Resonant photovoltaic effect in an inversion layer at the surface of a semiconductor

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The resonant photovoltaic effect, which occurs at the silicon surface as a result of excitation of the optical transitions between the size-quantization levels in the inversion layer, has been detected. This effect is attributable to the absence of an inversion center in this system.

Magarill and Éntin[1] derived a theory which shows that a size-quantized 2D system can generate a steady photocurrent along the surface. This photocurrent, which is produced as a result of the action of light that gives rise to inter-subband transitions, is attributable to the absence of an inversion center in the film (inversion layer)—electromagnetic field system.

In this letter we report the first experimental observation of this effect in an inversion layer at the surface of silicon upon the excitation of an inter-subband resonance between the first and second quantization subbands by far-IR light with a photon energy $\hbar\omega = 10.45$ meV.

The test samples that we studied were MOS transistors synthesized at the silicon surface which was tilted at an angle $\theta = 9.5^\circ$ from the (100) surface about the [011] direction. These samples were used to allow us to excite transitions between quantum subbands in the case of a normal incidence of light where the electric field vector of the wave is directed along the inversion layer. These samples were $1200\times400\ \mu$m in size and the thickness of the gate dielectric substrate material was $d_{\mathrm{SiO}_2} \approx 1200$ Å. As the gate we used a thin semitransparent titanium film with a surface resistivity of 1 $k\Omega/\square$. The substrate was doped to the level $N_A = 10^{13}$ cm^{-3}. At 4.2 K the electron mobility at the maximum was in the range $\mu = 1.6\times10^4$–1.9×10^4 cm^2/(V·s). As the light source we used a far-IR laser operating at a wavelength of 119 μm. The experiment was carried out at a temperature $T = 4.2$ K. The experimental geometry is shown in Fig. 1a. As can be seen in this figure, the experimental structure consists of two MOS transistors which are oriented along the direction of the slope **A** (transistor 1) and perpendicular to it (transistor 2). The linearly polarized light is incident normal to the surface of the structure, while the direction of the electric field **E** of the wave varies arbitrarily in its plane.

Figure 1b is a plot of the photoconductivity of the test samples as a function of the gate voltage, with **E**‖**A**. We see that at $V_g = 3.1$ V the photoconductivity of each transistor has a sharp peak, indicating the occurrence of an inter-subband resonance between the first and second quantum subbands. At $V_g = 3.1$ V the distance between these subbands corresponds to the photon energy. With **E**⊥**A** this peak, as expected, is

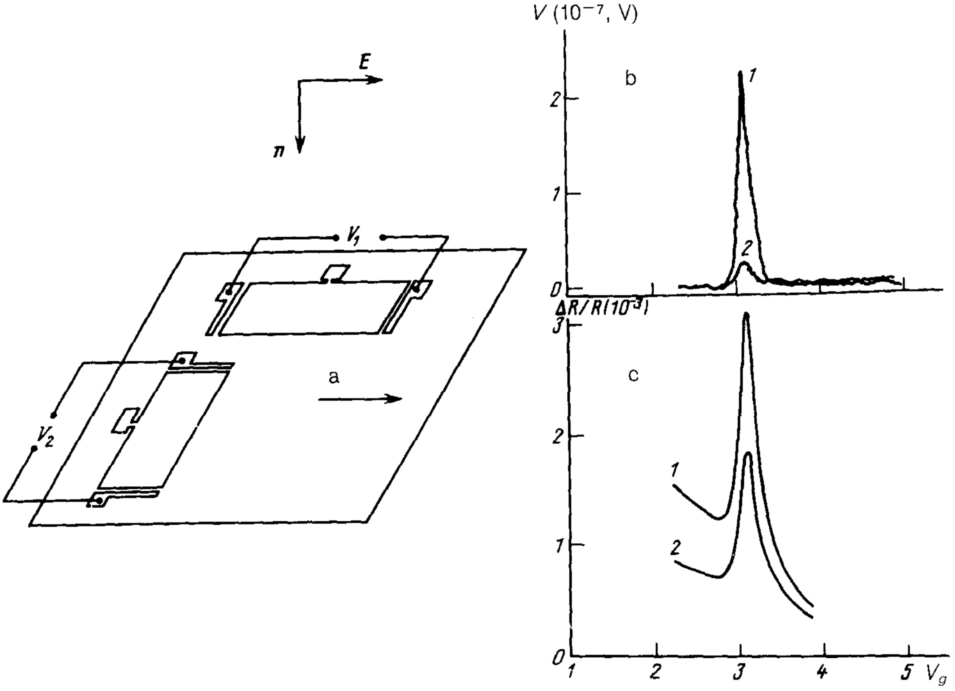

FIG. 1. (a) Experimental geometry; (b) photoconductivity versus V_g; (c) photo-emf versus V_g.

absent. This polarization dependence of the photoconductivity at resonance has been observed for the first time. The behavior of the photoconductivity of the samples under study is similar to the behavior of the resonant photoconductivity in the inversion channels when the inter-subband transitions are excited by the normal component of the electric field of the light.[2,3]

