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LETTER TO THE EDITOR

A new mechanism for high-frequency rectification in a ballistic quantum point contact

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Abstract. A large DC voltage response, which depends strongly on the number of occupied subbands, is observed when a quantum point contact is subjected to high-frequency (~THz) radiation. This signal is explained by rectification caused by the non-linear one-dimensional transport properties of the point contact.

The observation of ballistic transport of electrons through quantum point contacts (QPCs) with widths smaller than the Fermi wavelength has excited much interest [1, 2]. In spite of the tremendous activity in this field, we know of only two reports of the photoresponse of QPCs to THz radiation in the literature [3, 4]; the effects reported were in both cases attributed to bolometric effects. This is all the more surprising when one considers the vast amount of work performed on the high-frequency (HF) photoresponse of classical point contacts; such point contacts have widths much greater than the Fermi wavelength [5, 6]. However, in this paper we report the first observation of a DC voltage response of a QPC to far-infrared (FIR) radiation. We demonstrate that the response is due to HF rectification of the radiation E field due to the non-linear current–voltage (I–V) characteristics of the QPC. This non-linearity is caused by an unequal population of the one-dimensional (1D) subbands for the two velocity directions in the contact [7, 8], and directly reflects the quantum mechanical nature of the QPC; the quantum mechanical character of the detection mechanism is also clearly shown by the presence of strong oscillations in the detected signal as the width of the QPC is varied. In contrast, the rectification observed in classical point contacts results from a non-linear I–V characteristic caused by electron–phonon scattering [9].

The QPC device was fabricated on a standard high-mobility GaAs–(Ga, Al)As heterojunction with carrier density $N_s \approx 2\times10^{11}$ cm^{-2} and 4 K mobility $\mu \approx 1\times10^6$ cm^2 V^{-1} s^{-1}. The Schottky gate consists of a metal line, 0.5 μm wide, bisecting the mesa into a source and drain; the split in this gate defines the 0.5 μm wide constriction. The device was current biased using a small AC current (83 Hz) superimposed on a DC source–drain current. Chopped unpolarized radiation (11 Hz) from a FIR laser was guided onto the device in a ^{3}He insert. The photoresponse signal (V_{Det}) between the voltage probes on either side of the split gate was detected with a lock-in amplifier referenced to the chopping frequency of the laser and recorded as a function of gate voltage (V_g). A second lock-in, referenced to the AC current, was used to measure the differential resistance of the device.

Figure 1 shows the detected signal for a laser frequency of 525 GHz (2.18 meV), with zero bias (upper curve), and with a 75 nA DC bias current (lower curve). At zero bias

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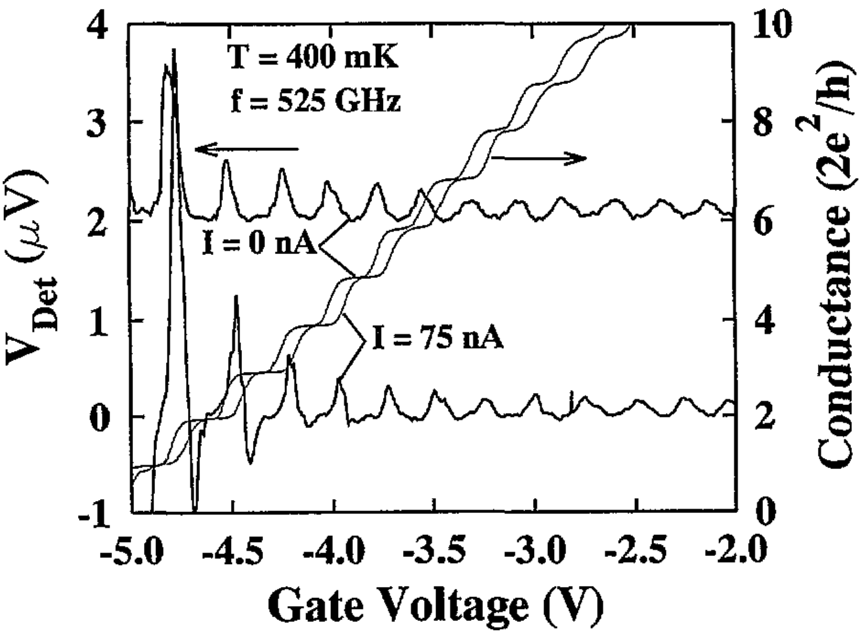

