Observation of a frequency dependence of the photoconductivity under conditions of the quantum Hall effect

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A photoconductivity of a 2D electron gas, which depends on the frequency of the microwave radiation, has been observed in metal-insulator-semiconductor structures based on Si-(100) under conditions corresponding to the quantum Hall effect. This observation is evidence that thermally activated electrons can be photoexcited to the mobility threshold. Differences in the behavior of the photoresponse in different test samples stem from the nature of the potential relief.

One of the central questions in reaching an understanding of the quantum Hall effect is the structure of the quantum levels of the 2D electron gas under the conditions corresponding to this effect. Several papers (e.g., the recent papers in Refs. 1 and 2) assume that the potential relief varies slowly over a distance equal to the magnetic length $l_B = (\hbar c/eB)^{1/2}$. There are experimental data which cannot be explained on the basis of such a model, e.g., the pronounced difference between the activation energy, found from an analysis of the temperature dependence of the conductivity minimum, 2nd the value $\hbar\omega_c/2$ where $\omega_c = eV/mc$ is the cyclotron frequency. A study of the photoconductivity of a 2D electron gas to electromagnetic radiation with a photon energy comparable to the activation energy may prove useful for determining the characteristics of the potential distribution under condition of the quantum Hall effect.

The photoresponse has been studied previously both in silicon metal-insulator-semiconductor structures[3,4] and in GaAs-$Al_xGa_{1-x}As$ heterojunctions.[5-8] In all of these studies it has been noted that the magnetic-field dependence of the photoresponse is similar to the dependence of the derivative of the conductivity with respect to the temperature and is distinguished by a sharp increase in the signal either in the cyclotron-resonance region[3-8] or in the region of the electron spin resonance.[5] At an integer filling in strong magnetic fields (under conditions corresponding to the quantum Hall effect), a photoconductivity signal has not been observed. Guldner *et al.*[8] took up the problem of studying the regime of the fractional quantum Hall effect on the basis of the photoconductivity, but they again were unable to observe a change in the conductivity which was qualitatively different from that produced by heating.

In the present letter we report a study of the photoconductivity of a 2D electron gas in a Si-(100) metal-insulator-semiconductor structure. For the measurements we used four Hall geometry samples, whose basic parameters are listed in Table I. All the samples had a semitransparent titanium gate. The radiation source was a backward-wave tube, capable of operation over wavelengths from 1.16 mm to 1.90 mm. The radiation was chopped at a frequency of 210 Hz by a mechanical chopper. The changes in the resistance of the sample were detected by means of a phase-sensitive amplifier in a four-point arrangement, with subsequent digitization and storage in a computer memory. In addition to the signal which depended on the current, there was a photo-emf, which was usually small and could easily be substracted (the phase was taken into account).

To verify that the radiation was indeed reaching and interacting with specifically the 2D electrons, we observed the cyclotron resonance which was manifested as an increase in the photoconductivity signal. [3-8] The upper plot in Fig. 1 shows a typical photoconductivity of one of the samples (2). In the central part of Fig. 1 we have plotted the temperature derivative of the resistance, $\partial\rho_{xx}/\partial T$, found by subtracting the curves of the dependence of ρ_{xx} on the magnetic field B at the temperatures $T_1 = 1.95$ K and $T_2 = 1.65$ K. Shown at the bottom of Fig. 1 is the quantity ΔT found by dividing the extrema in $\Delta\rho_{xx}$ in the upper plot by the temperature derivative at the corresponding points.[6] In our opinion, the result of this procedure is proportional to the change caused in the electron temperature by the absorbed radiation [the open

TABLE I.

Sample	Substrate type	Channel dimensions, mm	Max. mobility, $cm^2/V\cdot s$ ($T = 4.2$ K)	Activation energy E_A/k_B, K ($B = 7.5$ T, $i = 4$)	Potential dimension, Å (according to Ref. 9)
1	*n*	1,2 X 0,4	17700	19,1	70
2	*n*	1,2 X 0,4	15300	12,8	77
3	*p*	2,5 X 0,25	10100	12,0	–
4	*p*	1,2 X 0,4	6900	10,7	–

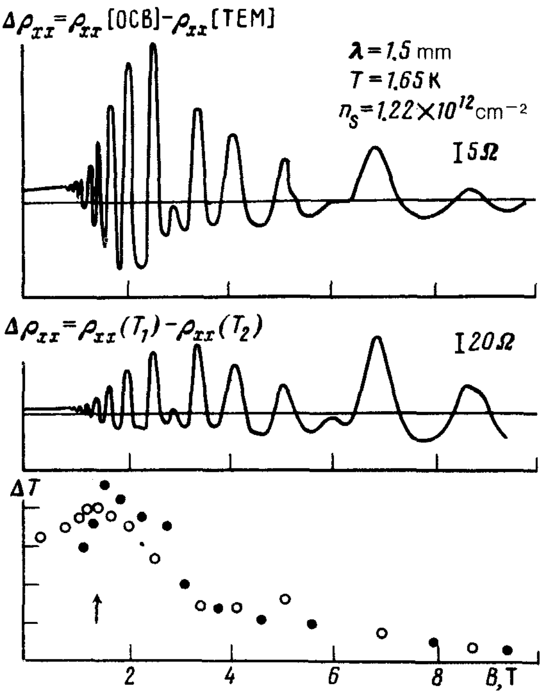

FIG. 1. Experimental results for sample 2.

symbols refer to minima of $\rho_{xx}(B)$ and the filled symbols to maxima]. The arrow shows the resonant field at the given radiation frequency. Upon a change in the frequency, the maximum in the plot of ΔT versus B correspondingly changes position.

