Giant terahertz photoconductance of tunneling point contacts

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We report on the observation of the giant photoconductance of a quantum point contact (QPC) in tunneling regime excited by terahertz radiation. Studied QPCs are formed in a GaAs/AlGaAs heterostructure with a high-electron-mobility two-dimensional electron gas. We demonstrate that irradiation of strongly negatively biased QPCs by laser radiation with frequency \( f = 0.69 \) THz and intensity 50 mW/cm\(^2\) results in two orders of magnitude enhancement of the QPC conductance. The effect has a superlinear intensity dependence and increases with the dark conductivity decrease. It is also characterized by strong polarization and frequency dependencies. We demonstrate that all experimental findings can be well explained by the photon-mediated tunneling through the QPC. Corresponding calculations are in a good agreement with the experiment.

I. INTRODUCTION

The quantum point contact (QPC), discovered in 1988 [1, 2], is one of the most remarkable quantum devices in condensed matter physics [3, 4]. QPCs offer an elegant way to investigate one-dimensional phenomena in electronic transport by the electrostatic squeezing of a two-dimensional electron gas (2DEG) and become attractive for fundamental research of charge transport in mesoscopic conductors and numerous applications. Due to the fact that characteristic energies of QPCs are of the order of meV and can be electrically tuned by gate voltages, they become an important candidate for frequency-sensitive terahertz detection [5]. A conversion of high frequency (terahertz/microwave) electric fields in a dc electric current has been demonstrated in QPCs operating in various regimes and attributed to either electron gas heating [6–8] or rectification due to the nonlinearity of the QPC current-voltage characteristics [8–10]. Qing Hu considered a feasibility of the photon-assisted quantum tunneling transport [11] but follow up experiments did not provide an evidence for this effect because the observed photoresponse has been dominated by the electron gas heating effects [12, 13]. We note that almost all works on the terahertz/microwave response of QPCs were devoted to either the open regime with \( G > 2e^2/h \), in which the conductance quantization in units of \( 2e^2/h \) is detected, or the pinch-off regime at \( G \leq 2e^2/h \).

First studies of the photocurrent in QPCs operating in tunneling regime \( (G \ll 2e^2/h) \) have been carried out most recently and demonstrated quite unexpected results - a giant microwave photoconductance in response to 100 GHz radiation [14]. The experiments reveal an enhancement of the QPC conductance by more than two orders of magnitude for a rather small microwave power density of about 10 mW/cm\(^2\). The effect has been detected for traditional split-gate QPCs as well as for QPCs with a specially designed bridged-gate. In the latter structures, a photoresponse about ten times larger than in the ordinary split-gate QPC has been detected. The photoconductivity and the difference between the two types of gates have been shown to be caused by the influence of microwaves on the steady-state electron distribution function near the tunnel contact, i.e. a specific form of electron gas heating [14].

Here, we demonstrate that the giant photoconductance in QPCs operating in tunneling regime can also be obtained by applying radiation of substantially higher frequencies in the terahertz (THz) range. We show that at THz frequencies, the effect is caused by the photon-assisted tunneling and exhibits a strong polarization and frequency dependency. We present a microscopic theory of the photon-mediated tunneling in QPCs, which is in good quantitative agreement with the experimental findings.

II. SAMPLES AND METHODS

A. Samples

Our samples were fabricated on the basis of modulation doped GaAs/AlGaAs heterostructures with a 2DEG. Several samples have been prepared from two different wafers. The first wafer, referred to as #A in this paper, has a carrier density and mobility of the 2D electrons at liquid helium temperature of about \( n_s = 7\times10^{11} \) cm\(^{-2}\) and \( \mu = 1.5\times10^6 \) cm\(^2\)/Vs, respectively. This mobility corresponds to a mean free path of 30 µm, which substantially exceeds the QPC size being of the order of 100 nm. The second wafer (#B) has the density \( n_s = 5\div6 \times 10^{11} \) cm\(^{-2}\) and a much lower mobility \( \mu = 4 \times 10^5 \) cm\(^2\)/Vs (the corresponding mean free path is about 4 µm). Figures 1(a) and (b) show schematically quantum point contacts with a traditional split-gate and bridged-gate placed on two parts of a Hall bar sample.
FIG. 1: (a) and (b) Sketch of Hall bar samples with two QPC structures obtained by gates placed on two parts of the sample. The double arrow indicates the electric field vector $E(\omega)$ of normally incident THz radiation. The orientation of $E(\omega)$ with respect to the $x$-axis is described by the azimuthal angle $\alpha$, see panel (b). (c) Microphotograph of the gated part of the sample. (d) and (e) Zoomed images of the bridged-gate QPC and a traditional split-gate QPC, respectively.

