Shot Noise in Linear Macroscopic Resistors

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We report on direct experimental evidence of shot noise in a linear macroscopic resistor. The origin of the shot noise comes from the fluctuation of the total number of charge carriers inside the resistor associated with their diffusive motion under the condition that the dielectric relaxation time becomes longer than the dynamic transit time. The present results show that neither potential barriers nor the absence of inelastic scattering are necessary to observe shot noise in electronic devices.

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Nyquist noise and shot noise are the two prototypes of current noise displayed by electronic devices. Nyquist noise, originally found by Johnson in resistors [1], is displayed by all electronic devices at thermal equilibrium and is associated with the equilibrium thermal fluctuations. The spectral density of the current fluctuations of Nyquist noise is white and given by [2]

$$S_I^{\text{Nyquist}} = \frac{4k_BT}{R}, \tag{1}$$

where k_B is the Boltzmann constant, T is the temperature, and R is the linear resistance. Shot noise, originally found in saturated vacuum tubes [3], is displayed under nonequilibrium conditions and is associated with the discreteness of the electric charge. Its current spectral density at low frequency is usually given by [3]

$$S_I^{\text{shot}} = 2qI, \tag{2}$$

where I is the average current and q is the carrier charge. Shot noise is routinely found in many solid-state electronic devices such as tunnel and Schottky diodes, p-n junctions [4], and more recently in mesoscopic structures [5]. The existing claim is that shot noise can be observed in electronic devices provided there exists an internal potential energy barrier [4] or in the absence of inelastic scattering [5–7]. Here, we report on direct experiment evidence of shot noise in a linear macroscopic resistor, which does not satisfy the above requirements.

In a macroscopic linear resistor, the possibility to observe shot noise is conditioned to the fact that the electrical charge can pile up inside the device [8–10] or, conversely, to the fact that the instantaneous number of free carriers inside the sample can fluctuate in time [11]. This possibility can be accomplished when the dielectric relaxation time of the material, i.e., the time required for a charge fluctuation to vanish, $\tau_d = \epsilon\epsilon_0\rho$, becomes longer than the dynamic transit time, i.e., the time a particle lasts to cross the sample at its drift velocity, $\tau_T = L^2/(\mu V)$. Here ϵ_0 is the vacuum permittivity, ϵ_r is the relative static dielectric constant of the material, ρ its resistivity, L its length, μ its mobility, and V the applied voltage. Under such a condition, the long range Coulomb interaction does not induce correlations between current fluctuations; thus, charge neutrality of the device can be violated and shot noise can be observed. In order to fulfill this constraint ($\tau_T \ll \tau_d$), numerical estimates indicate that the choice of the sample is limited to highly resistive materials such as semi-insulating semiconductors. In relatively good conductors, such as metals or highly doped semiconductors, the above constraint is hard, if not impossible, to be achieved under realistic experimental conditions.

In the present work, we have considered a resistor made of a 2 mm thick semi-insulating CdTe semiconductor embedded between two gold plates of $2 \times 10\ \text{mm}^2$. The choice of CdTe has been motivated by the fact that this semiconductor material allows for a high degree of compensation [12], thus presenting the desired semi-insulating property. Moreover, it displays linear velocity-field characteristics up to several kV/cm at room temperature [12], thus allowing one to apply considerable high voltages without the presence of hot-electron effects. Furthermore, the use of metal-semiconductor contacts is motivated by the fact that metals on semi-insulating materials exhibit the required nearly perfect Ohmic behavior in a wide range of voltages, since the carrier density at the interface imposed by the contact is of the same order of magnitude as the free carrier density of the semi-insulating material [13]. This fact avoids the presence of spurious space charge effects. Taken, for example, at $T = 323$ K, the device displays almost symmetric linear current-voltage (I-V) characteristics between 50 and $+50$ V. The forward characteristics is shown in Fig. 1 in a log-log scale showing the linear behavior from the lowest to the largest voltage bias. A best fit to the experiments gives a resistance $R_{323\text{K}} = 0.233\ \text{G}\Omega$,

