Detecting noise with shot noise using on-chip photon detector

Y. Jompol1,*, P. Roulleau1,*, T. Jullien1, B. Roche1, I. Farrer2, D.A. Ritchie2 & D.C. Glattli1

The high-frequency radiation emitted by a quantum conductor presents a rising interest in quantum physics and condensed matter. However, its detection with microwave circuits is challenging. Here, we propose to use the photon-assisted shot noise for on-chip radiation detection. It is based on the low-frequency current noise generated by the partitioning of photon-excited electrons and holes, which are scattered inside the conductor. For a given electromagnetic coupling to the radiation, the photon-assisted shot noise response is shown to be independent on the nature and geometry of the quantum conductor used for the detection, up to a Fano factor, characterizing the type of scattering mechanism. Ordered in temperature or frequency range, from few tens of mK or GHz to several hundred of K or THz respectively, a wide variety of conductors can be used like Quantum Point Contacts (this work), diffusive metallic or semi-conducting films, graphene, carbon nanotubes and even molecule, opening new experimental opportunities in quantum physics.
Using quantum conductors to detect high-frequency radiations is very promising\textsuperscript{1,2}. However, it faces some fundamental issues. In particular, the important mismatch between the quantum conductor impedance (\(\sim \hbar/e^2\)) and the circuit impedance (typically 50\,\Omega) strongly limits the sensitivity. Recent realizations of on-chip quantum detection\textsuperscript{6–12} have circumvented this issue using spatially close detectors with larger impedance providing high sensitivity up to high frequency. On-chip detectors have been realized using GaAs/AlGaAs two-dimensional electron gas (2DEG)-patterned quantum dots\textsuperscript{8,9} and Aluminium or Niobium SIS junctions\textsuperscript{6,10–12}. The photon response of quantum dots depends on an energy scale set by their geometry, and that of superconducting junctions is limited by a characteristic energy gap and both systems show tunnel resistance variability. Regarding bolometric detectors their temperature and shows slow response time.

In this letter, we propose an on-chip radiation detection based on photo-assisted shot noise (PASN). When a quantum conductor is subjected to a time-dependent drain-source voltage, electrons and holes are created which then scatter inside the conductor is subjected to a time-dependent drain-source voltage, on photo-assisted shot noise (PASN). When a quantum...
To understand the photon detection principle, let us first assume that the detector line is excited by a coherent radiation at frequency $\Omega/2\pi$ such that $V_{\text{rad}}(t) = V_{\text{rad}} \cos(\Omega t)$. Electrons in the detector line can absorb $j$ photons of energy $E_i = \hbar \Omega$ by creating an electron-hole pair with a probability $P(E_i) = |f(E_i V_{\text{ac}}/\hbar\Omega)|^2$, with $f_i$ the $i$th Bessel function. Electrons and holes are independently and randomly partitioned by the QPC detector between left and right contacts. This generates a PASN whose low-frequency spectral density of current fluctuations $S_n(\omega)$ is given by$^{13-16}$:

$$S_n(\omega) = \frac{2e^2}{h} \left[ 4k_B T e \sum_n D_{D,n}^2 + 2 \sum_n D_{D,n} (1 - D_{D,n}) \sum_{l=\infty}^{i+\infty} E_l P(E_l) \coth \left( \frac{E_l}{2k_B T} \right) \right]$$

with $T_e$ the electronic temperature and $D_{D,n}$ the transmission of the $n$th electronic mode contributing to the QPC detector conductance $G_D$, $n = 1, 2, ...$. We introduce the Fano factor $F$ defined as $F = \sum_n D_{D,n} (1 - D_{D,n})/\sum_n D_{D,n}$. For weak ac voltage $eV_{\text{ac}} \ll \hbar \Omega$ and zero temperature, a direct relation can be established between the radiation power $P_{\text{rad}} = V_{\text{rad}}^2/2Z_{\text{rad}}$ and the current noise: $S_n(\omega) \approx 2G_n F(Z_{\text{rad}}^{1/2}/h)P_{\text{rad}}/\Omega$, where $Z_{\text{rad}}$ is the radiation impedance assumed smaller than the QPC detector conductance $G_D$ and $F$ the Fano factor. In equation (1), the sum over the energies $E_l$ gives the probability to generate electron-hole pairs. This probability only depends on the excitation and not on the details of the detector.

