

Shot-noise suppression in Schottky barrier diodes

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We give a theoretical interpretation of the noise properties of Schottky barrier diodes based on the role played by the long range Coulomb interaction. We show that at low bias Schottky diodes display shot noise because the presence of the depletion layer makes the effects of the Coulomb interaction negligible on the current fluctuations. When the device passes from barrier to flat band conditions, the Coulomb interaction becomes active, thus introducing correlation between different current fluctuations. Therefore, the crossover between shot and thermal noise represents the suppression due to long range Coulomb interaction of the otherwise full shot noise. Similar ideas can be used to interpret the noise properties of other semiconductor devices. © 2000 American Institute of Physics. [S0021-8979(00)03418-6]

It is well known that, in the absence of $1/f$ contributions, excess noise in Schottky barrier diodes (SBD) exhibits shot noise followed by thermal noise (neglecting hot-carrier effects).^{1,2} Shot noise is attributed to the presence of a barrier which controls the exponential increase of current with applied voltage. By contrast, the thermal behavior is attributed to the series resistance which controls the more or less linear increase of the current at the highest voltages. A phenomenological approach to describe the cross over from shot to thermal behaviors is to express the current spectral density, S_I , as the partition between two noise generators as^{1,2}

$$S_I = \frac{2q\bar{I}R_j^2}{(R_j + R_s)^2} + \frac{4k_B T R_s}{(R_j + R_s)^2}, \quad (1)$$

where $\bar{I}$ is the average electric current, q the electron charge, R_j the junction resistance, R_s the series resistance, k_B Boltzmann's constants, and T the temperature.

Microscopic approaches at hydrodynamic^{3,4} and kinetic levels^{5,6} confirm the above expression without resorting to two independent noise sources, but providing a self-consistent solution of the dynamics together with the Poisson equation. However, a physical interpretation of the noise properties of SBD, and in particular of the crossover between shot and thermal noise, is still lacking in the current literature and constitutes an intriguing question.

The aim of this article is to address this issue by showing that the crossover between shot and thermal noise behaviors represent the suppression due to long range Coulomb interaction of the otherwise full shot noise. This suppression occurs in SBD when the device passes from barrier to flatband conditions because of the following: By increasing the free carrier concentration the originally negligible screening effects due to the Coulomb interaction become relevant, thus acting as a shot noise suppressor. Accordingly, when con-

trolled by screening effects carrier number fluctuations give a negligible contribution to the total noise power, which is now practically given by only the velocity fluctuations, thus providing thermal noise.

The starting point of our approach is the nondegenerate fluctuating drift-diffusion equation which, for the case of one dimensional geometries and low frequencies, is⁷

$$\frac{I(t)}{A} = qn(x,t)\mu E(x,t) + qD \frac{dn(x,t)}{dx} + \frac{\delta I_x(t)}{A}, \quad (2)$$

where I is the instantaneous electric current, A the cross-sectional area, n the number density, μ the mobility, E the electric field, and D the diffusion coefficient. Moreover, $\delta I_x(t)$ is a Langevin diffusion noise source that accounts for current fluctuations, and has zero mean and correlation function⁷

$$\overline{\delta I_x(t) \delta I_{x'}(t')} = 2Aq^2 D n(x) \delta(x - x') \delta(t - t'). \quad (3)$$

Henceforth, a bar denotes an averaged quantity. In previous equations the time variable specifies that the quantities are changing with time due to the existence of fluctuations. Equation (2) must be completed with the Poisson equation and with appropriate boundary conditions to take into account the long range Coulomb interaction and the thermionic emission processes, respectively. For the rectifying contact the boundary condition reads³

$$n_0(t) - n^{\text{eq}} = \frac{I(t) - \delta I_{\text{TE}}(t)}{qAv_r}, \quad (4)$$

where v_r is the recombination velocity of the contact, $n^{\text{eq}} = N_C e^{-q\beta\phi_{bn}}$ the contact equilibrium density, with N_C being the effective density of states in the conduction band, ϕ_{bn} the barrier height, and $\beta = 1/k_B T$, and $\delta I_{\text{TE}}(t)$ is an additional Langevin noise source that accounts for the fluctuations due to the random emission of carriers. It has zero mean and spectral density³

