Article:

Detecting noise with shot noise: a new on-chip photon detector

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The high frequency radiation emitted by a quantum conductor presents a rising interest in quantum physics and condensed matter[1, 6, 3, 4, 5, 7, 8]. However its detection with microwave circuits is challenging. The important mismatch between the quantum conductor impedance ($\sim h/e^2$) and the circuit impedance (typically 50 Ω) strongly limits the sensitivity. Recent realization of on-chip quantum detection [7, 9, 10, 11, 12, 13] have circumvented this issue using spatially close detectors with larger impedance providing high sensitivity up to high frequency. However, they lack of a universal photon-response. Here, we propose to use the Photon-Assisted Shot Noise (PASN) 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 [14, 15, 16, 17]. For a given electromagnetic coupling to the radiation, the PASN response is 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/frequency range, from few tens of milli-Kelvin/GHz to several hundreds of Kelvin/THz, 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.

To circumvent impedance mismatch limitation, different types of on-chip photon detectors have been developed using a second nearby quantum conductor and exploiting its photon detection ability. On-chip detectors have been realized using GaAs/AlGaAs 2D electron gas patterned quantum dots [9, 10] and Aluminium or Niobium SIS junctions [11, 12, 13, 7]. The photon-response of quantum dots depends on an energy scale set by their geometry, that of superconducting junctions is limited by a characteristic energy gap and both systems show tunnel resistance variability. Regarding bolometric detectors their efficiency depends on the phonon relaxation time, requires low temperature and shows slow response time.

In this letter, we propose a novel on-chip radiation detection based on PASN. When a quantum conductor is submitted to a time dependent drain-source voltage, electrons and holes are created which then scatter inside the conductor. Their partitioning between source and drain contacts leads to a current noise called Photo-Assisted Shot Noise. Remarkably, there is a simple link between PASN and the incident radiation power up to a noise Fano factor characterizing the statistics of partitioning. This simple link is better understood if we remark that PASN is the quantum manifestation of the rectification property of ordinary shot noise [18, 19, 20, 21] which is proportional to the absolute value of the drain-source voltage.

Figure 1 shows the principle of the on-chip detection. It consists of two separate excitation and measurement circuit lines etched in a high mobility two-dimensional electron gas (2DEG). Each line involves two QPCs in se-

ries. On the upper line, the left QPC is the high-frequency emitter. When biased by the dc voltage V_{ds}^E it generates shot noise up to the frequency eV_{ds}^E/h [20, 22]. The right QPC tuned on a conductance plateau acts as a stable series resistance R_S^E converting current noise into voltage noise. In the lower line the left QPC is the detector. In series with the right QPC, also tuned on a resistance plateau R_S^D, it experiences the emitter line voltage fluctuations via the coupling capacitance C_C up to the cut-off frequency f_{max} [23]. The number of electron-hole pairs generated in the detector line is a direct function of the radiated noise power integrated up to frequency $\min(eV_{ds}^E/h, f_{max})$. Their scattering by the QPC detector generates a low-frequency PASN which is measured. f_{max} depends on all QPC resistances and on the self-capacitance C_{self} of the 2DEG part between the QPCs in series.

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 $V_{ds}^E(t) = V_{ac}\cos(\Omega t)$. Electrons in the detector line can absorb l photons of energy $E_l=l\hbar\Omega$ by creating an electron-hole pair with a probability $P(E_l)=$ $\mid J_l(eV_{ac}/\hbar\Omega) \mid^2$, with J_l the lth 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_I^{PASN} is given by [14, 15, 16, 17]:

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$$S_I^{PASN} = \frac{2e^2}{h}[4k_B T_e \sum_n D_{D,n}^2 +$$

$$2\sum_n D_{D,n}(1-D_{D,n}) \sum_{l=-\infty}^{l=+\infty} E_l P(E_l) \coth \frac{E_l}{2k_B T_e}] \qquad (1)$$

with T_e the electronic temperature and $D_{D,n}$ the transmission of the nth electronic mode through the detector QPC, n=1, 2, ... For weak ac voltage $eV_{ac} \ll \hbar\Omega$ and zero temperature a direct relation can be established between the radiation power $P_{rad} = V_{ac}^2/2Z_{rad}$ and the current noise: $S_I^{PASN} \simeq 2G_D F(Z_{rad}e^2/\hbar)P_{rad}/\Omega$, where Z_{rad} is the radiation impedance assumed smaller than the QPC detector conductance G_D and F the Fano factor.

