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TEMPORALLY CORRELATED TRANSPORT AND SUPPRESSION OF SHOT NOISE IN A BALLISTIC QUANTUM POINT CONTACT

M. REZNIKOV, M. HEIBLUM, H. SHTRIKMAN and D. MAHALU

Braun Center for Submicron Research, Department of Condensed Matter Physics, Weizmann Institute of Science, Rehovot 76100, Israel

Abstract—Wide band shot noise, associated with d.c. current flow through a quantum point contact (QPC), is measured in the microwave frequency range of 8–18 GHz. As the number of conducting channels in the QPC changes, the noise power oscillates, with almost zero value at the conductance plateaus. Consistent with existing theories the noise peaks depend linearly on the d.c. current. Surprisingly, however, in the pinch off region, where QPC is expected to behave as a classical injector, we find strong noise suppression, possibly mediated by the Coulomb interaction in the QPC region.

It is well known that the conductance of a QPC, e.g. a smooth one-dimensional constriction made in a two-dimensional electron gas, is quantized in units of $2e^2/h$. This quantization is a direct result of almost perfect transmission ($T \cong 1$) through the one-dimensional channels confined in the QPC. Aside from that quantization, it was predicted by Khlus[1] and Lesovik[2] that when $T = 1$ another remarkable effect is taking place: a total **suppression** of *shot noise* in the QPC. The shot noise, originating from the *granularity* of the electrons and their stochastic injection, is characterized by averaged squared current fluctuations. In classical systems such as the vacuum diode where electron emission can be considered as a truely stochastic (Poisson like) process, the average of the squared current fluctuations, Δi, measured in a frequency range $\Delta\nu$, is given by the *classical shot noise* expression $S(\nu)\cdot\Delta\nu = \langle(\Delta i)^2\rangle_{\Delta\nu} = 2eI\cdot\Delta\nu$. $S(\nu)$ is the *white* (frequency independent) spectral density and I the average current. In a QPC the theoretically obtained low frequency spectral density of the current fluctuations, at zero temperature θ, for energy independent T_is is[1–3]

$$S(\nu = 0) = 2e\cdot\frac{2e^2}{h}\cdot V_{DS}\cdot\sum_{i=1}^{N} T_i(1 - T_i), \qquad k_B\theta \ll eV_{DS}, \quad (1)$$

with V_{DS} the voltage across the QPC, N the number of occupied channels in the QPC and T_i the transmission coefficient through the channel I. Since

$$\frac{2e^2}{h}\cdot V_{DS}\cdot T_i = I_i$$

is the ith channel current, a noise suppression of $(1 - T_i)$, relative to the classical noise for the ith channel, is expected. In an experiment where the T_is are continuously varied, the shot noise is expected to have a maximum (half of the classical shot noise due to one channel) whenever the transmission of the uppermost conducting channel is 1/2. Note that the frequency dependence of $S(\nu)$ was shown (neglecting Coulomb interactions between electrons) to decrease linearly with ν with $S(\nu_{cutoff}) = 0$ for $h\nu_{cutoff} = eV_{DS}$ (i.e. for $V_{DS} = 1$ mV, $\nu_{cutoff} \cong 250$ GHz)[4].

Several attempts to measure shot noise in a QPC, with[5,6] and without[7] the application of a magnetic field, were published. However, they had been restricted to low frequencies ($\nu < 100$ kHz) where $1/f$ noise or fluctuations and instabilities of the conductance are dominant. Moreover, the noise power was found to have a square dependence on the d.c. current and not the expected linear dependence. A linear dependence, though, was observed for noise measured in diffusive mesoscopic conductors[8].

First some order of magnitude estimates. The injected d.c. current, I_{in}, and the applied voltage, V_{DS}, should be as small as possible in order to: (a) prevent electron heating, and (b) prevent injection into higher one-dimensional channels. However, the applied voltage V_{DS} should be greater than $K_B\theta/e$ in order to make eqn (3) applicable. For example, $V_{DS} = 1$ mV leads, according to eqn (3), to a peak noise $S(0) = 6.2\cdot10^{-27}\,A^2\,Hz^{-1}$. At high enough frequencies this *shot noise-signal* has to compete with the noise of the amplifiers. Even a cold amplifier has an equivalent noise temperature of 40 K at its 50 Ohm input impedance, leading to a spectral density of unwanted noise $k_B\Theta/50 = 10^{-23}\,A^2\,Hz^{-1}$ Hz, more than three orders of magnitude higher than the shot *noise* we are searching for. Consequently, in order to improve the *signal-to-noise ratio* (S/N) we modulate the d.c. current through the QPC at low frequency