From equation (1), it is clear that the maximum PASN will be obtained for total transmission $D_{D} = \sum_n D_{D,n} = k + 1/2$, $k$ an integer. In addition to shot noise, a photon-assisted dc current $I_{\text{ph}}$ is generated when considering the (weak) energy dependence of the QPC transmission:

$$I_{\text{ph}} = \frac{2e}{h} \int dc \left( -\frac{\partial f}{\partial c} \right) \left( \sum_n \frac{\partial D_{D,n}}{\partial c} \right) \sum_{l=-\infty}^{i+\infty} E_l^2 P(E_l)$$

$f(c)$ is the equilibrium Fermi distribution. Photocurrent requires the energy dependence of the QPC. After photons absorption, electron-hole pairs are generated. As electrons and holes do not have the same transmission, a net DC current is induced. The energy dependence of transmission is strongly sample dependent and makes the photocurrent response not universal. On the contrary, the PASN response only depends on the Fano factor, which can be measured from conductance for a single-mode QPC, or is even universal, that is, 1/3, for a diffusive conductor. Modelling the QPC transmission with a saddle point potential$^{23,24}$, it can be shown that $dD_{D,n}/dc \propto D_{D,n} (1 - D_{D,n})$: maximum photocurrents will be also obtained at half-integer $D_{D}$.

In the present case, the excitation is not coherent but due to random fluctuations of the QPC detector drain-source voltage that originates from the capacitive coupling with the noisy QPC.
emitter. The above expressions can be generalized, giving the PASN as:

\[
S_{l}^{\text{PASN}} = \frac{2e^{2}}{\hbar} \left[ 4k_{B}T_{e} \sum_{n} D_{0,n}^{2} + 2 \sum_{n} D_{D,n}(1 - D_{D,n}) \int E P(E) \coth \left( \frac{E}{2k_{B}T_{e}} \right) dE \right]
\]

and the photocurrent:

\[
I_{ph} = \frac{2e}{\hbar} \int dc \left( - \frac{\partial f}{\partial k} \right) \left( \sum_{n} \frac{\partial D_{D,n}}{\partial k} \right) \int E^{2} P(E) dE
\]

The generalized probability distribution \( P(E) \) is similar to the \( P(E) \) function used in the dynamical Coulomb blockade theory (Supplementary Discussion 2). It is a direct function of the radiation power to be detected, which acts as a shot noise itself if a maximum for \( D_{E} = 0.5 \).

**Photocurrent measurement.** We first focus on the photocurrent whose measurement set-up is described in Fig. 2a. Source \( V_{in} \) leads to a current in the upper line and to the voltage difference \( V_{ph}^{ds} \) across the emitter. The resulting shot noise induces a photocurrent \( I_{ph} \) in the detector. We modulate \( V_{in} \) at frequency 174 Hz and detect the induced photocurrent using lock-in techniques. Series resistances are tuned on a plateau for each line, whereas the emitter and detector transmissions are varied. Following the saddle point potential model of a QPC23,24, the transmission of the \( n \)th mode can be written \( D_{D,n}(V_{g}) = 1/(1 + e^{2\Delta(V_{g} - V_{r})/V_{g}}) \), where \( V_{g,n} \) is related to the negative curvature of the saddle point potential. The photocurrent is given by (Supplementary Discussion 3):

\[
I_{ph} = \frac{e}{\hbar} \sum_{n} \frac{2\pi}{V_{g,n}} D_{D,n}(1 - D_{D,n})
\]

\( V_{g,n} \) and the lever arm \( \Delta = \frac{e\hbar}{2\pi} V_{g} \) are extracted from a study of the differential QPC conductance versus gate and bias voltages. We have introduced \( T_{E}^{\text{ph}} \) as the effective noise temperature of the circuit, which, up to a coupling factor, includes a combination of the shot noise temperature of the emitter: \( (1 - D_{E})^{2}k_{B}T_{E}^{\text{ph}} \) plus other equilibrium thermal noise contributions of the circuit surrounding the detector QPC. The coupling capacitance \( C_{C} \) appears in \( T_{E}^{\text{ph}} \) via the transimpedance of the system, which characterizes the strength of the coupling. Considering the geometry of \( C_{C} \), independent simulations give \( C_{C} \sim 1 \text{ fF} \).

The colour plot in Fig. 2b shows the measured photocurrent as a function of the emitter and detector transmissions \( D_{E} \) and \( D_{D} \), up to two transmitting orbital electronic modes. Above the colour plot, the photocurrent is plotted as a function of \( D_{E} \) for a fixed value of \( D_{D} \sim 0.45 \). As expected, it is maximum for half transmission of the emitter electronic modes and vanishes for integer transmission. These measurements have been found essential for a fine calibration of the electrical circuit and for complementary characterization of the PASN effect (Supplementary Fig. 3).