In the present letter we are reporting the observation of a frequency-dependent photoconductivity under conditions corresponding to the quantum Hall effect. This photoconductivity is not of a heating nature. Figure 2 shows the photoconductivity $\Delta\rho_{xx}$ as a function of the microwave frequency for two different temperatures for sample 1. The filling factor is 4. The straight lines correspond to plots of $\Delta\rho_{xx}$

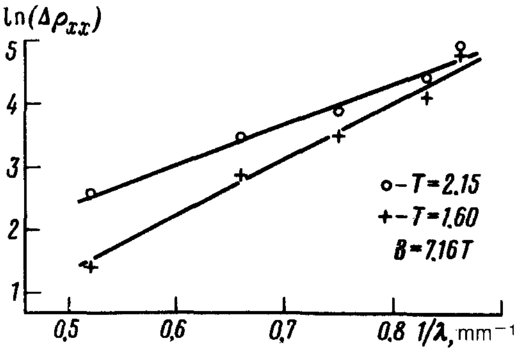

FIG. 2. Frequency dependence of the photoresponse $\Delta\rho_{xx}$ for sample 1 at the conductivity minimum. The filling factor is $i=4$.

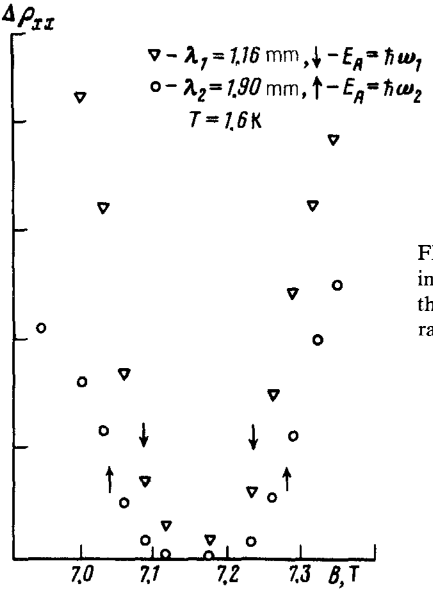

FIG. 3. Photoresponse of sample 1 versus the magnetic field in the vicinity of $i = 4$. The arrows show the fields at which the activation energy is equal to the photon energy of the radiation.

$\sim\exp(\hbar\omega/k_B T)$. The current through the sample was 4 μA; linearity in the current was verified. The scatter in the experimental points stems from difficulties in accurately determining the intensity of the radiation at a sample with dimensions comparable to the radiation wavelength. Nevertheless, the points conform fairly well to an exponential curve. A corresponding functional dependence $\Delta\rho_{xx} \sim \exp(\hbar\omega/k_B T)$ with a decreasing coefficient of the exponential function is observed in strong magnetic fields at a constant filling factor.

Figure 3 shows the photoconductivity $\Delta\rho_{xx}$ as a function of the magnetic field near a filling factor $i = 4$ for two radiation frequencies. The arrows show the magnetic fields at which the activation energy became equal to the corresponding photon energy of the radiation.

In sample 4 the activation energy in the maximum field reached, $B = 10$ T, was $E_Å/k_B = 15$ K. We observed a fourfold growth of the photoconductivity with the frequency, between $\lambda = 1.90$ mm and $\lambda = 1.16$ mm. This result agrees qualitatively with the results found for sample 1 (the growth is by a factor of 6 in Fig. 3 for $E_Å\ /k_B = 15$ K).

In terms of its parameters in a zero magnetic field, sample 2 is similar to sample 1. The activation energy (Table I) in a field $B = 7.5$ T, however, is much smaller than both $\hbar\omega_c/2$ and the activation energy for sample 1. The hotoconductivity in this Field does not depend on the frequency at our accuracy level, and in a field $B = 10$ T (the extrapolated activation energy is $E_Å\ /k_B = 18$ K) we do not observe a photoconductivity. The same qualitative behavior of the photoconductivity was exhibited by sample 3.

To explain the results, let us assume that the conductivity at the minimum is described by the expression $\sigma \sim \exp(-E_{\AA}/k_B T)$ with activation at a mobility threshold, where $E_{\AA}$ is the energy distance from the level of the chemical potential to the mobility threshold. During illumination, the system contains a certain number of carriers which have been excited a distance $\hbar\omega$ above the level of the chemical potential. In the case $\hbar\omega/k_B T \gg 1$, the conductivity during illumination is determined by these carriers, and we have the following expression for the behavior of the photoconductivity: $\Delta\rho_{xx} \sim \exp(-E_{\AA} + \hbar\omega/k_B T)$. Another sequence of events would also be possible: a photoscattering of thermally activated electrons to the mobility threshold. In either case, a necessary condition for photoexcitation would be the presence of states of suitable energy ($\Delta E = \hbar\omega$) over a distance on the order of the magnetic length l_B. In the case of large-scale potential fluctuations, i.e., in a case in which the potential varies only slightly over a distance l_B, there will be no photoexcitation by photons with $\hbar\omega < E_{\AA}$. It is with the characteristic dimensions of the inhomogeneities that we link the difference in the behavior of the photoconductivities of samples 1 and 2. We made attempts to relate the characteristic dimension of the potential in a quantizing magnetic field with the characteristic of the potential in a zero magnetic field, found from the temperature dependence of the conductivity in accordance with Ref. 9. It can be seen from Table I that the samples are not greatly different in terms of this parameter.

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