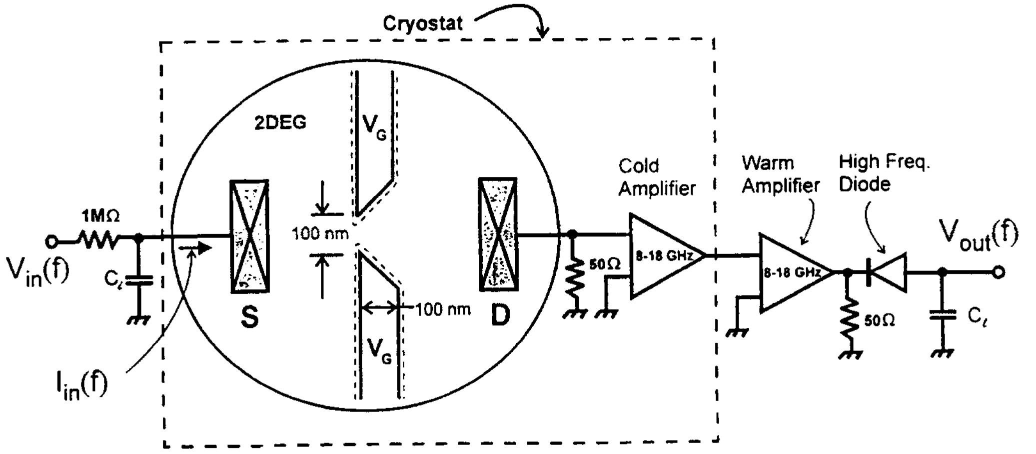

Fig. 1. The experimental setup. The voltage V_G controls the number of one-dimensional conducting channels in the QPC. The current, modulated at low frequency F, is provided to the QPC via variable current source, with a voltage $V_{DS}(f)$ appearing across the QPC. A high frequency path to ground is provided via a capacitor C_i. The current and its high frequency fluctuations are fed into a low noise cooled amplifier with a power gain of 10^3 in the band 8–18 GHz. Another "warm amplifier" follows—terminated by a high frequency diode and a load capacitor C_l, providing the low frequency output $V_{out}(f) \propto \langle(\Delta i)^2\rangle_{10\text{GHz}}$.

f (less than 1 kHz) and measure the amplified *noise*, synchronously with f, using a lock in technique. It turns out that the wide band measurements improve the S/N relative to the ratio of the spectral densities given above by a factor of $(\Delta\nu/\Delta f)^{1/2}$, where Δf is the low frequency bandwidth (determined by the time constant of the lock-in amplifier). We thus expect that measuring the shot noise synchronously, in a band $\nu = 8$–18 GHz ($\Delta\nu = 10$ GHz) with $\Delta f < 1$ Hz will improve the S/N ratio by a factor of $(1–3)\cdot 10^5$, leading to an acceptable $S/N \approx 10^2$. This improvement is crucial for the success of this experiment and is therefore discussed in detail in the Appendix.

Our QPC is induced electrostatically in the plane of a 2DEG, embedded in a GaAs-AlGaAs heterostructure only 33 nm below the surface. The 2DEG has an area electron density of $4.6\cdot 10^{11}\,\text{cm}^{-2}$ and a low temperature mobility of $5\cdot 10^5\,\text{cm}^2\,\text{V}^{-1}\,\text{s}^{-1}$. The QPC is formed by direct electron beam writing and metal gate (TiAu) deposition, with a 100 nm gap between the two gates (shown schematically in Fig. 1). The voltage V_G, applied to the gates via a low pass filter with an upper frequency of 1 MHz, controls the number of one-dimensional conducting channels in the QPC. Under all conditions of the experiment no measurable gate leakage current was found. The d.c. voltage drop across the sample was monitored during the measurement with a lock-in amplifier and was kept constant via a feedback loop (taking into account series resistance). Similarly, the d.c. current was kept constant by monitoring the d.c. voltage drop on a series 1 MOhm resistor. Note that high frequency path to ground is provided via the capacitor C_i, effectively maintaining a constant voltage on the sample. The high frequency current fluctuations are amplified in the 8–18 GHz band, and are finally applied to a high frequency diode and a load capacitor C_l. The low frequency output $V_{out}(f) \propto \langle(\Delta i)^2\rangle_{10\text{GHz}}$† is converted, after a calibration of the system gain and the diode sensitivity, to the spectral density at the input $S[A^2\,\text{Hz}^{-1}]$.