Microphotographs of the gated parts of the sample are shown in Figs. 1(c)-(e). The bridged-gate QPC consists of a single piece of metal with a semi-elliptical narrowing, see Fig 1(d).

The gates are fabricated on the surface of the heterostructure using electron beam lithography with a distance of about 90 nm between the gate and the 2DEG. The resistance $R = 1/G$ was measured using the electric circuit shown in Fig. 1(a) and conventional lock-in technique with a frequency of 3 Hz and currents $J = (10^{-10} \div 10^{-8})$ A. Figure 2 shows the gate voltage dependence of the normalized dark conductance $G_{\text{dark}}(V_{g}^{\text{eff}})/G_0$ obtained for $J = 10^{-10}$ A. Here, $G_0 = 2e^2/h$ is the conductance quantum. The data obtained for the non-illuminated #A and #B structures reveal that at a temperature of $T = 4.2$ K and in the used range of gate voltages, the conductance $G(V_g)$ is much smaller than $G_0$, i.e. all QPCs operate in the tunneling regime. Note that while the overall characteristics of the QPCs remain the same, values of the gate voltage corresponding to the conductance $G_0$ depend on the cooldown procedure and differ from sample to sample. This is ascribed to cooldown dependent charge trapping in the insulator. To compare the measurements taken at different sample cooldowns we plot the data as a function of the effective gate voltage $V_{g}^{\text{eff}} = V_g - V_g(0.1G_0)$ with $V_g(0.1G_0)$ being the gate voltage at which the conductance is equal to $0.1G_0$.

The regime of complete tunneling of a QPC, with the resistance up to several MΩ is realized for samples cooled below $T \approx 10$ K. This can be seen in the temperature dependence of the conductance shown for the bridged-gate QPC (made of wafer #A) and the split-gate one (made of wafer #B) in the inset in Fig. 2. It is seen that the temperature dependencies are similar for both kinds of samples, demonstrating exponential growth for $T > 15$ K (with activation temperature of about 60 K) and saturation of the conductance at low temperatures. The latter gives an evidence for the tunneling regime in the latter case. For the similar value of the saturated conductance $G_{\text{dark}} = 7 \times 10^{-4} G_0$ we estimate the barrier height being of about 5 and 4.5 meV for bridged-gate sample #A and split-gate sample #B, respectively. Note that in spite of the different parameters of the 2DEG and different QPC shapes, we obtain almost the same barrier heights for the same dark conductance.

B. Methods

To measure the terahertz photoconductance of the QPCs we used a THz gas laser [15, 16] optically pumped by a CO$_2$ laser [17]. Radiation with frequency $f = 0.69$ and 1.63 THz (wavelengths of $\lambda = 432$ and 184 µm) have been obtained using CH$_3$O$_2$ and CH$_2$F$_2$ gases, respectively. The corresponding photon energies $\hbar \omega$ are 2.85 and 6.74 meV, respectively. All experiments are performed at normal incidence of radiation, see Fig. 1(a), and a temperature of $T = 4.2$ K. The normal incidence is used to exclude other possible photoresponses caused by photogalvanic or photon drag effects, which for this
also shows that the photoconductive signal corresponding to the conductance $G_{ph}$ is substantially larger for lower mobility samples, see data in Fig. 2 for bridged-gated samples #A and #B. Furthermore, its magnitude is larger for the bridged-gate QPC than for the split-gate structure. This difference has been previously observed in the microwave range on similar structures [14]. Studying the photoresponse as a function of the radiation power, we observed that it is characterized by a superlinear dependence, see the inset in Fig. 3.

Exploiting the advantage of THz laser radiation, which, in contrast to radiation in the microwave frequency range, permits to carry out accurate polarization experiment [24], we investigated the variation of the photoresponse as a function of the orientation of the radiation electric field vector. Figure 4 shows the dependence of the photoconductance $G_{ph}/G_{dark}$ on the azimuthal angle $\alpha$ measured for bridged-gate samples #A and #B. The inset reveals that the photoresponse can be well fitted by $G_{ph}/G_{dark} \propto \cos^2 \alpha$ and achieves its maximum for a radiation electric field vector oriented perpendicular to the gate stripes ($E \parallel x$).

