PHYSICAL REVIEW B VOLUME 49, NUMBER 19 15 MAY 1994-I

Experimental study of reduced shot noise in a diffusive mesoscopic conductor

F. Liefrink and J. I. Dijkhuis
Faculty of Physics and Astronomy, and Debye Institute, University of Utrecht, P.O. Box 80.000, 3508 TA Utrecht, The Netherlands

M J. M. de Jong,* L. W. Molenkamp, and H. van Houten
Philips Research Laboratories, 5656 AA Eindhoven, The Netherlands
(Received 4 February 1994)

We demonstrate that a diffusive narrow wire of a length much longer than the elastic scattering length and the phase-coherence length, but of the order of the energy relaxation length, exhibits shot noise with an intensity lower than the full shot-noise level. At 4.2 K, the reduction factor is shown to vary between 0.2 and 0.45, depending on the width of the wire. The reduction is consistent with recent theoretical predictions.

Due to the discreteness of the electron charge, an electrical current through a conductor may exhibit shot noise.[1] Usually, shot noise is associated with the emission of electrons across a potential barrier inside the conductor. If this emission occurs completely at random the shot-noise intensity is maximal, i.e., $S_I = 2eI$, where I is the dc current passed through the conductor. In recent years, the phenomenon of shot noise has become an important issue in the study of electron transport through nanostructure devices. This has led to a large number of contributions, mainly concerning the theoretical aspects of shot noise in the phase-coherent transport regime.[2] It has been calculated that shot noise is indeed present in such a conductor, but with an intensity strongly dependent on the specific transport properties.

In particular, predictions have been reported concerning the shot-noise intensity in the phase-coherent *diffusive* transport regime.[3,4] In this regime, the length L of the conductor is much longer than the electron mean free path, but shorter than the phase-coherence length. The phase-coherence length is determined by electron-electron scattering and electron-phonon interactions. Using random matrix theory, it has been shown that in this case the *ensemble averaged* shot-noise intensity $S_I = \frac{2}{3}eI$ at zero temperature. The occurrence of reduced shot noise in the quantum diffusive transport regime has been ascribed to the bimodal distribution of the transmission probabilities of the quantum channels in the conductor. The shot noise is suppressed because part of the electron transport in the diffusive transport regime proceeds via noiseless open quantum channels, which have a transmission probability of nearly unity, whereas the remainder of the quantum channels has a transmission probability small compared to unity, thus contributing to the shot noise. Remarkably and importantly for the present work, the partial suppression of shot noise has subsequently also been found from a semiclassical approach, suggesting that the suppression in the diffusive transport regime does not require the existence of discrete quantum channels or, equivalently, phase coherence.[5] This is in agreement with a recent paper, which demonstrates that phase-breaking collisions do not affect the shot-noise power,[6] as long as the sample length is shorter than the inelastic scattering length.

Previously, Li *et al.* reported on shot noise in the ballistic transport regime.[7] In this paper we will present the experimental study of low-frequency shot noise in the diffusive transport regime. We measure the current noise in a wire fabricated from a (Al,Ga)As heterostructure, which contains a two-dimensional electron gas (2DEG) of density $n_s = 2.6 \times 10^{15}$ m^{-2}. The electron mobility μ in the 2DEG is limited by ionized-impurity scattering and temperature-dependent acoustic-phonon scattering. In general, the mobility depends on temperature as $\mu^{-1} = \mu_0^{-1} + \alpha T$.[8] For our material we find that $\mu_0 = 24$ m^2/V s and $\alpha = 3.7 \times 10^{-4}$ V s/m^2 K. This corresponds to a mean free path $l_{\text{imp}} \approx 2$ μm at zero temperature. A wire of lithographic length $L = 16.7$ μm and width $W = 0.5$ μm is created by electrostatic lateral confinement of the 2DEG using a split-gate technique.[9] In Fig. 1, the wire resistance R has been plotted versus V_g, measured using a low-frequency phase-sensitive technique. The gate voltage was supplied by a dry battery and connected to the gate electrodes via a low-pass RC filter in order to suppress the fluctuations in the gate-voltage source. From Fig. 1 it is clear that R strongly increases with decreasing V_g, which is due to a simultaneous decrease of n_s, W, and the effective mean free path l_{eff} with V_g.