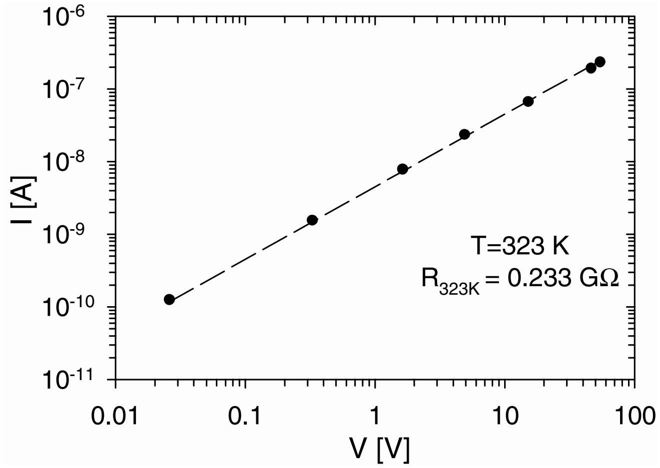

FIG. 1. Current-voltage characteristics of the CdTe resistor at $T = 323$ K (filled circles). A best linear fit to the experiments (dashed line) gives a resistance $R_{323\mathrm{K}} = 0.233$ GΩ.

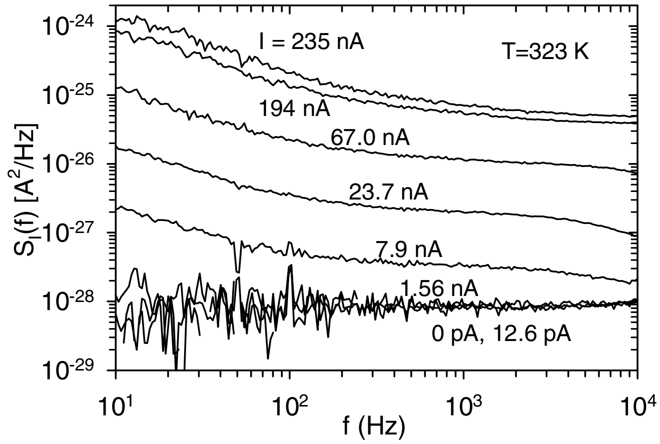

FIG. 2. Spectral density of the current fluctuations as a function of frequency for different values of the electric current at $T = 323$ K.

which implies a resistivity $\rho = 0.233$ GΩ cm. From these parameters, and by using [12] $\epsilon_r = 12$, the dielectric relaxation time for the material is $\tau_d \sim 0.3$ ms. Therefore, by extracting a mobility corresponding to holes $\mu = 50\ \mathrm{cm}^2/(\mathrm{V\,s})$ from the measurement of the cutoff frequency in the noise spectra in the shot noise region [14] (the sample is known to be *p* type [15]), and for an applied bias of 10 V, the transit time is $\tau_T \sim 0.08$ ms, thus making accessible the shot noise condition ($\tau_T \ll \tau_d$) for applied bias above a few tens of volts.

Current noise experiments have been performed on the CdTe resistor by means of the correlation technique implemented on a state of the art noise spectrum analyzer able to probe noise levels as low as 10^{-30} A^2/Hz and to reach frequencies up to 10^5 Hz at room temperature [16]. The characteristics of the measurement setup allow reaching the extremely low current noise levels present in semi-insulating materials and to cover a wide enough range of frequencies to get rid of the $1/f$ contribution that may hide the presence of the shot noise plateau. Figure 2 reports the spectral density of the current fluctuations measured at $T = 323$ K for different values of the current. At thermal equilibrium (i.e., zero current), the spectrum is white and takes a value in agreement with Nyquist noise, Eq. (1), as it should be. At increasing currents, the spectrum becomes current and frequency dependent. It displays a $1/f$ region at low frequencies, followed by a plateau at intermediate frequencies, and a cutoff region at the highest frequencies.