From Eq. (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_{ph} is generated when considering the (weak) energy dependence of the QPC transmission :

$$I_{ph} = \frac{2e}{h} \int d\epsilon (-\frac{\partial f}{\partial \epsilon})(\sum_n \frac{\partial D_{D,n}}{\partial \epsilon}) \sum_{l=-\infty}^{l=+\infty} E_l^2 P(E_l) \qquad (2)$$

$f(\epsilon)$ is the equilibrium Fermi distribution. Modeling the QPC transmission with a saddle point potential [24, 25], it can be shown that $\frac{\partial D_{D,n}}{\partial \epsilon} \propto D_{D,n}(1-D_{D,n})$: 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 which originates from the capacitive coupling with the noisy QPC emitter. The above expressions can be generalized, giving the PASN as:

$$S_I^{PASN} = \frac{2e^2}{h}[4k_B T_e \sum_n D_{D,n}^2 +$$
$$2\sum_n D_{D,n}(1 - D_{D,n}) \int EP(E) \coth \frac{E}{2k_B T_e} dE] \qquad (3)$$

and the photocurrent:

$$I_{ph} = \frac{2e}{h} \int d\epsilon(-\frac{\partial f}{\partial \epsilon})(\sum_n \frac{\partial D_{D,n}}{\partial \epsilon}) \int E^2 P(E) dE \qquad (4)$$

The generalized probability distribution $P(E)$ is similar to the $P(E)$ function used in the dynamical Coulomb blockade theory (see Supplementary Information). It is a direct function of the radiation power to be detected, which as a shot noise itself is maximum for $D_E = 0.5$.

We first focus on the photocurrent whose measurement set-up is described in Fig. 2(a). Source V_{in} leads to a current in the upper line and to the voltage difference V_{ds}^E 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 while the emitter and detector

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transmissions are varied. Following the saddle point potential model of a QPC [24, 25], the transmission of the nth mode can be written $D_{D,n}(V_g) = 1/(1+e^{2\pi(V_0-V_g)/V_{g,n}})$ where $V_{g,n}$ is related to the negative curvature of the saddle point potential. The photocurrent is given by (see Supplementary Information):

$$I_{ph} = \frac{e}{h}\frac{1}{\Delta}\frac{k_B T_E^* e^2}{C_{\text{self}}} \sum_n \frac{2\pi}{V_{g,n}} D_{D,n}(1 - D_{D,n}) \tag{5}$$

$V_{g,n}$ and the lever arm $\Delta = \partial\epsilon/\partial V_g$ are extracted from a study of the differential QPC conductance versus gate and bias voltages. We have introduced T_E^* 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: $(1 - D_E)\frac{eV_{ds}^E}{2k_B}$ plus other equilibrium thermal noise contributions of the circuit surrounding the detector QPC (see the supplementary Information).

The color plot in Fig. 2(b) 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 color plot, the photocurrent is plotted as a function of D_D for a fixed value of $D_E \sim 0.45$. 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 photon-assisted shot noise effect (see the Supplementary Information).

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We now consider PASN measurements. The cross correlation noise measurement set up is described in Fig. 3(a). To characterize the detector line, the QPC detector transmission is set to $D_D = 0.5$ while a dc bias is applied on the detector line. The resulting shot noise measured, black dots in Fig. 3(b), perfectly agrees with the theory in red solid line. We extract an electronic temperature $T_e = 310$ mK close to the fridge temperature $T = 300$ mK . Then we turn off the applied bias on the detector line and the QPC emitter is biased and also tuned at transmission $D_E = 0.5$. 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. 3(c), black circle. The detected PASN, $\Delta S_I^{PASN,D}$, is expected to be:

$$\Delta S_I^{PASN,D} \simeq -\frac{4e^2}{h} D_D (1 - D_D) \frac{e^2}{C_{self}} \frac{T_E^*}{6T_e} \qquad (6)$$

Here, considering $P(E)$ takes only important values for $E \ll k_B T_e$, a low-energy expansion of Eq. (3) has been made. The $T_E^*(V_{ds}^E)/C_{self}$ amplitude compatible with the detector geometry (estimated C_{self}=3 fF and C_c=1 fF) and obtained from photocurrent measurements can now be compared to the noise measurement. The theoretical prediction (red solid line) following Eq. 6 also includes an additional term due to 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_{ds}^D and sweep the detector transmission (red circles in Fig. 4(a)). 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" anomaly [26, 27, 28, 29]. 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 $D_D = 1$. To understand it, we must consider heating effects. Since 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 Wiedemann-Franz law, we obtain [18]:

$$T_e(V_{ds}) = T_{fridge}^2 + \frac{24}{\pi^2} \frac{G}{G_m} (1 + \frac{2G}{G_m})(\frac{eV_{ds}}{2k_B})^2 \qquad (7)$$

with G_m the total conductance linking the QPC to the ohmic contacts, and T_{fridge} the base temperature. Considering this effect, a QPC tuned on a plateau will not be noiseless anymore. We find a good agreement with measurements, black solid line.