We now discuss how these quantities depend on V_g. The density n_s inside the wire is obtained from measurements of the Shubnikov–de Haas oscillations. We may write R as a sum of a diffusive Drude resistance and a Sharvin contact resistance,[10]

$$R = \frac{L}{W}\frac{\hbar k_F}{n_s e^2 l_{\text{eff}}} + \frac{h}{2e^2}\frac{\pi}{k_F W}. \tag{1}$$

Here, $k_F = (2\pi n_s)^{1/2}$ is the Fermi wave vector. The mean free path in the wire, l_{eff}, is generally lower than l_{imp}, because of diffusive boundary scattering. Assuming that 80% of all boundary collisions are specular and 20% are diffusive,[11] we may extract l_{eff} and W by fitting Eq. (1) to the data in Fig. 1. The results are summarized in Table I. We also tabulate the electron-phonon scattering length l_{ep}, that has been estimated from $l_{ep} \equiv (D\tau_{ep})^{1/2}$, assuming that the electron-phonon

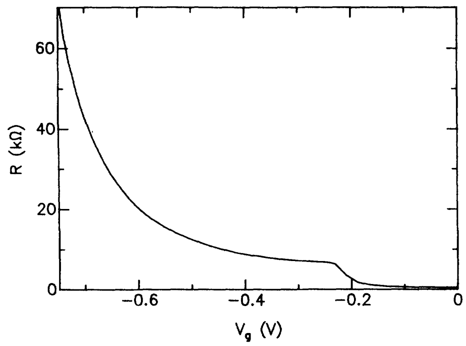

FIG. 1. The wire resistance R vs V_g for $T = 4.2$ K.

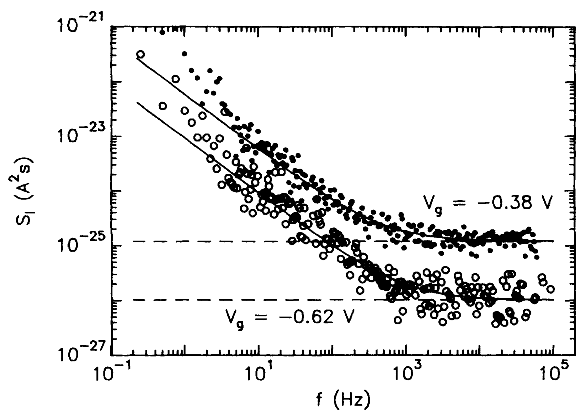

FIG. 2. Typical examples of $S_I(f)$ at $T = 4.2$ K for $V_g = -0.38$ V (closed circles) and $V_g = -0.62$ V (open circles). Solid curves represent fits to the data by the sum of a $1/f$ and white-noise contribution. The latter contribution is separately indicated by dashed lines.

scattering time $\tau_{ep} = m/e\alpha T$ is independent of V_g, and taking for the diffusion constant $D = \frac{1}{2} v_F l_{\rm eff}$, with v_F the Fermi velocity.

To measure the current noise, the narrow wire is placed in series with a resistor of 100 kΩ and biased with a dc current I. The bias current is supplied by a dry battery and is varied between 100 nA (for high resistances) and 3 μA (for low resistances). The voltage $V = IR$ across the wire is fed into an ultralow-noise amplifier (Brookdeal 5004) and subsequently registered and Fourier transformed with a digital spectrum analyzer (Advantest R9211A). The noise spectra are measured in the frequency range from 0.1 Hz to 100 kHz. Note that shot noise is characterized by a frequency-independent spectral density. In order to obtain a spectrum $S_I(f)$ of the excess current noise in the wire and to be able to extract the expected shot-noise contribution from this spectrum, three different measurements have to be carried out. First, we measure the noise in the presence of the dc bias current. This measurement, $S_0(f)$, includes the relevant signal superimposed on the current-independent Johnson-Nyquist noise, the amplifier noise, and other spurious noise sources. Second, a background measurement $S_b(f)$ with zero bias current is performed in order to be able to subtract the spurious noise sources. Third, using a calibrated white-noise source (Quan-Tech 420) connected to the electrical setup, a noise measurement is carried out for calibration of the spectrum, yielding the spectrum $S_c(f)$. As a result, $S_I(f)$ can be calculated from