Typical results for the d.c. conductance G and the noise signal $V_{out}(f)$, measured as a function of gates voltage V_G, at $T = 1.5$ K, are shown in Fig. 2. The

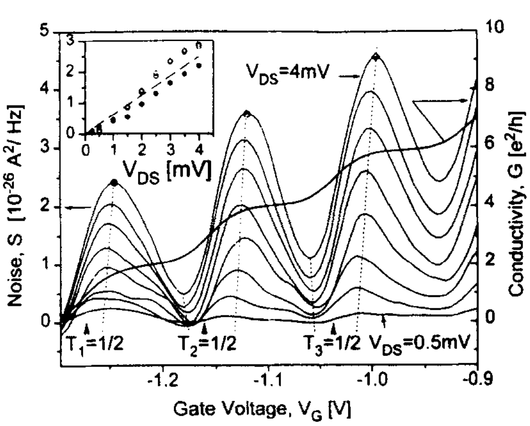

Fig. 2. Noise spectral density $S(\nu)$ and normalized linear conductance G, measured with current 10 nA vs gate voltage V_G. The noise is measured for $V_{DS} = 0.5, 1, 1.5, \ldots, 4$ mV. The lines through the maxima and minima of the peaks are only guides to the eye. Positions of $T_i = 1/2$, where the noise maxima are theoretically expected to be are marked with arrows. Inset: dependence of the peaks height (same scale as in main figure) on injection voltage V_{DS}: ●, ○, ◇ mark the first three conducting one-dimensional channels. The dashed straight line is the predicted behavior.

†The a.c. input current leads to a noise with a modulated power at frequency f. The diode, being a fast nonlinear device, produces current proportional to the power of the input signal. The capacitor C_l is the low frequency load.

linear conductance is quantized in units of $2e^2/h$, after subtracting the series resistance of the ohmic contacts. The *noise-signal*, $S \propto V_{out}(f)$, is measured for different injection voltages,

$$V_{DS}(f) = \frac{V_{DS}}{2}(1 + \cos 2\pi f t),$$

imposed on the QPC. As predicted by eqn (3), keeping V_{DS} **constant** allows the injected current $I_{in}(f)$ to change as the conductance of the QPC varies, leading to a noise dependence proportional to $T(1 - T)$. Indeed the measured *noise-signal*, as a function of V_G and for different V_{DS}, exhibits strong oscillations. Even though the magnitude of the peaks agree rather well with the predicted noise maxima, being $(1/4)\cdot 2e\cdot(2e^2/h)\cdot V_{DS}$, the peak positions (and respective minima) shift from the predicted positions at V_G ($T_i = 1/2$) (and $T_i = 1$ for the minima) to V_G (higher T_is)—a shift that increases with V_{DS}. From first sight these shifts could qualitatively be explained if transport takes place through more than a single channel, mediated by the finite temperature and the injection voltage, thus leading to added noise from the upper channel and to an apparent shift in the peaks position. We thus applied a strong magnetic field (B), normal to the plane of the 2DEG, which is known to improve the accuracy of the conductance quantization. With $B = 3$ T, corresponding to a filling factor of six, the accuracy of the conductance quantization improves but the effect on peaks position is small (not shown here). Moreover, the fact that the measured *noise-signal* drops to "zero" at the minima implies that $T_i = 1$, $T_{i+1} \approx 0$ at the minima, making the above hypothesis questionable.

Another important point to consider is the fact that eqn (3) is valid only for energy independent transmission and zero temperature, while in an actual QPC $T = T(E)$ and the temperature is finite. As was pointed out in Refs[9,10] we actually measure an *excess nois*, : a combination of *thermal* and *shot noise*. Integrating $T(E)$ over an energy range eV_{DS}[9,10], taking into account currents from source (S) to drain (D) and *vice versa* and the low energy cutoff due to the channel quantization, we find that the calculated noise peaks shift toward **smaller** Ts; contrary to our data. This indicates that another mechanism plays a role in the observed modification of the noise behaviour in the QPC. We return later to this issue.

