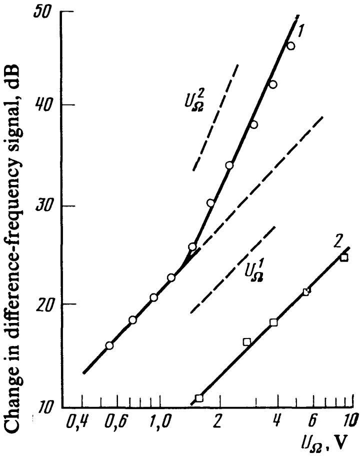

FIG. 3. Change in the level of the signal at the difference frequency versus the amplitude of the alternating voltage. 1—$\Omega/2\pi = 10$ MHz. 2—$\Omega/2\pi = 224$ MHz.

Under these experimental conditions the length of the sound wave satisfies the relation $qL = \pi$. In this case the current i_k is nonzero at odd values of k, in agreement with experiment (Fig. 2). Expression (1) gives a quantitative description of the curves in Fig. 3 of the signal at the difference frequency versus the amplitude (U_Ω) of the alternating voltage. The solid curves here are theoretical predictions of expression (1) for $k = -1$; the parameters used in the calculations correspond to the experimental conditions. In (1) the U_Ω dependence of i_k (and the deviation from linearity—curve 1) is described by the factor S_{-1}, which reflects the redistribution of electrons between waves with different values of k as a function of the electric field E_Ω and of the frequency ratio Ω/ω_s.

In summary, by using a periodic array of ohmic contacts on the surface of a semiconductor film in a multilayer structure of a piezoelectric dielectric and a semiconductor film we have been able to excite and directly detect stimulated electron waves with frequencies $\omega_k = \omega_s \pm k\Omega$. The experimental results are in good qualitative and quantitative agreement with the theory describing the redistribution of electrons between different electron waves, with allowance for the phase at which the electron waves are excited and detected by the periodic array.

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