According to Magarill and Éntin's[1] prediction, we should then be able to observe a photo-emf resonance along with the photoconductivity resonance. The theory[1] was derived for an isotropic energy spectrum. A generalization of this theory to the case (which has been observed experimentally) in which the optically active lower subbands are formed from an ellipsoid, whose major axis is deflected by a small angle θ with respect to the normal, yields the following expression for the photocurrent in the case of a normal decrease in the light intensity:

$$\mathbf{j} = \mathrm{Im}\left[\frac{\mathbf{E}^* \cdot (\mathbf{E} \cdot \mathbf{A})}{\hbar\omega - \epsilon_{21} + i\gamma}\right] \frac{e^3 N_s Z_{21}}{\omega} \; C \, \frac{m_\parallel - m_\perp}{m_\perp^2} \sin\theta \, , \qquad (1)$$

where ϵ_{21} is the distance between the first and second subbands, Z_{21} is the matrix element of the transverse coordinate of the electron, N_s is the density of 2D electrons, γ is the broadening, C is a constant on the order of unity which depends on the transverse wave functions of the electron, and $|\mathbf{A}| = 1$. In (1) only the ballistic component of the photocurrent is taken into account, i.e., the contribution associated with the anisotropy of the momentum photoexcitation of the electrons. There is generally also a displacement component which is linked with the displacement of the electron along the surface during the inter-subband transition, but this component is small in the parameter[2] θ. Equation (1) takes both the linear and circular effects into account. In the case of linear polarization used experimentally, we can write the current $\mathbf{j} = \text{const}\cdot\mathbf{E}\ (\mathbf{EA})$.

Figure 1c is a plot of the measured photo-emf versus V_g for transistors 1 and 2, with $\mathbf{E}\|\mathbf{A}$, i.e., the case in which both transistors reveal a resonant photoconductivity shown in Fig. 1b. We see that at $V_g = 3.1$ V transistor 1 exhibits a photovoltaic resonance. Transistor 2 also has a signal, but its strength is an order of magnitude lower. Expression (1) predicts this type of behavior of photo-emf (a low signal detected in transistor 2 seems to be attributable to the inaccurate alignment of the structure's plane relative to the incident light). This behavior is also evidence that this is not abolometric effect (V_1 and V_2 in this case would be of comparable magnitude). With $\mathbf{E}\perp\mathbf{A}$, neither transistor 1 nor transistor 2 has a photo-emf, also in agreement with (1).

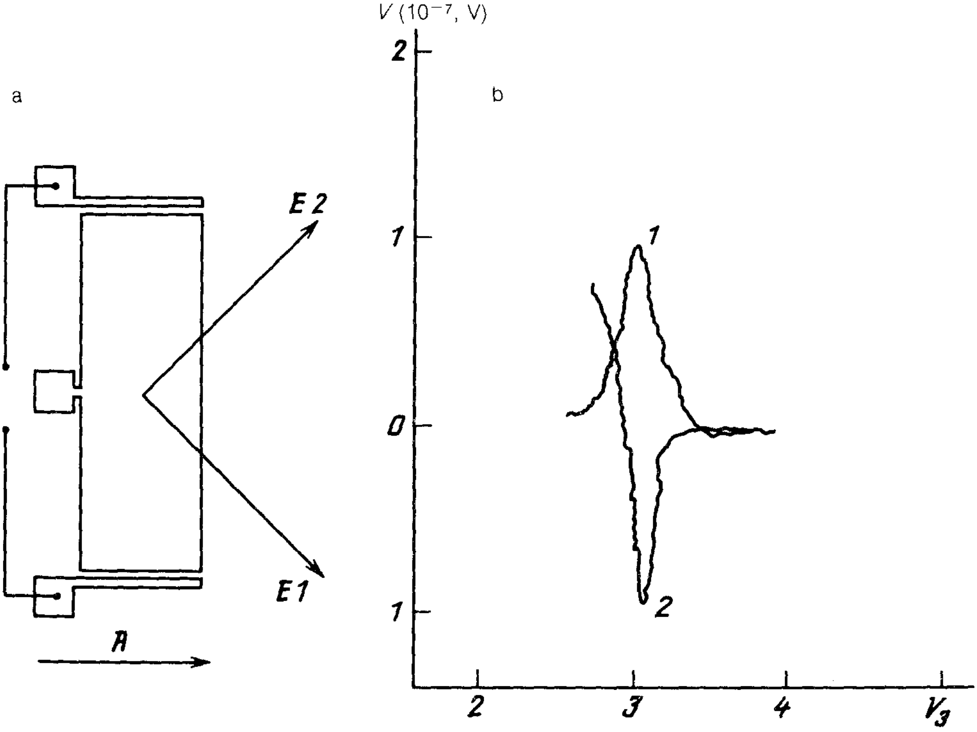

FIG. 2. The resonant photo-emf for two directions of E for transistor 2.

Equation (1) predicts an intriguing polarization dependence of the photo-emf for transistor 2: its sign changes due to the change in the sign of the angle between **E** and **A**. As can clearly be seen in Fig. 2, the experiment confirms this prediction. A quantitative comparison of this signal with (1) at resonance also yields a reasonably good agreement: A calculation based on (1) with $C=1$ yields $V=1.8\times 10^{-7}$ V.

It should be noted that the effect which we detected is related to the surface photocurrent[4,5] which was initially observed in the interband transitions at the surface of GaAs. This effect, however, has several fundamental differences. First, since it occurs in a size-quantized system, it is a resonant effect, whereas a system of classical electrons was analyzed in Refs. 4 and 5. Second, in our case the photovoltaic effect occurs in the case of a normal incidence of light[4,6] rather than an oblique one, as was stipulated in Ref. 5.

In summary, we have observed for the first time a resonant photovoltaic effect which occurs as a result of excitation of the optical transitions between the size-quantized subbands in an inversion layer at the surface of a semiconductor and which is due to the absence of an inversion center in this system. Since this effect identifies a new class of phenomena in 2D electron systems, its further study is imperative, especially in a magnetic field. This effect is also a new tool in the spectroscopy of size-quantized systems.

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