As seen in Fig. 2 there is a gradual monotonic rise of the background noise with increasing conductivity and with increasing V_{DS}. We attribute this to electron heating (proportional to $V_{DS}^2\cdot G$) and to a possible injection into higher channels, respectively. While this monotonic background grows super linearly with the injected current the amplitude of the peaks (each peak relative to the average of two adjacent minima) grow almost linearly with the current, as seen in the inset of Fig. 2. This linear dependence of the spectral density also agrees with eqn (3) quantitatively and is a crucial fact in substantiating the origin of the noise.

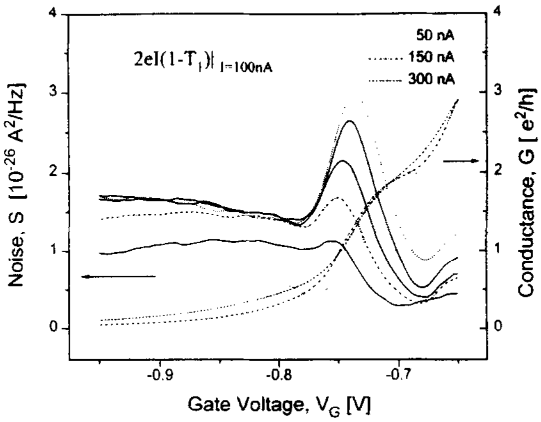

Fig. 3. Noise spectral density S vs gate voltage V_G for different currents through the QPC (50–300 nA with 50 nA step). Curve for expected noise according to eqn (3) for $I = 100$ nA is added. The noise is sharply suppressed for $T < 1/2$ and is smaller by approximately a factor of 3, for a current of 50 nA and even much more for larger currents. Conductance curves measured at three different currents are given.

We performed detailed investigations of the noise in the *pinch off* region of the QPC, namely, when all carriers are depleted from the QPC and transport is via tunneling or via thermally assisted emission. As the gate voltage becomes more negative and the resistance of the QPC increases, the current and its fluctuations tend to zero. We thus performed noise measurements at a **constant current**, I, expected to get the behavior $S = 2eI\cdot(1 - T_1)$, which is nearly classical when $T_1 \ll 1$. The noise-signal is expected to rise monotically with decreasing V_G saturating eventually at a value twice as large as that for $T = 1/2$ (as shown in Fig. 3 by the dotted lines). Contrary to that, we find, with and without application of magnetic field, that the *noise-signal* peaks around $T = 1/2$, drops at lower Ts and saturates with values more than three times smaller than expected. We wish to stress again that, unlike the measurements with constant V_{DS}, these measurements are done with constant d.c. currents; hence the peaks near $T_1 = 1/2$ **are not expected**. Another remarkable fact is, that for $T \ll 1$, as the d.c. current increases above some 100–150 nA the *noise-signal* **does not increase!** Since $T \ll 1$ and correlation due to Fermi statistics are absent[1,2], we speculate that correlation due to Coulomb repulsion between electrons sets in; this correlation is not accounted for by the existing theories. We rule out noise suppression resulting from a possible reduction of l_{in} at high V_{DS} since $l_{in} \gg L$ (where $L \sim 100$ nm) all through the experiment.

Coulomb mediated correlation should become significant when the *dwell time* in the QPC becomes the limiting factor in determining the current rather than the transmission coefficient, T, through the barrier. This happens when the dwell time becomes comparable to the average time interval $\Delta t = e/I$ between electrons entering the barrier. As saturation of the *noise-signal* is apparent at $I > 150\,\text{nA}$ then $\Delta t < 1$ ps. The dwell time, on the other hand, is the tunneling time or the traveling time of the thermally activated electrons through the barrier. Even though there is no common accepted view for the tunneling time, we chose to estimate it via the semiclassical time $\Delta t_{\text{tunn}} \approx \Delta x/v$, where Δx is the tunneling length and v is the value of the *tunneling velocity* given by $\sqrt{2(\Phi - E_F)/m}$, with $\Phi - E_F$ the effective barrier above the Fermi energy[11]. For our barrier with dimensions of the metallic gates, $\Delta x \approx 100\,\text{nm}$, a tunneling transmission of the order of $T_1 \approx 0.1$ is achieved when the effective barrier is on the order of 1 meV. The *tunneling velocity* is then $v \approx 10^7\,\text{cm s}^{-1}$ and the dwell time is $\Delta t_{\text{tunn}} \approx 1$ ps. Similarly, if transport is via thermionic emission, we have to take for the velocity the thermal velocity, leading to a dwell time of the same order. Since the dwell time is quite similar to the average entering time interval, transport is correlated with current $I = e/\Delta t_{\text{dwell}}$. As the current increases Δt_{dwell} becomes smaller.