The values of the plateaux for the different current values extracted by a best fit function that includes the plateaux and the cutoff regions are reported as a function of current in Fig. 3. The dependence of the current spectral density at the plateaux on current is found to exhibit three distinct behaviors. At the lowest currents, the spectral density keeps a constant value corresponding to Nyquist noise. At intermediate currents, the spectral density exhibits a sharp increase (crossover region) until approaching an asymptotic linear increase with current that merges with the full shot noise behavior. We note that the onset of shot noise occurs at a current around 100 nA, which corresponds to a voltage ~20 V, in agreement with the voltage estimated above. These experiments prove that a linear macroscopic resistor can display shot noise under the condition that the dynamic transit time is shorter than the dielectric relaxation time of the sample. It is also worth remarking that the crossover between Nyquist and shot noise is found to depart from the standard cothlike behavior observed in many solid-state devices (dotted line in Fig. 3).

In order to show that the shot noise displayed by the CdTe resistor is not related to the presence of some sort of potential energy barrier or to the absence of inelastic

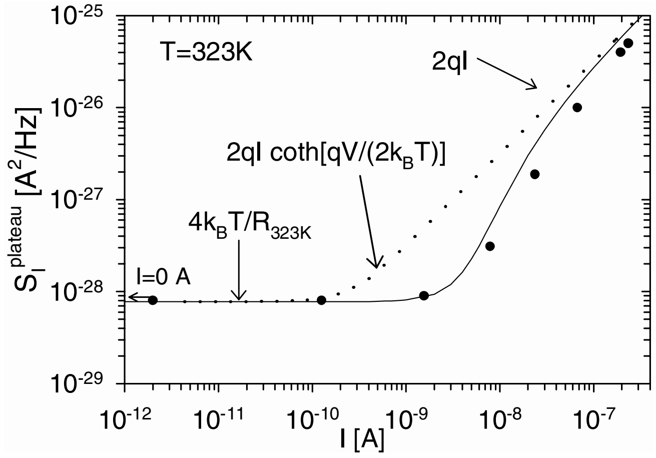

FIG. 3. Experimental values of the current spectral density at the white plateaux as a function of the current at $T = 323$ K (filled circles). The continuous line corresponds to the theoretical prediction of the unipolar drift-diffusion model. The dotted line corresponds to the standard cothlike behavior.

scattering, we provide a quantitative theoretical interpretation of the experiments by means of a unipolar drift-diffusion noise model recently developed by two of the authors [10]. The model assumes that charge transport and current fluctuations are due to the drift and diffusion of free carriers in a spatially homogeneous (in average) electric field. The fact that the resistor is macroscopic is implicitly accounted for by assuming that the free carriers are in local thermal equilibrium with the lattice at the bath temperature due to the energy exchange with the lattice phonons. In the model, the only source of noise is that related to the diffusive motion of the carriers The analytical solution of the model can be obtained, giving for the low frequency current spectral density the following relation [10]:

$$S_I = \frac{4k_BT}{R}(1 + s_I^{\mathrm{ex}}), \tag{3}$$

where

$$s_I^{D,\mathrm{ex}} = \frac{(\lambda_2^2 - \lambda_1^2)(e^{\lambda_1} - 1)(e^{\lambda_2} - 1)}{2\lambda_1^2\lambda_2^2(e^{\lambda_1} - e^{\lambda_2})^2} \times [\lambda_2(e^{\lambda_2} - 1)(e^{\lambda_1} + 1) - \lambda_1(e^{\lambda_1} - 1)(e^{\lambda_2} + 1)], \tag{4}$$

with

$$\lambda_{1,2} = -\frac{1}{2}\frac{\tau_D}{\tau_T}\left(1 \pm \sqrt{1 + 4\frac{\tau_T^2}{\tau_D\tau_d}}\right). \tag{5}$$