Now, we turn to the photoresponse obtained for higher radiation frequency. Increasing the frequency by about 2.5 times, we observed a drastic (by more than one order of magnitude) reduction of the photoconductance $G_{ph}/G_0$. This is shown in Fig. 5 for bridged-gate samples #A and #B excited by radiation with frequencies $f = 0.69$ and $1.63$ THz. Furthermore, for higher frequencies, the photoresponse becomes almost independent on the effective gate voltage.

IV. DISCUSSION

The giant terahertz photoconductance of a tunneling point contact and its behavior upon variation of radiation polarization, frequency and intensity can be well described by the model of coherent photon assisted tunneling in QPCs developed in Ref. [25].

Let’s first consider, at a qualitative level, the enhancement of the electric current in a QPC operating in the tunneling regime under the action of normally incident linearly polarized microwave/terahertz radiation. The effect of the radiation field is twofold: (i) It causes an additional force in the direction of the tunneling current due to the $x$-component of the terahertz electric field $E(\omega)$ and (ii) It reduces the tunneling barrier due to the $E_z(\omega)$-component of the electric field originating from the near field of diffraction [26, 27]. The model of the potential modification and the corresponding enhancement of tunneling is shown in Fig. 6. It is assumed that the QPC in the tunneling regime can be considered as a one-dimensional barrier $U(x) = U_0/ch^2(x/W)$ (blue solid curve), where $U_0$ is the barrier height and $W$ is its characteristic width. Figure 6(a) and (b) illustrate the influence of the $E_z$-field component resulting in a force $eE_0z(\omega)\cos(\omega t) = [dV(x)/dx] \cos(\omega t)$ applied along $x$-direction shown in Fig. 6(a) by the magenta line for one half of a period of the wave. The force results in a time-
dependent potential $U(x) + V(x) \cos(\omega t)$, which increases the tunneling current for one half of a period of the radiation field and decreases it for the other half. The corresponding potentials are shown in Fig. 6(b) by solid and dashed curves. Obviously the effect is maximal for the radiation polarized along the current, i.e. in $z$-direction, as detected in our experiment. The second mechanism, considering the action of the potential $V(x) = V_0/\sqrt{\omega^2(x/W)^2}$, is illustrated in Fig. 6(c) and (d). It is based on the reduction of the tunneling barrier $U(x)$ due to the $z$-component of the electric field. In the vicinity of the QPC formed by the spiked split-gate and for a radiation electric field oriented along $x$-direction, i.e. normal to the gate stripes, near field diffraction results in a field $E_z$ directed along $z$-direction for one half of a period and $-z$ for the other. The corresponding time-dependent variation of the potential is shown in Fig. 6(d) by solid and dashed curves. The reduction of the potential barrier yields the increase of the tunneling current and, consequently, the conductance. For an electric field oriented along $y$-direction, the $E_z$-component becomes more complex and has opposite signs for opposite sides of the spiked gates forming the QPC and the effect vanishes.

Figure 6 and the above discussion present a semiclassical description of the radiation induced tunneling in QPCs, which illustrates the basic physics of the phenomena. This model, however, is valid only for rather low frequencies at which the characteristic time of electron tunneling through the potential barrier $U(x)$ is smaller than $1/\omega$ [28]. For arbitrary frequencies the effect can be described by the theory of the photon-assisted transmission [29] adopted for QPC in the tunneling regime in Ref. [25]. In the framework of this model, the Schrödinger equation with the time-dependent potential $U(x) + V(x) \cos(\omega t)$ is solved numerically, where $U(x)$ and $V(x)$ are approximated by piecewise constant functions (step approximation) as Coon and Liu suggested in Ref. [29]. For incident electrons having energy $E_0$, the coefficient $D$ of total multichannel transmission was determined by taking into account the essential channels $\mathcal{E} = E_0 \pm n\hbar\omega$ with absorption/emission of $n$ photons. The conductance was found by the Landauer formula at
presents the results of calculations carried out for the dependence of the normalized photoconductance $G_{ph}/G_0$ and $G_{ph}/G_{dark}$ on the dark conductance $G_{dark}/G_0$, see Fig. 8. We note that plotting $G_{ph}$ against $G_{dark}$ allows to compare experiment and modeling independently of the parameters of the 2DEG, the kind of structure, or the shape of gate. In particular, the calculations reveal a drastic suppression of the photoreponse both for the transition of the QPC from tunneling to open regime and for the change of frequency in the tunneling regime from 0.69 to 1.63 THz. This is in full agreement with the experimental results, see Figs. 5 and 8(b).