Is the Coulomb repulsion energy sufficient to correlate the electrons? For a distance $\Delta x \approx 100\,\text{nm}$ and with negligible screening we find the repulsive energy $\sim 1.3\,\text{meV}$. It is sufficiently large, relative to the temperature ($\sim 0.13\,\text{meV}$) and the effective barrier height ($\sim 1\,\text{meV}$), to suppress transfer of a second electron when one electron dwells in the barrier. If true, the resultant temporally correlated transport persists for currents larger than $\sim 100\,\text{nA}$ and is expected to have a spectral peak at $\nu = I/e = 1/\Delta t_{\text{dwell}} > 1$ THz. We thus propose that our measured noise, when $T \ll 1$, represents a sample of the spectral *tail* in the 8–18 GHz band, with peak noise increasing in magnitude and shifting to higher frequencies as the current increases, thus keeping the noise-signal in the *tail* almost constant. This rather crude estimate is consistent with our data in Fig. 3. The application of a magnetic field ($B = 3$ T) seems to suppress the noise-signal even further (and the peak near $T = 1/2$ disappears, not shown), suggesting even enhanced correlation.

We now come back to the *noise-signal* peaks seen in Fig. 2. For our applied voltage $V_{DS} > 1$ mV the d.c. current through each channel is of the order of $\sim 100\,\text{nA}$, and thus a Coulomb mediated correlation can be effective between plateaus for $T_i \ll 1$. This noise reduction, beyond the *Fermi related reduction*, can shift the apparent noise peaks from $T = 1/2$ to higher Ts and broaden the minima around $T = 1$, explaining qualitatively the shift of the peaks. A more careful theoretical analysis of the temporal correlation taking also into account Coulomb interactions is needed. Experiments of the frequency dependence of the noise might also provide a means of measuring the dwell time in the barrier.

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REFERENCES

1. V. A. Khlus, *Sov. Phys. JETP* **66**, 1243 (1987).
2. G. B. Lesovik, *JETP Lett.* **49**, 592 (1989).
3. M. Buttiker, *Phys. Rev. Lett.* **65**, 2901 (1990).
4. G. B. Lesovik and L. S. Levitov, *Phys. Rev. Lett.* **72**, 538 (1994).
5. F. Liefrink and A. J. Scholten, *Physica B* **175**, 213 (1991).
6. S. Washburn *et al.*, *Phys. Rev. B* **44**, 3875 (1991).
7. Y. P. Li *et al.*, *Appl. Phys. Lett.* **57**, 774 (1990); F. Liefrink, J. I. Dijkhuis and H. van Houten, *Semicond. Sci. Tecnol.* **9**, 2178 (1994), and references herein.
8. F. Liefrink*et al.*, *Phys. Rev. B* **49**, 14066 (1994).
9. R. Landauer and Th. Martin, *Physica B* **175**, 167 (1991).
10. G. B. Lesovik and R. Loosen, *Zeitschrift fur Physik B* **91**, 531 (1993).
11. M. Buttiker and R. Landauer, *Phys. Rev. Lett.* **49**, 1739 (1982).
12. A. Van der Ziel, *Noise in measurements*, p. 30. Wiley, New York (1976).

APPENDIX

DEPENDENCE OF THE SIGNAL-TO-NOISE RATIO ON THE BANDWIDTH OF THE AMPLIFIER

The signal current at the output of the amplifier can be expressed as $\tilde{I}(t) = \int \alpha(t - \xi) I(\xi)\,d\xi$, where $I(\xi)$ is the input signal and $\alpha(t)$ the transfer function of the amplifier. We assume that

$$\alpha = \begin{cases} 0, & t < 0 \\ (1/\tau)\exp(i\omega_0 t - t/\tau), & t > 0 \end{cases}.$$

The Fourier transform of α is

$$\alpha(\omega) = \frac{1/\tau}{i(\omega_0 - \omega) + 1/\tau}$$

which means that the amplifier has a bandwidth $1/\pi\tau$ around the central frequency $\nu_0 = \omega_0/2\pi$.