Figure 1. The photoresponse signal (left-hand scale) and conductance (right-hand scale) under applied FIR radiation of 525 GHz as a function of V_g and two different bias conditions. The upper trace is offset by 2 μV.

and negative V_g, where the QPC conductance exhibits quantized plateaus, we observe strong (positive) oscillations in the detected signal (upper curve). The peaks in this signal occur at gate voltages where the conductance of the point contact changes stepwise because of a change in the number of occupied 1D subbands. When a bias current is applied (lower curve) the peaks in the detected signal evolve into asymmetric oscillations, a part of which becomes negative. A shift of the plateaus with bias current is also observed in the conductance curves; this is caused by the different potential distribution between source, gate and drain [7, 8]. We studied the photoresponse for FIR energies ranging from 250 GHz to 4.25 THz (1 to 17.7 meV) and DC bias currents between 0 and 250 nA. For all energies upto 2.5 THz, oscillations in the gate voltage characteristics were observed.

Before proceeding to analyse the rectification mechanism, we must discount other possible causes of the photoresponse. In previous works [3, 4], bolometric heating of the device has been used to explain the oscillatory signals observed. One method of modelling the bolometric response is to measure the conductivity of the QPC at two known temperatures, and then to subtract the two sets of data. However, we have found that uncertainties arise in this approach due to the non-reproducibility of consecutive gate voltage sweeps. Very slight shifts in the gate voltages at which the risers between conductance plateaus occur can result in severe changes in the shape of the calculated 'bolometric response'. Such problems are visible in the calculations of Wyss *et al* [4], which fail to reproduce the negative signals seen in the original data. Instead, we have performed a calculation of the heating effect using the theoretical approach of Bagwell and Orlando [10], which is known to describe the temperature dependence of QPC conductivity very well; this technique is able to reproduce the negative signals observed in the data of Wyss *et al* [4]. We find that in order to reproduce the size of the response observed in our QPC, bolometric heating of ~1.5 K must be used in the model. The low laser powers used (1 to 100 μW) and the small number of absorption processes possible in a semiconductor heterojunction makes heating of this order in the QPC very unlikely, and in any case, our simultaneous recordings of the QPC resistance indicate that the warming of the device can be no more than a few tens of mK. Perhaps the most important clue that the photoresponse of the device is not bolometric is that the signals are still observed under conditions of zero bias. A possibility for a signal in the absence of bias might be a thermo-electric effect [11]; however, temperature differences of the order of a 100 mK directly across the channel are required to reproduce signals of the observed size. This seems highly unlikely since the device geometry is symmetric and the FIR wavelength is a thousend times larger than the constriction size.

Having discounted thermal effects as the cause of the photoresponse, we turn to the mechanism of rectification of the HF electric field by the non-linear device, by analogy with classical point contacts [5]. We assume that the HF (THz) electric field couples to the 'antenna' formed by the split gate and leads to a THz time varying field between the source and the drain contact. For this case the detected signal will be proportional to the second derivative (SD) of the I–V curves as a function of source–drain voltage. We have therefore calculated $(\mathrm{d}^2V/\mathrm{d}I^2)_{\mathrm{sd}}$ from the measured $(\mathrm{d}I/\mathrm{d}V)_{\mathrm{sd}}$ of a second identical device [8]; $(\mathrm{d}I/\mathrm{d}V)_{\mathrm{sd}}$ depends of course on V_g. The results are shown in figure 2 as a function of source–drain voltage for several different values of V_g. The observed non-linear behaviour for the source–drain conductance is a result of the unequal population of 1D subbands for the two velocity directions in the channel, as explained by Patel *et al* [8, 12]. Non-linearities $S = (\mathrm{d}^2V/\mathrm{d}I^2)/(\mathrm{d}V/\mathrm{d}I)^2 = (\mathrm{d}^2I/\mathrm{d}V^2)/(\mathrm{d}I/\mathrm{d}V) \approx 50\ \mathrm{V}^{-1}$ are found at the optimum bias voltage for the lowest-order transition; these are of order five times those of in a classical point contact [5].