**PASN detection.** We now consider PASN measurements. The cross-correlation noise measurement set-up is described in Fig. 3a. To characterize the detector line, the QPC detector transmission is set to \( D_{D} = 0.17 \), whereas a dc bias is applied on the detector line. The resulting shot noise measured, black dots in Fig. 3b, perfectly agrees with the theory in red solid line. We extract an electronic temperature \( T_{E} = 310 \text{ mK} \) close to the fridge temperature \( T = 300 \text{ mK} \). Then, we turn off the applied bias on the detector line and the QPC emitter is biased and also tuned at \( D_{E} = 0.5 \). Both series resistances are tuned on the first plateau. Because of the coupling capacitance, voltage fluctuations are reported on the detector line. The only dc current flowing through the detector line being the weak dc photocurrent, no detectable transport shot noise is expected. However, we detect some noise, confirming that the PASN detection works as illustrated in Fig. 3c, black circle. The detected PASN, \( \Delta S_{l}^{\text{PASN,D}} \), is expected to be (Supplementary Discussion 4):

\[
\Delta S_{l}^{\text{PASN,D}} \approx - \frac{4e^{2}}{\hbar} D_{D}(1 - D_{D}) \frac{e^{2}}{C_{self}} T_{E}^{\text{ph}}
\]

Here, considering \( P(E) \) takes only important values for \( E \ll k_{B}T_{E} \), a low-energy expansion of equation (3) has been made. The \( T_{E}^{\text{ph}}(V_{in}^{DS})/C_{self} \) amplitude compatible with the detector geometry (estimated \( C_{self} \sim 3 \text{ fF} \) and \( C_{C} = 0.9 \text{ fF} \) and obtained from photocurrent measurements can now be compared with the noise measurement. The theoretical prediction (red solid line) following equation (6) also includes an additional term because of heating effect. We discuss this point in the following.

We open the series QPC of the detector line such that the current-to-voltage fluctuation conversion is now mediated by the smaller resistance of the long resistive mesa. Then we apply a fixed bias \( V_{in}^{DS} \) and sweep the detector transmission (red circles in Fig. 4a). As expected, the shot noise is maximum for \( D_{D} = 0.5 \) and cancels for \( D_{D} = 1 \). The slight disagreement with the theoretical prediction (red solid line) around \( D_{D} \sim 0.7 \) reveals a weak ‘0.7’ anomaly25–28. Then we tune the series QPC on its first plateau and repeat the same experiment (black circles). Surprisingly, the
shot noise does not cancel anymore for \( D_0 = 1 \). To understand it, we must consider heating effects (Supplementary Discussion 5). As the size of the QPC is much smaller than the electron-phonon relaxation length, there is a temperature gradient from the QPC to the ohmic contacts assumed to be at the base temperature of the fridge. Combining Joule heating together with the Fano factor is even constant 1/3 (ref. 29) and such a detector only depends on the transmission. For metallic diffusive system, \( F_\text{C} \) results from the similar heating effect (Supplementary Fig. 5).

Discussion

The agreement between theory and experimental data confirms our good understanding of the ‘on-chip’ detection mechanism: both photocurrent and PASN result from the same photon-assisted effect. As the photon current detector is based on the energy dependence of the transmission, which is strongly geometry dependent, it raises the question of use of such a detector based on a common calibration. On the contrary, PASN detection only depends on the transmission. For metallic diffusive system, the Fano factor is even constant 1/3 (ref. 29) and such a detector could be used on a large scale. Regarding the photodetection efficiency, there is a competition between the direct coupling \( C_G \) of the two lines and the shortcut to the ground characterized by \( C_{\text{off}} \). In the future, we will increase the number of fingers of the interdigitated \( C_G \) and reduce the area between the QPC to lower \( C_{\text{off}} \) and therefore reach the most efficient regime where \( C_{\text{off}} \ll C_G \).

To conclude, we have described a way of detecting high-frequency voltage fluctuations based on PASN measurement and seconded by photocurrent measurement. If the latter depends on the details of the mesoscopic conductor used, PASN is universal up to a noise Fano factor. The PASN approach for noise or photon radiation detection can be applied to other systems. This technique offers the possibility to probe mesoscopic properties at very high frequency (GHz and THz) of various materials (GaAs, graphene, carbon nanotube).

Methods

Emitter and detector lines were patterned using e-beam lithography on a high-mobility 2DEG formed at the GaAs/GaAlAs heterojunction. The 2DEG, located at a depth of 100 nm below the surface, has a density of \( 1.8 \times 10^{11} \) cm\(^{-2} \) and mobility of \( 2.69 \times 10^5 \) cm\(^2\) V\(^{-1}\) s\(^{-1} \). Measurements were performed in cryogen-free He cryostat at 300 mK (base temperature).

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Author contributions

D.C.G. designed the project. Y.J., P.R., T.J. and B.R. performed the experiments and analysed data. P.R. and D.C.G. wrote the manuscript. Y.J. and, P.R. set-up the measurement system. Y.J. fabricated the sample: I.F. and D.A.R. grew the wafer.

Additional information

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