The intensity at the output of the amplifier is

$$\tilde{P}(t) = \frac{\tilde{I}(t)\tilde{I}^*(t)}{2} = \tfrac{1}{2}\iint \alpha(t - \xi)\alpha^* \times (t - \xi')I(\xi)I(\xi')\,d\xi\,d\xi'. \quad \text{(A1)}$$

We will assume the average current to be zero, as the d.c. signal is not transmitted through the amplifier. At frequencies much smaller than the inverse correlation time for the signal (which is supposed to be of the order of eV/h according to Ref. [14], one may consider fluctuations of $I(t)$ to be uncorrelated: $\langle I(t)I(t')\rangle = S_I \cdot \delta(t - t')$, S_I being the (double side) spectral density of the current fluctuations and $\langle\rangle$ means ensemble averaging[12]. Hence we get for an average measured noise intensity

$$\langle \tilde{P}(t)\rangle = \frac{S_I}{2}\int \alpha(t - \xi)\alpha^*(t - \xi)\,d\xi = \frac{S_I}{4\tau}. \quad \text{(A2)}$$

Thus the effective bandwidth for the noise measured by a selective amplifier is $1/4\tau$. If one modulates the current through the sample and hence, the current fluctuations S_I by 100% at some small frequency f, the peak-to-peak value of the *noise-signal* is given by eqn (A2). Consequently an RMS signal measured by the lock-in is $S_I/8\sqrt{2}$.

We have to compare this signal with the intensity of the amplifier noise, which is the main source of unwanted noise in the system. We will characterize this noise by the equivalent spectral density $S_N \cdot \delta(t - t') = \langle N(t)N(t')\rangle$, where

$N(\xi)$ is the equivalent current fluctuation at the input of the amplifier. We have to calculate a correlator $K(t, t') = \langle \tilde{P}_N(t)\tilde{P}_N(t')\rangle$, where $\tilde{P}_N(t)$ is the intensity of the current fluctuations at the output of the amplifier determined similarly to eqn (A1)

$$K(t, t') = \tfrac{1}{4}\iint\iint \alpha(t-\xi)\alpha^*(t-\xi')\alpha(t-\zeta)\alpha^* \times (t-\zeta')\langle N(\xi)N(\xi')N(\zeta)N(\zeta')\rangle \, d\xi \, d\xi' \, d\zeta \, d\zeta.$$

We assume the amplifier noise to be white. This means that the noise amplitudes are uncorrelated: $\langle N(t)N(t')\rangle = S_N \cdot \delta(t-t')$, where S_N is the spectral density of the amplifier noise and the quantity being averaged can be decoupled into the product of the pair averages

$$\langle N(\xi)N(\xi')N(\zeta)N(\zeta')\rangle = S_N^2\{\delta(\xi-\xi')\delta(\zeta-\zeta') + \delta(\xi-\zeta)\delta(\xi'-\zeta') + \delta(\xi-\zeta')\delta(\xi'-\zeta)\}.$$

Performing trivial integration we end with

$$K(t, t') = \frac{1}{16\tau^2} S_N^2 \times \left\{1 + \left(1 + \frac{1}{1+(\omega_0\tau)^2}\right)\cdot \exp\left(-\frac{2(t-t')}{\tau}\right)\right\}, \quad t > t.$$

Thus the noise intensity has a constant component and a fluctuating part with correlation time $\tau/2$. The spectral density of these fluctuations at small frequency $f \ll 1/\tau$ is

$$K(f \approx 0) = \frac{S_N^2}{16\tau^2}\left(1 + \frac{1}{1+(\omega_0\tau)^2}\right)\cdot\frac{\tau}{2} = \frac{S_N^2}{32\tau}\left(1 + \frac{1}{1+(\omega_0\tau^2)}\right) \approx \frac{S_N^2}{32\tau}.$$

A lock-in amplifier with time constant τ_L measures only the component of the signal which is in phase with the reference signal and hence, has an effective bandwidth for the noise measurements $1/8\tau_L$, two times smaller than the selective amplifier with the same τ [see eqn (A2)]. Thus, the average intensity of the amplifier noise fluctuations measured by the lock-in is

$$\langle N^2\rangle \approx \frac{S_N^2}{128\tau\tau_L}.$$

Finally we end up with a signal-to-noise ratio of

$$\frac{\langle P(t)\rangle}{\sqrt{\langle N^2\rangle}} \approx \frac{S_I}{S_N}\cdot\sqrt{\frac{\tau_L}{\tau}} = \frac{S_I}{S_N}\cdot\sqrt{\frac{\tau_L \Delta\nu}{\pi}},$$

where $\Delta\nu$ is the bandwidth of the amplifier. Thus the signal-to-noise ratio is improved by a factor of $\sim 10^5$ for $\Delta\nu = 10^{10}$ and $\tau = 3$ s, making the signal measurable.