Here, $\tau_D = L^2/D$ is the diffusion transit time, i.e., the time required for a particle to travel a distance L due to diffusion, with D being the diffusion coefficient, related to the mobility through Einstein's relation, $D/\mu = k_BT/q$. By considering the right-hand side of Eq. (3), we note that the first term corresponds to the expected Nyquist noise contribution, while the second term is due to finite size effects controlled essentially by the interplay between the values of the dynamic transit time and the dielectric relaxation time [10]. The continuous line in Fig. 3 corresponds to the theoretical results obtained from the model after using the parameters of the device under test. The agreement between theory and experiments is within experimental uncertainty, which is remarkable in view of the absence of any adjustable parameters. In particular, the anomalous crossover between Nyquist and shot noise found in the experiments is well reproduced by the theory. Therefore, we conclude that the shot noise observed in our sample is due to the inelastic drift and diffusion of the carriers under the condition that the long range Coulomb interaction is not affecting the current fluctuations, and is not related to a potential energy barrier or to the absence of inelastic scattering. According to the present view, the fact that shot noise is not observed in macroscopic resistors made of good conductors (e.g., metals) is due to the strong correlations induced by the long range Coulomb interaction in these samples that inhibits the pileup of charge carriers under realistic experimental conditions, rather than due to the presence of inelastic scattering processes, as sometimes claimed in the literature [5–7]. It is worth noting that the absence of long range Coulomb correlations is also at the basis of the presence of shot noise in vacuum tubes and ballistic diodes under saturation [17] and Schottky barrier diodes [18] or number fluctuations in nondegenerate Fermi gases [19].

The strong dependence on temperature of the resistivity of semi-insulating CdTe [12] allows us to perform experiments for different sample resistivities by simply varying the sample temperature. Figure 4 reports the forward measured I-V characteristics for the device under study at $T = 280$ and $T = 300$ K (for an easier comparison the results at $T = 323$ K are also displayed). At the different temperatures, the device still exhibits a linear behavior in a broad range of applied bias (only at $T = 280$ K minor deviations from linearity are observed at the highest voltages probably due to some injection effects from the contacts). The lines in Fig. 4 represent a best linear fit to the experimental results, giving for the resistances $R_{300\mathrm{K}} = 1.6$ and $R_{280\mathrm{K}} = 10$ GΩ. The measurements of the current spectral density as a function of frequency at $T = 280$ and $T = 300$ K are found to exhibit the general features of the spectra reported in Fig. 2. The values of the spectra at the intermediate white plateaux are plotted in Fig. 5 as a function of the current (the results obtained at $T = 323$ K are also displayed for an easier comparison). As seen in the figure, the results for the different resistivities follow the general trends already described for $T = 323$ K (see Fig. 3), and, in particular, they

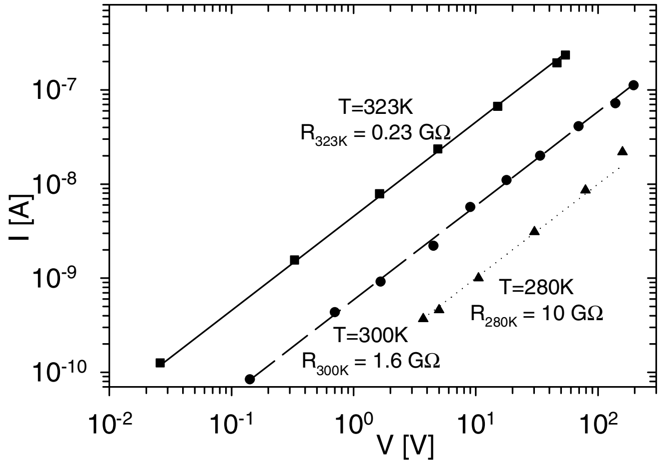

FIG. 4. Current-voltage characteristics for the CdTe resistor at three different temperatures: $T = 280$ K (filled triangles), $T = 300$ K (filled circles), and $T = 323$ K (filled squares). The lines correspond to a best linear fit to the experiments: continuous line $T = 323$ K, dashed line $T = 300$, and dotted line $T = 280$.