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$$S_I^{\text{TE}} = 2q[\bar{I} + 2I_C], \quad (5)$$

with $I_C = qn^{\text{eq}}v_rA$. For the ohmic contact, if the sample is long enough we can neglect their effects and take

$$n_L(t) = N_D. \quad (6)$$

By dividing Eq. (2) by the Wronskian

$$W(x, t) = e^{-q\beta \int_0^x E(x', t) dx'}, \quad (7)$$

and integrating the result between $x=0$ and $x=L$, where L is the sample length, one obtains (see also Refs. 3 and 8)

$$I(t) = I_L(t) - I_0(t) + \delta I_D(t), \quad (8)$$

where

$$I_0(t) = qAv_D(t)n_0(t); \quad I_L(t) = qAv_D(t)\frac{n_L(t)}{W_L(t)}, \quad (9)$$

and

$$\delta I_D(t) = \bar{v}_D \int_0^L \frac{\delta I_x(t)}{DW(x)} dx. \quad (10)$$

To arrive at the previous results we have made use of Einstein's relation $D = \mu k_B T/q$, and have introduced the diffusion velocity as

$$\frac{1}{v_D(t)} = \int_0^L \frac{dx}{DW(x, t)}. \quad (11)$$

From Eqs. (8), the average current is given by

$$\bar{I} = \bar{I}_L - \bar{I}_0 = I_s(e^{q\beta\bar{V}} - 1), \quad (12)$$

where $I_s = qn^{\text{eq}}v_r\bar{v}_D/(v_r + \bar{v}_D)A$ and $\bar{V}$ is the applied bias. In deriving Eq. (12) we have used the averaged version of Eqs. (4), (6), and (9), and the fact that $\bar{W}_L = \exp[-q\beta(\bar{V} - V_{\text{bi}})]$, with $V_{\text{bi}} = k_B T/q \ln(N_D/n^{\text{eq}})$ being the built-in voltage.

Notice that in the definition of $\bar{v}_D$ we have included the sample (and not only the depletion layer). As a result, the formal expression for the I - V characteristics holds in the entire range of applied bias. For low applied bias I_s is nearly constant, and the I - V characteristic is exponential. At larger applied bias (above flatband conditions), I_s depends on $\bar{V}$ in such a way as to cancel the exponential behavior and give rise to a linear characteristics.⁹

The current fluctuations can be obtained by linearizing Eq. (8) around the stationary state. After some algebra one arrives at

$$\delta I(t) = \delta I_L^*(t) - \delta I_0^*(t) + \delta I_E(t) + \delta I_D(t), \quad (13)$$

where

$$\delta I_0^*(t) = qA\bar{v}_D\delta n_0(t); \quad \delta I_L^*(t) = qA\frac{\bar{v}_D}{W_L}\delta n_L(t), \quad (14)$$

and

$$\delta I_E(t) = \int_0^L H(x)\delta E_x(t), \quad (15)$$

with

$$H(x) = -Aq^2\bar{v}_D\frac{\bar{n}(x)}{W(x)} = -q^2\beta A\bar{v}_D N_C e^{\beta[F_n(x) - E_C(0)]}. \quad (16)$$

Here $E_C(0)$ is the edge of the conduction band and $F_n(x)$ the quasi-Fermi level. By substituting the linearized version of Eqs. (4) and (6) into Eq. (14), and substituting the result into Eq. (13), one finally obtains

$$\begin{aligned} \delta I(t) = & \frac{\bar{v}_D/v_r}{1 + \bar{v}_D/v_r} \delta I_{\text{TE}}(t) + \frac{1}{1 + \bar{v}_D/v_r} \delta I_D(t) \\ & + \frac{1}{1 + \bar{v}_D/v_r} \delta I_E(t). \end{aligned} \quad (17)$$

The meaning of the different contributions to the current fluctuations in Eq. (17) is the following:

(i) The term involving $\delta I_{\text{TE}}(t)$ represents the contribution to the current fluctuations of the thermionic emission processes.