$$S_I(f) = \frac{S_0(f) - S_b(f)}{S_c(f) - S_b(f)} P_{\rm cal}, \tag{2}$$

with $P_{\rm cal}$ the intensity of the calibrated white-noise source. We note that $S_I(f)$ is the *equivalent* current noise. This means that we have corrected for noise suppressions due to the external measurement circuit.

TABLE I. Typical values of the transport parameters for three values of V_g.

V_g (V)	n_s (10^{15} m^{-2})	W (μm)	$l_{\rm eff}$ (μm)	l_{ep} (μm)[a]
−0.38	2.2	0.32	1.5	6.2
−0.48	2.0	0.24	1.4	5.8
−0.62	1.6	0.14	1.3	5.3

[a]Calculated for $T = 4.2$ K.

In Fig. 2 we have plotted two typical examples of $S_I(f)$ versus f. These spectra are taken at 4.2 K for $V_g = -0.38$ and −0.62 V. At low frequencies, the noise spectra are dominated by a $1/f$ contribution, whereas the spectra are white at higher frequencies. Such spectra are characteristic for all gate voltages ($-0.70 < V_g < -0.35$ V) and temperatures ($0.4 < T < 50$ K) examined. We have found that the intensity of the $1/f$ noise increases quadratically with I, whereas the shot noise increases linearly. In this paper, we will exclusively focus on the white-noise contribution to the spectra. The $1/f$ noise will be the subject of a following paper.

In Fig. 3, the intensity of the white-noise contribution, henceforth denoted as S_I, has been plotted versus I for $V_g = -0.38$, −0.48, and −0.62 V. The temperature was 4.2 K, i.e., $k_B T \ll eV$. It is evident from Fig. 3, that the noise intensity varies linearly with I for all values of V_g. Solid lines in the figure denote linear fits to the data, yielding values for $S_I/2eI$ of 0.4 for $V_g = -0.38$ V, 0.3 for $V_g = -0.48$ V, and 0.2 for $V_g = -0.62$ V. We have collected all our measurements of $S_I/2eI$ versus V_g in Fig. 4 and find that $S_I/2eI$ varies between 0.45 at high V_g and 0.2 at low V_g.

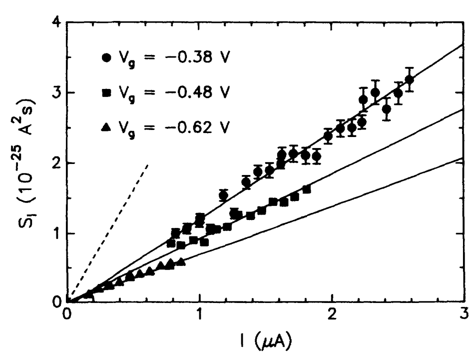

FIG. 3. Current dependence of S_I at $T = 4.2$ K, for $V_g = -0.38$, −0.48, and −0.62 V. Solid lines represent linear fits to the data. The dashed line shows the current dependence of S_I as expected for full shot noise.

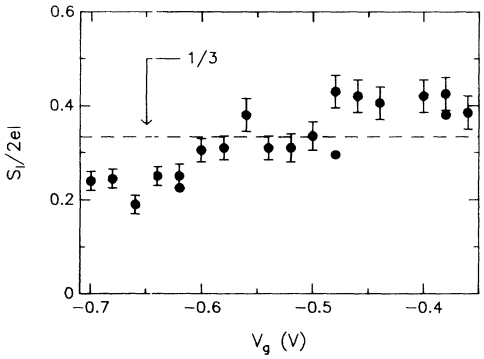

FIG. 4. Gate-voltage dependence of $S_I/2eI$ at $T = 4.2$ K. The dashed line indicates the ensemble averaged value of $S_I/2eI$ as expected from theory.