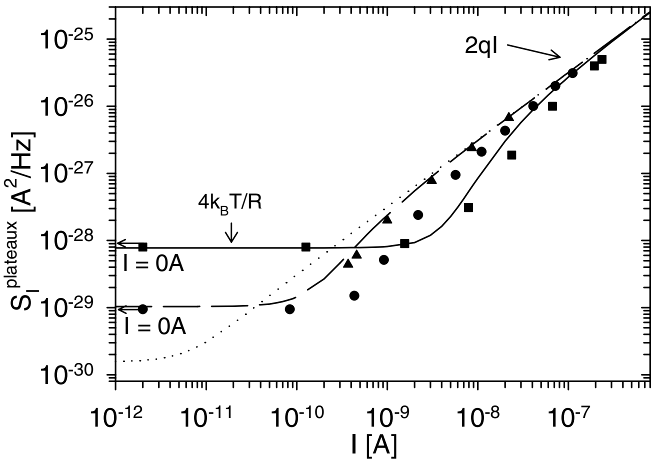

FIG. 5. Experimental values of the current spectral density at the white plateaux as a function of current at three different temperatures: $T = 280$ K (filled triangles), $T = 300$ K (filled circles), and $T = 323$ K (filled squares). The lines correspond to the theoretical predictions of the unipolar drift diffusion model: continuous line $T = 323$ K, dashed line $T = 300$, and dotted line $T = 280$.

confirm the presence of shot noise in macroscopic resistors. The simple unipolar drift-diffusion model (lines in Fig. 5) reproduces the main trends of the experimental results for the different temperatures in spite of the absence of any adjustable parameter and of its extreme simplicity. The disagreements observed in the crossover region between Nyquist and shot noise are probably due to generation-recombination noise neglected here [20].

In summary, we have presented experimental evidence of the existence of shot noise in linear macroscopic resistors, and proved that shot noise can be observed in electronic devices even in the absence of an internal potential energy barrier or in the presence of inelastic scattering processes. Present findings provide support for the existence of an additional physical situation in which shot noise can be present in electronic devices.

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[1] J. B. Johnson, Phys. Rev. **32**, 97 (1928).
[2] H. Nyquist, Phys. Rev. **32**, 110 (1928).
[3] W. Schottky, Ann. Phys. (Leipzig) **57**, 541 (1918).
[4] A. van der Ziel, *Noise in Solid-State Devices and Circuits* (Wiley, New York, 1986).
[5] Ya. M. Blanter and M. Büttiker, Phys. Rep. **336**, 1 (2000).
[6] A. Shimizu and M. Ueda, Phys. Rev. Lett. **69**, 1403 (1992).
[7] M. J. M. de Jong and C.W. J. Beenakker, Phys. Rev. B **51**, 16 867 (1995).
[8] K. M. van Vliet and J. Blok, Physica (Utrecht) **22**, 231 (1956).
[9] M. Büttiker, in *Noise in Physical Systems and 1/f Fluctuations*, edited by V. Bareikis and R. Katilius (World Scientific, Singapore, 1995), p. 35.
[10] G. Gomila and L. Reggiani, Phys. Rev. B **62**, 8068 (2000).
[11] R. Landauer, Phys. Rev. B **47**, 16 427 (1993).
[12] A. J. Strauss, Rev. Phys. Appl. **12**, 167 (1977).
[13] G. Gomila, I. R. Cantalapiedra, and L. Reggiani, J. Appl. Phys. **93**, 375 (2003).
[14] M. Sampietro, G. Ferrari, and M. Bertuccio, J. Appl. Phys. **87**, 7583 (2000). We note that the value reported in this reference for the mobility [25 $\mathrm{cm}^2/(\mathrm{V\,s})$] was calculated assuming that the cutoff frequency is equal to the inverse of the transit time. According to the calculations in Ref. [10], the cutoff frequency is half the inverse of the transit time, where the value of 50 $\mathrm{cm}^2/(\mathrm{V\,s})$ was used for the mobility in the present Letter.
[15] A. Cavallini (private communication).
[16] M. Sampietro, L. Fasoli, and G. Ferrari, Rev. Sci. Instrum. **70**, 2520 (1999).
[17] G. Gomila, I. R. Cantalapiedra, T. González, and L. Reggiani, Phys. Rev. B **66**, 075302 (2002).
[18] G. Gomila, L. Reggiani, and J. M. Rubí, J. Appl. Phys. **88**, 3079 (2000).
[19] C. M. Wilson, L. Frunzio, and D. E. Prober, Phys. Rev. Lett. **87**, 067004 (2001).
[20] G. Gomila and L. Reggiani, Appl. Phys. Lett. **81**, 4380 (2002).