Interband photoconductivity of a mesoscopic GaAs sample

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A fundamentally new feature has been observed in the behavior of the interband photoconductivity of a mesoscopic GaAs sample: This conductivity oscillates aperiodically in time. The averge oscillation frequency is proportional to the light intensity. Analysis of the photoconductivity shows that at low intensities it is caused by a charge exchange involving a number of impurities on the order of unity.

Research on mesoscopic systems based on semiconductors is presently being carried out on a wide front.[1–3] The photoelectric properties of these systems, on the other hand, have not previously been studied. In the present letter we report the first study of the interband photoconductivity of a mesoscopic GaAs sample. We have observed that this photoconductivity oscillates in time; with increasing intensity of the incident light, both the amplitude and average frequency of the oscillations increase. These results mean that the mesoscopic semiconductor is exhibiting a fundamentally new type of photoconductivity. The samples in the present study were δ-doped GaAs layers of submicron dimensions. The technique for synthesizing them has been described elsewhere.[4] The properties of the original δ-layer were $n_s = 3.5 \times 10^{12}$ cm^{-2} and $\mu = 4200$ cm^2/(V·s). Their length was $L = 1$–2 μm, and their width W = 0.2–0.5 μm. The photoconductivity was measured over the temperature interval 1.7–4.2 K in a four-point arrangement with an resistive bridge. The sample was exposed to the light from an AlGaAs light-emitting diode, which had a maximum at the wavelength $\lambda = 670$ nm. Measurements of the photoconductivity of macroscopic samples of δ-doped GaAs ($L = 500$ μm, W = 200 μm) showed that it behaved in the usual way. The growth kinetics was described by the classical expression

$$\Delta\sigma_{\rm ph}(t) = \Delta\sigma_{\rm st}(1 - \exp(-t/\tau)),$$

where $\Delta\sigma_{\rm st} = e\mu\beta n_{\rm ph}\tau$ (τ is the lifetime, β is the quantum yield, and $n_{\rm ph}$ is the photon flux density) with $\tau = 10^2 - 10^3$ s.

Figure 1a shows the results of the measurements of $\Delta\sigma_{\rm ph}(t)$ of a mesoscopic sample with $L = 1$–1.5 μm and $W = 0.2$–0.4 μm at $T = 1.7$ K. Clearly, there are several fundamentally new features in the behavior of the photoconductivity in this case: 1) The photoconductivity oscillates aperiodically in time. The oscillations persist for a certain time after the light is turned off. 2) We see from Fig. 1b, which shows the average number of maxima and minima of the photoconductivity per second, $\bar{n}$, versus the number of incident photons, $n_{\rm ph}$ (the flux density was calibrated with the help of a silicon photodiode with a known β), that the frequency of the fluctuations in the photoconductivity at $n_{\rm ph} \lesssim 10^9$ cm^{-2}·s^{-1} increases roughly in proportion to $n_{\rm ph}$. The

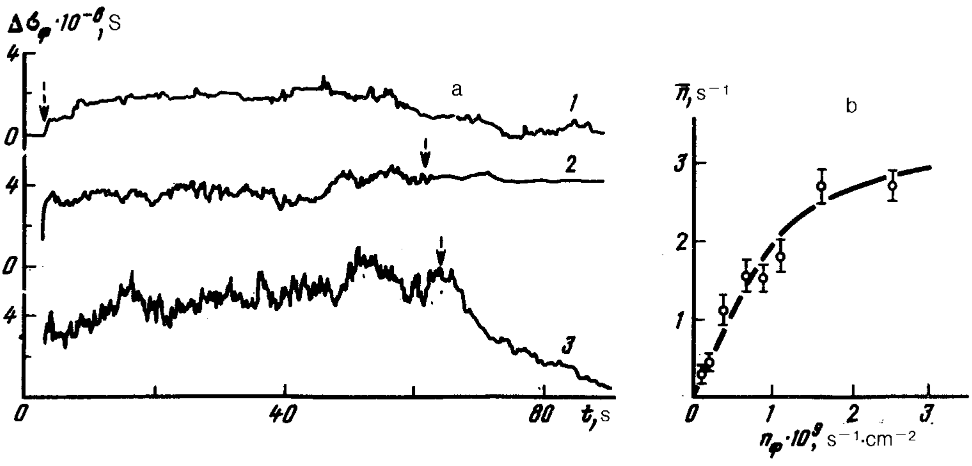

FIG. 1. a: Time dependence of photoconductivity of a mesoscopic GaAs sample at various photon flux densitities $n_{\rm ph}$ (in units of 10^9 cm^{-2}·s^{-1}). 1–0.2; 2–1.1; 3–5 ($T = 1.7$ K). Solid arrow) The light is turned on; dashed arrow) off. b: Average number of maxima and minima in the photoconductivity per second versus $n_{\rm ph}$.

growth in $\bar{n}$ then slows down, and the plot of $\bar{n}(n_{\rm ph})$ essentially reaches saturation. 3) The Fourier spectrum (Fig. 2) of these $\Delta\sigma_{\rm ph}(t)$ curves shows that the spectrum of the signal contains a set of frequencies. The amplitude of the Fourier components increases with decreasing frequency (and is reminiscent in this regard of the spectrum of a $1/f$ noise), while it decrease with decreasing intensity. 4) The average amplitude of the oscillations, $\delta\sigma_{\rm ph} = \sqrt{\langle\Delta\sigma^2_{\rm ph}\rangle}$, increases with increasing $n_{\rm ph}$ (see the inset in Fig. 2). 5) The value of $\delta\sigma_{\rm ph}$ increase with decreasing temperature, roughly in accordance with $\delta\sigma_{\rm ph} \sim T^{-0.5\pm0.15}$.