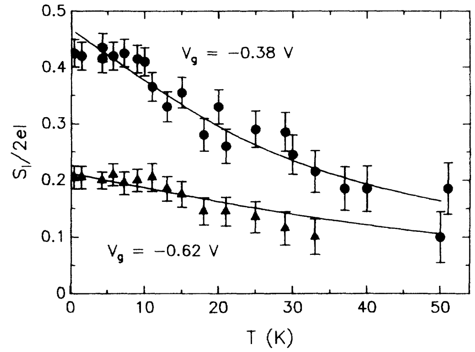

FIG. 5. Temperature dependence of $S_I/2eI$ for $V_g = -0.38$ and -0.62 V. Solid curves represent fits by Eq. (3).

In Fig. 5 we present $S_I/2eI$ versus T for $V_g = -0.38$ and -0.62 V. We used fixed bias voltages $V = 9$ and 14 mV, respectively. The white-noise intensity decreases monotonically with temperature for both settings of V_g. Below 10 K the noise intensity remains approximately constant. Solid lines in Fig. 5 represent fits of Eq. (3) to the experimental data as discussed below.

Since $S_I(f)$ is found to be white at frequencies above approximately 1 kHz and linearly dependent on current, we conclude that the measurements shown in Figs. 3 and 4 point to shot noise. From these measurements it is also apparent that the shot-noise intensity is suppressed below the full shot-noise level and varies between 0.20 at low V_g and 0.45 at high V_g, close to the predicted shot-noise reduction factor of $\gamma = \frac{1}{3}$. A suppression factor of about $\frac{1}{3}$ was also found in a wire with a length L of 6.2 μm. This means that the shot-noise suppression cannot be ascribed to inelastic scattering that would give a suppression factor l_{ep}/L, i.e., proportional to $1/L$. We thus wish to discuss our findings in terms of the theoretical predictions concerning shot noise in the diffusive transport regime. We know that the electron transport through the wire indeed proceeds diffusively. However, phase coherence is absent since the effective electron temperature T_e in the wire in much higher than the lattice temperature T, as a result of current heating of the electron gas $[T_e - T \propto (I/W)^2]$.[12] The current heating leads to an enhancement of non-phase-conserving electron-electron scattering with a calculated l_{ee} much smaller than 100 nm.[13] This suggests that the assumption of complete phase coherence in the random matrix theory is not a necessary one in order to arrive at $\gamma = \frac{1}{3}$. In addition, one might expect the presence of a large Johnson-Nyquist contribution $S_{\rm JN} = 4k_BT_e/R$ proportional to I^2. As seen in Fig. 3, the noise is observed to be linear in I even though $4k_BT_E/R$ would be larger than S_I. This clearly proves that such a contribution is absent. We thus conclude that the Johnson-Nyquist noise is determined by the equilibrium temperature T of the external reservoirs connected to the wire, instead of T_e in the wire.

We will now turn to the temperature dependence of S_I (Fig. 5). If $kT \sim eV$, the excess noise is no longer equal to the zero-temperature limit. According to Refs. 14 and 5,

$$S_I = 2eI\left[(1-\gamma)\frac{2k_BT}{eV} + \gamma \coth\left(\frac{eV}{2k_BT}\right)\right] - 4k_BTG$$
$$= 2eI\gamma\left[\coth\left(\frac{eV}{2k_BT}\right) - \frac{2k_BT}{eV}\right], \qquad (3)$$

where the reduction factor $\gamma = \frac{1}{3}$. From our low-temperature experiments we learned that γ is not necessarily equal to $\frac{1}{3}$. Therefore, we use Eq. (3) to fit the data of Fig. 5 with γ as a free parameter. The solid lines in Fig. 5 represent these fits, yielding $\gamma = 0.22$ for $V_g = -0.62$ V and $\gamma = 0.45$ for $V_g = -0.38$ V. In view of the crudeness of the model, in which, e.g., the temperature-dependent electron-phonon scattering is not taken into account, we find the agreement satisfactory.