The expected response as a function of V_g can now be reconstructed from the SD curves such as those in figure 2. The values of the SD (points) and the detected signal (full curve) are both plotted in figure 3, and it is immediately seen that the shape and position of the oscillations corresponds very well for this region of V_g. We use a restricted region of V_g because the source–drain voltage generated by the bias current is then approximately constant. Nevertheless, we found that the behaviour of the SD is the same for the other transitions. This agreement demonstrates the quantum mechanical origin of the oscillating signal in the experiment.

The $(\mathrm{d}I/\mathrm{d}V)_{\mathrm{sd}}$ curve (top graph in figure 2) shows a pronounced tilting of the base line a result of an asymmetry induced by biasing the gate against one of the current-carrying contacts [7, 8], which implies that for V_g at the middle of the transition between quantized plateaus the SD is finite at zero bias. Therefore exclusively positive peaks in the detected signal are present at zero bias, as is indeed observed (figure 1 upper trace). In the inset of figure 3 the inverse of the amplitude (normalized to the maximum amplitude) of the response in figure 1 (for zero bias) is shown as a function of the quantum number n of the transition. The experimental data show a linear dependence on the quantum number n, showing that the amplitude of the oscillations is quantized. This result is expected for rectification since $\mathrm{d}^2V/\mathrm{d}I^2 = R\ \mathrm{d}R/\mathrm{d}V$, and R is quantized as a function of V_g while $\mathrm{d}R/\mathrm{d}V$ is constant and non-zero at the transitions. We have tried to simulate the data using the model based on heating of the 2DEG [10]. The results are shown in the inset of figure 3, making it clear that the calculated amplitude does not reproduce the quantized behaviour of the data.

It is well established that a change from classical (energy-independent) to quantum (energy-dependent) detection occurs when the non-linearity in the I–V curves becomes large on a voltage scale comparable to the radiation energy ($\hbar\omega/e$). A full quantum theory describing the classical and quantum regime of HF detection and HF mixing for a general

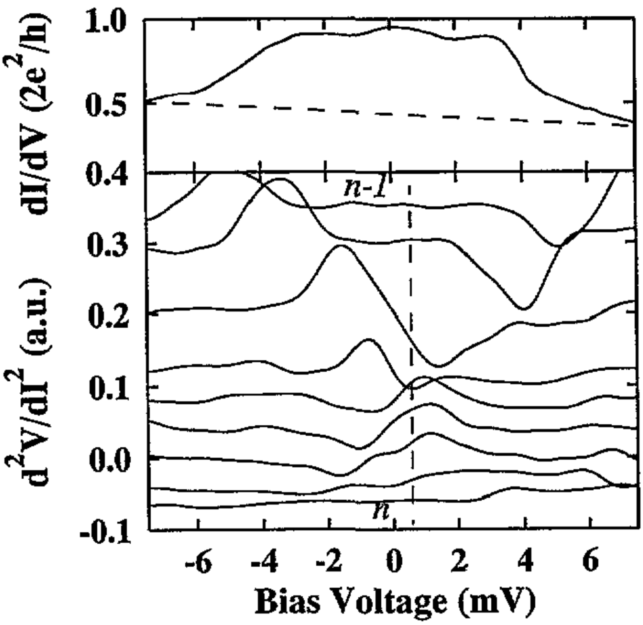

Figure 2. Top graph: example of a measured $\mathrm{d}I/\mathrm{d}V$ curve as a function of source–drain bias voltage for V_g at the middle of a transition between two quantized conductance plateaus. Bottom graph: calculated second derivative ($\mathrm{d}V^2/\mathrm{d}I^2 = R\ \mathrm{d}R/\mathrm{d}V$) for different values of V_g. The lowest curve corresponds to a conductance of $n\,2e^2/h$ and the upper curve to $(n-1)\,2e^2/h$. The curves are offset for clarity. The dashed line is a guide to the eye and corresponds approximately to a bias current of 75 nA.