Let us analyze these experimental facts. It was shown theoretically in Refs. 5 and 6 that a mesoscopic conductor may undergo a significant change in conductivity if there is a change in the configuration of the scattering potential due to a charge exchange involving a single impurity. This property of a mesoscopic sample can explain, at least at a qualitative level, all of the new features in the behavior of a photoconductivity which we listed above, if we assume that the nonequilibrium carriers excited by the light initiate (through, say, ionization or capture) a change in this configuration. This assumption is supported by the circumstance that after the sample is exposed to a photon flux density $n_{\rm ph} \gtrsim 10^8$ cm^{-2}·s^{-1} for a time $t \approx 60$ s, there was a substantial change in the pattern of conductivity fluctuations as a function of the magnetic field. It is accordingly interesting to estimate that number (ν) of photons incident per second on the sample which corresponds to $\bar{n}$ at $n_{\rm ph} < 10^9$ cm^{-2}·s^{-1}. This estimate yields $\bar{n} = (1\text{–}3)\nu$ (the uncertainty in this result stems primarily from the complicated geometry of the particular submicron sample which we studied). This result means that one structural feature in the photoconductivity corresponds to the absorption of one to three photons.

It follows that if the absorption of one photon is accompanied by a charge ex-

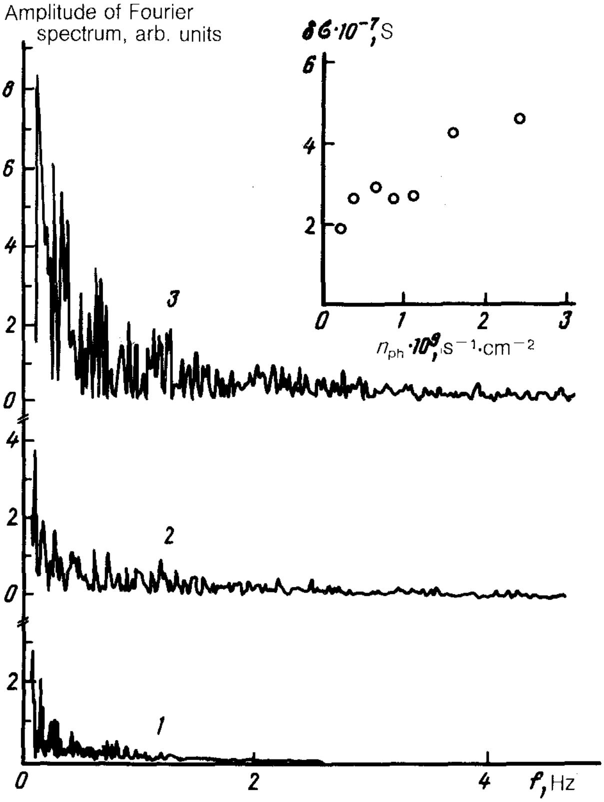

FIG. 2. Behavior of the Fourier amplitude of the photoconductivity spectrum at various light intensities (the values of n_{ph} are the same as in Fig. 1a). The inset shows the mean square deviation of the photoconductivity versus the light intensity.

change involving one impurity, the photoconductivity stems from a change in the state of a number of impurities which is on the order of unity. This conclusion is supported by an estimate of the number of impurities which undergo charge exchange based on the average amplitude of the fluctuations in the photoconductivity and the theory of Refs. 5–7. That theory predicts that for a fluctuation $\delta\sigma$ to be $\frac{e^2}{h}\left(\frac{W}{L}\right)^{1/2}\frac{L_\varphi}{L}$ (L_φ is the phase coherence length) it is necessary that $(N_s l_p^2/\kappa)^{1/2}$ impurities undergo charge exchange (N_s is the density of impurities, l_p is the mean free path, and $\kappa = 0.23$). It can be seen from this expression that as the temperature is lowered, the amplitude of the fluctuations in the conductivity at a fixed illumination level should increase in proportion to $L_\varphi \sim T^{-0.5}$; this is what we see experimentally. The value of $\delta\sigma$ can be determined from measurements in a magnetic field.[4] They yield $\delta\sigma = 5\times10^{-6}$ S. At the lowest light intensity we find $\delta\sigma_{\mathrm{ph}} = 2\times10^{-7}$ S (see the inset in Fig. 2). Hence the average number of impurities which undergo charge exchange is $= \frac{N_s l_p^2}{\kappa}(\delta\sigma_{\mathrm{ph}}/\delta\sigma)^2 = 2 - 3$. Consequently, the photoconductivity is caused under these conditions by the charge exchange of a number of impurities on the order of unity. Working from this picture, we can link the increase in $\delta\sigma_{\mathrm{ph}}$ with n_{ph} with an increase in Ω at high intensities. A capture of a number of electrons on the order of unity in surface states has been observed in silicon metal-insulator-semiconductor transistors with small dimensions.[8] A movement of a number of impurities on the order of unity has been observed in mesoscopic samples of Bi (Ref. 9) and Cu (Ref. 10). In those systems, however, the potential configuration changed in an uncontrollable way. In the present study we have achieved the first change in this configuration through a charge exchange of impurities due to the absorption of photons. We have shown that a photon, by exciting nonequilibrium carriers, makes it possible to change the charge state of a number of impurities on the order of unity in a controllable way. This effect is dominant. Specifically, it has the consequence that the photoconductivity of a mesoscopic conductor has some fundamentally new features, and we can assert that a new type of photoconductivity of semiconductors—a mesoscopic photoconductivity—has appeared.

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