Our experiments show that γ ranges from approximately 0.20 to 0.45, depending on V_g, whereas the theoretical value equals $\frac{1}{3}$. One explanation for this effect may be that the theory provides the ensemble-averaged reduction factor, whereas the experiment is carried out on a specific conductor. Indeed, calculations using random matrix theory have shown that generally deviations from $\frac{1}{3}$ as large as 0.1 can be expected,[4] consistent with our observations. Another explanation may be that it is assumed in Refs. 3 and 4 that the number of quantum channels inside the conductor, $N = k_FW/\pi$, is much larger than 1. In the experiment, however, N ranges from 12 for $V_g = -0.38$ V down to 4 for $V_g = -0.62$ V. This means that the condition of $N \gg 1$ is not fulfilled, possibly leading to deviations of the suppression factor from $\frac{1}{3}$. Finally, from Table I it is evident that for $T > 2$ K, $l_{ep} < L$, which may further suppress the shot noise.

In conclusion, we have experimentally demonstrated the existence of a nonvanishing shot-noise intensity in the phase-incoherent diffusive transport regime. We found that the shot-noise intensity is reduced below the full shot-noise level, in accordance with recent theoretical calculations. In order to elucidate the origin of the small but significant deviation of the suppression factor from the theoretical prediction of $\frac{1}{3}$, more experiments on samples with different dimensions have to be carried out. In addition, it would be desirable to extend the theory to include inelastic scattering (electron-electron and electron-phonon), so that the role of phase coherence and the high electron temperature in the wire can be elucidated.

We thank F. J. M. Wollenberg for invaluable technical assistance, R. W. Stok for carrying out a portion of the experiments, and C. T. Foxon for fabrication of the (Al,Ga)As wafers at Philips Research Laboratories (Redhill, Surrey, United Kingdom). This work was supported financially by the Netherlands foundations "Stichting voor Fundamenteel Onderzoek der Materie" (FOM) and "Nederlandse Organisatie voor Wetenschappelijk Onderzoek" (NWO).

* Also at Instituut Lorentz, University of Leiden, 2300 RA Leiden, The Netherlands.

[1] A. van der Ziel, *Noise in Solid State Devices and Circuits* (Wiley, New York, 1986).

[2] G. B. Lesovik, Pis'ma Zh. Eksp. Teor. Fiz. **49**, 515 (1989) [JETP Lett. **49**, 594 (1989)]; M. Büttiker, Phys. Rev. Lett. **65**, 2901 (1990); Th. Martin and R. Landauer, Phys. Rev. B **45**, 1742 (1992).

[3] C. W. J. Beenakker and M. Büttiker, Phys. Rev. B **46**, 1889 (1992).

[4] M. J. M. de Jong and C. W. J. Beenakker, Phys. Rev. B **46**, 13 400 (1992).

[5] K. E. Nagaev, Phys. Lett. A **169**, 103 (1992).

[6] A. Shimizu and M. Ueda, Phys. Rev. Lett. **69**, 1403 (1992).

[7] Y. P. Li, D. C. Tsui, J. J. Heremans, J. A. Simmons, and G. W. Weimann, Appl. Phys. Lett. **57**, 774 (1990).

[8] T. Kawamura and S. Das Sarma, Phys. Rev. B **45**, 3612 (1992).

[9] For a review of quantum transport in semiconductor nanostructures, see C. W. J. Beenakker and H. van Houten, Solid State Phys. **44**, 1 (1991).

[10] M. J. M. de Jong, Phys. Rev. B **49**, 7778 (1994).

[11] L. W. Molenkamp and M. J. M. de Jong, Phys. Rev. B **49**, 5038 (1994).

[12] L. W. Molenkamp, H. van Houten, C. W. J. Beenakker, and R. Eppenga, Phys. Rev. Lett. **65**, 1052 (1990).

[13] One may estimate l_{ee} from $l_{ee} = v_F \tau_{ee}$, where τ_{ee} is the electron-electron scattering time for a 2DEG as derived in G. F. Giuliani and J. J. Quinn, Phys. Rev. B **26**, 4421 (1982).

[14] M. Büttiker, Phys. Rev. B **46**, 12 485 (1992).