single-particle tunnelling device has been developed by Tucker [13]. The application of HF voltages to a QPC has not been considered theoretically so far. However, a ballistic QPC is in many respects similar to a tunnelling device, although an essential difference is that the source and drain electrodes in a QPC are strongly coupled (i.e. no tunnelling barrier is present in the contact). The current through a QPC can be treated using an expression similar to that used for tunnelling devices, with the tunnelling probability (or transmission coefficient) replaced by a step function and the density of states in the electrodes constant (i.e. independent of energy). In the ballistic regime the transmission coefficient for every 1D subband in the channel is energy independent and changes between one and zero as a result of the bias-voltage-induced potential difference between the electrodes; this causes the non-linearity. Under the action of the HF field the electron energy distribution in one electrode will be modified with respect to the other, and change the current through the contact in a similar way to that observed for tunnelling devices. The HF detection in a QPC contact can therefore be understood phenomenologically, although the non-linearity is essentially different from that exhibited by all other tunnelling devices. At the last transition in the conductance we found $S = 50\ \mathrm{V}^{-1}$ which, for a frequency of 525 GHz, corresponds to a value of $0.1e/\hbar\omega$. We are clearly in the regime were classical rectification applies. Making a device with a very strong non-linearity or measuring at higher frequencies could very well result in quantum detection as was observed by Van der Heijden *et al* [6] in a classical point contact.

An important issue concerns the high-frequency detection limit of a quantum point contact. A fundamental limitation based on a classical argument is that the phase of the high-frequency field should not change during the passage of an electron through the constriction

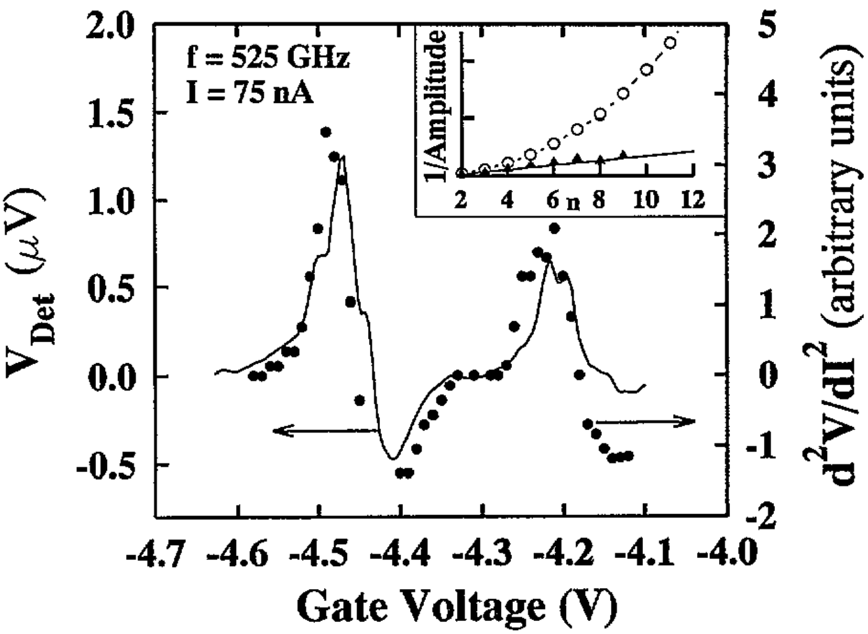

Figure 3. The photoresponse signal from figure 1 for 75 nA bias current and the second derivative as a function of V_g. Inset: inverse of the normalized amplitude versus quantum number n from figure 1 for zero bias (triangles). The circles are determined from a simple model based on heating.

region. This classical limit can be estimated from the transit time, and corresponds to a frequency in the range of $10^{12} - 10^{13}$ Hz. This is rather low in comparison with values for metal point contacts and resonant tunnelling barrier structures (RTBSs) [14]. This is due on the one hand to the low Fermi velocity in comparison to a metal and on the other hand the relatively long constriction length in comparison with the barrier widths of RTBSs. This limit might explain the absence of oscillations in the signal above energies of 2.5 THz ($\approx$10 meV), although in this regime poor coupling of radiation to the device could also be important. Nonetheless, the well defined ballistic transport properties of quantum-confined devices could offer an excellent system on which to study such problems in more detail.

In conclusion, we have observed the FIR photoresponse of a ballistic QPC for the first time. Clear effects are observed that indicate that the dominant mechanism in the photoresponse is the classical rectification of the applied high-frequency electric field. This rectification is generated by the strong non-linear $I-V$ characteristics, which are the results of an unequal number of populated 1D subbands for the two opposite directions of current in the constriction. We estimate that quantum detection should be feasible. This has many interesting applications in the study for of the fundamental properties of ballistic charge transport at ultra-high frequencies in quantum-confined electron devices.

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