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We now apply V_{ds}^E=6 mV on the emitter line, fixing $D_E \sim 0.5$ to get the maximum emitted signal. In Fig. 4(b), the PASN is measured as a function of D_D. The non zero value of the shot noise for $D_D = 1$ results from the similar heating effect. 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.*

To conclude, we have described a new way of detecting high frequency voltage fluctuations based on photon-assisted shot noise 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 two dimensional electron gas formed at the $GaAs/Ga_xAl_{1-x}As$ heterojunction. The two-dimensional electron gas is constituted 100nm below the surface has a density of 1.8×10^{11} cm^{-2} and mobility 2.69×10^6cm^2/ V s. Measurements were performed in cryogen free ^{3}He cryostat at 300 mK (base temperature).

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Author Contributions

Competing interests statement

Supplementary Information is available

Figure 1: Device structure. a Scanning electron microscope view of the sample. Two independent circuit lines defined by wet-chemical etching of the 2DEG are coupled via the capacitance C_C. On the upper line are patterned two QPCs in series: the QPC emitter (in red), and the QPC series resistor (in white) tuned on a plateau. On the lower line, the QPC detector is colored in blue. **b**, Equivalent circuit. In red the emitter line is coupled via the coupling capacitance C_C to the detector line in blue. The self capacitances C_{self} have been added that model the capacitance of each line between the two QPCs to the ground.

Figure 2: Photocurrent measurement. a, Schematic representation of the experimental set up for the photocurrent measurement. The QPC emitter is excited by a sine wave function $V_{pp} \sim 460$ μV at 174 Hz. The measurement of the photocurrent in the detector line is realized with a lock-in amplifier, with the excitation source as a reference signal. **b**, The photocurrentas a function of the total transmissions D_D (x-axis) and D_E (y-axis). On the upper graph is represented the photocurrent as a function of D_D (D_E tuned to 0.45). The right graph shows the photocurrent as a function of D_E (D_D tuned to 1.36).

Figure 3: PASN measurement. a, Schematic representation of the experimental set up for the PASN measurement. The QPC emitter being biased emits shot noise. Because of the capacitive coupling between the emitter and detector line, high frequency voltage fluctuations are transferred in the detector line, generating PASN. Shot noise measurements

are done by converting the current fluctuations into the voltage fluctuations across a RLC circuit, cooled at 300 mK using 3 MHz resonant frequency and 300 kHz typical bandwidth. Home made cryogenic amplifiers, with ultra low input voltage noise (0.2 nV/$\sqrt{Hz}$) and located on the 3 K stage amplify the voltage fluctuations. Using fast acquisition card and Fast Fourier Transform, the current noise cross-correlation is computed in real time. **b,** Measured shot noise S_V as a function of dc voltage V_{ds}^D across the QPC detector, when the QPC series resistor is opened. **c,** Measured PASN S_V^{PASN} as function of the V_{ds}^E accross the QPC emitter. QPCs emitter and detector are tuned at $D_D = D_E = 0.5$. Both series resistances are tuned on the first plateau.

Figure 4: Transmission dependence of the PASN. a, black dots: measured shot noise as a function of D_D for an opened series QPC together with our theoretical model (black solid line). red dots: same measurement with the series QPC tuned on a plateau. The non-zero value of the noise for $D_D = 1$ results from heating effect. In both cases $V_{ds}^D = 100\mu V$. **b,** red dots: measured PASN as function of D_D for the series QPC tuned on the first plateau and a fixed $D_E \sim 0.5$ (theoretical prediction represented by a black solid line). The applied DC bias is $V_{ds}^E = 6$ mV.

a

Emitter

C_{self}

R_S^E

C_C

Ohmic contacts

Detector

C_{self}

R_S^D

Acc.V Spot Magn   Det WD Exp
25.0 kV 1.0 2017x SE 16.1 0   20 µm

b

Emission circuit

C_C

Detection circuit

R_S^E

$S_I(V_{ds}^E)$

V_{ds}^E

C_{self} C_{self}

S_I^{PASN}

R_S^D

QPC emitter

QPC detector

a

V_{IN}
10MΩ
5kΩ
5kΩ
5kΩ
5kΩ
300mK
300K
V_{OUT}

Acc.V Spot Magn Det WD Exp
25.0 kV 1.0 2017x SE 16.1 0
20 μm

b

I_{ph} (pA)

20

10

0

D_D

0   1   2

I_{ph} (pA)

0   10   20

2

1   D_E

0.45

0

25

0

1.36

a

10MΩ
V_{DC}
5kΩ
5kΩ

Acc.V Spot Magn Det WD Exp   20 µm
25.0 kV 1.0 2017x SE 16.1 0

δV_1
δV_2

300mK

3K
3K

$\delta V_1 \delta V_2$
300K

b

S_I (10^{-28} A^2/Hz)

V_{ds}^{D} (µV)

c

S_I^{PASN} (10^{-28} A^2/Hz)

V_{ds}^{E} (mV)