The higher photoconductance for 0.69 THz ($\hbar \omega = 2.85$ meV) is explained by transitions to the channels $E = E_0 \pm n\hbar \omega$, $n = 0, 1$. These channels belong to the tunneling mode and thus have classical turning points with a high probability density of discovering the electron, whereas for 1.63 THz ($\hbar \omega = 6.74$ meV) the channel $E_0 + \hbar \omega$ already belongs to the open mode with larger delocalization, smaller probability density in the barrier, and, therefore, reduced transition efficiency.

Finally, we note that the fitting of the model to the experiment is mainly determined by two parameters — the characteristic width $W$ of the QPC barrier and the intensity of irradiation described by $V_0$ (or $E_{0,x}$). The values for optimal fitting $W = 115$ and 85 nm for bridged-gate and split-gate samples are close to the lithographic size of the gates. The amplitude of the high frequency potential $V_0 = 5.5$ meV corresponds to the extreme value $dV(x)/dx = 423$ V/cm or $E_{0,x} = 176$ V/cm, which is almost 70 or 30 times larger than the maximum value calculated for the incoming plane wave ($E_0 = 6.14$ V/cm at the radiation intensity $I = 50$ mW/cm$^2$). This observation agrees with previous studies relying on the near field of diffraction for which a strong enhancement of the field amplitude in the vicinity of a metal edge (in our case the spiked gates forming the QPC) has been reported [27, 30, 31].

V. POSSIBLE ROLE OF THE ELECTRON GAS HEATING

Finally, we discuss a possible role of electron gas heating in the observed phenomena. First, we address the effect of the electron temperature increase. A substantial contribution of this mechanism can be ruled out based on the polarization dependence of the photoconductivity and on estimations of the electron temperature provided by independent measurements on the macroscopic part of the sample. A strong variation of the photoreponse with rotation of the radiation electric field vector $\mathbf{E}$, see Fig. 4, indicates that the tunneling current across the QPC has a maximum for $\mathbf{E}$ oriented parallel to the current ($\alpha = 0$) and vanishes for $\alpha = 90^\circ$. For the electron gas heating mechanism, however, the increase of the tunneling probability is caused by the rise of the 2DEG...
which is characterized by a weaker frequency dependence in this case is also proportional to the Drude absorption, the same time, the magnitude of the photoconductivity near the tunnel contact considered in [14] and does not depend on the electron temperature. At radiation on the steady-state electron distribution function along \( x \)-direction, as observed in the experiment, and does not depend on the electron temperature. At the same time, the magnitude of the photoconductivity in this case is also proportional to the Drude absorption, which is characterized by a weaker frequency dependence as that detected in our experiments, see Fig. 5. According to this model, changing the frequency from 0.69 to 1.63 THz should result in a decrease of the photoresponse magnitude by about 5 times. In experiments, however, this factor is about 50, i.e. by one order of magnitude larger. Thus, the theory of Ref. [14] yielding a good agreement for microwave frequencies does not explain a strong frequency dependence of the terahertz radiation.
induced photoconductivity in the QPC structure.

VI. SUMMARY

To summarize, we have observed a giant terahertz photoconductive response of the QPC operating in the tunneling regime. Experimental observations are in good agreement with the theory of the photon-mediated tunneling regime. The observed effect enlarges the family of photon/phonon assisted tunneling phenomena, previously detected in semiconductor systems for superlattices [27, 32, 33], resonance tunneling diodes [34, 35], quantum cascade laser structures [36], quantum dot systems [37] and semiconductors doped with deep impurities [38, 39]. The observed change in conductivity by more than two orders of magnitude in response to rather week terahertz radiation with a power of the order of several milliwatts demonstrate that a QPC in tunneling regime can be considered a good candidate for detection of terahertz radiation. As for the future work, the most challenging task is the search for the step-like dependency of the photoconductive response, known for the photon-assisted tunneling in superconductors [40–42] and semiconductor superlattices [27, 32, 33]. The theory developed in Ref. [25] reveals that this behavior is expected for an even deeper tunneling regime and lower temperature.

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