(ii) The term involving $\delta I_E(t)$ describes the current fluctuations resulting from a response to an electric field fluctuation. This term accounts for the effects of the long range Coulomb interaction on the current fluctuations. To obtain their statistical properties one needs to compute explicitly the electric field fluctuations.^{3,4} For this communication it is enough to notice that $\delta I_E(t)$ is negligible when $H(x)$ is constant (or nearly constant), since then $\delta I_E(t) \approx H \int_0^L dx \delta E_x(t) = H \delta V(t) = 0$, where current fluctuations are calculated under fixed bias conditions.

(iii) The term involving $\delta I_D(t)$ represents the current fluctuations due only to diffusion processes since it is directly related to the fundamental diffusion noise source, $\delta I_x(t)$. From Eqs. (3) and (10) it can be shown that the current fluctuations associated to $\delta I_D(t)$ always display a low frequency spectral density, $S_I^D = 2 \int_{-\infty}^{+\infty} dt \delta I_D(t) \delta I_D(0)$, of the shot noise type (see Refs. 3 and 8):

$$S_I^D = 2q[\bar{I}_0 + \bar{I}_L] = 2q\bar{I} \left(\frac{\bar{I}_L + \bar{I}_0}{\bar{I}_L - \bar{I}_0} \right) = 2q\bar{I} \coth \left(\frac{\Delta F_n}{2k_B T} \right), \quad (18)$$

where $\Delta F_n = F_n(L) - F_n(0)$ is the quasi-Fermi level drop across the sample.

Since thermionic emission and diffusion are independent processes, one can compute their joint contribution to the current fluctuations. We obtain

$$\begin{aligned} S_I^{\text{TE}, D} = & \left(\frac{\bar{v}_D/v_r}{1 + \bar{v}_D/v_r} \right)^2 S_I^{\text{TE}} + \left(\frac{1}{1 + \bar{v}_D/v_r} \right)^2 S_I^D \\ = & 2q[\bar{I} + 2I_s] \\ = & 2q\bar{I} \coth \left(\frac{q\bar{V}}{2k_B T} \right), \end{aligned} \quad (19)$$

which is of the full shot noise type. This result is just a manifestation of the fact that both diffusion and thermionic emission processes are in origin uncorrelated processes. Notice, that from the present derivation, this result is valid for the whole range of applied bias.

We are now in a position to develop a physical interpretation of the noise properties of SBD, in particular of the crossover between shot and thermal noise behaviors. We will consider the case of low applied bias. As is well known, in this range of bias the device is controlled by the depletion layer present near the rectifying contact, where almost all of the applied potential drops. This implies that the quasi-Fermi level is nearly constant all over the sample, and hence, according to Eq. (16), $H(x)$ is also (nearly) constant. Therefore, we may neglect the contribution of the long range Coulomb interaction term $\delta I_E(t)$. Accordingly, the current fluctuations are determined by the diffusion and thermionic emission terms, thus giving rise to a spectrum of the shot noise type [see Eq. (19)]. On the contrary, for higher applied bias the depletion layer disappears and the applied bias drops all over the sample. In this situation the quasi-Fermi level is no longer constant, and the self-consistent term $\delta I_E(t)$ plays a relevant role. This term introduces correlations between the otherwise uncorrelated thermionic emission and diffusion processes, thus suppressing the shot noise. Therefore, the thermal noise associated to series resistance³ may be interpreted as just suppressed shot noise due to long-range Coulomb interaction.

The previous results can be understood physically by considering the density profile corresponding to these devices. At low voltages these devices display a density distribution with a deep depletion layer near the interface followed by a quasineutral region that extends up to the back ohmic contact. Since the device is controlled by the depletion layer, one only needs to take into account this part in the discussion. But, in the depletion layer the number density becomes very small. As a consequence, screening effects are very small and long range Coulomb interaction can be neglected, in agreement with the mathematical prove presented above. On the other hand at higher voltages, the density distribution is nearly uniform and equal to the doping density, thus providing appreciable screening effects, which are the responsible of suppressing the shot noise.

In summary, we have developed a theoretical approach to interpret physically the noise properties of Schottky di-

odes. We have shown that the occurrence of shot noise at low bias has to be attributed to the fact that the density distribution is such as to make negligible the effects of the long range Coulomb interaction. As a result the originally uncorrelated diffusion and thermionic emission processes remain uncorrelated, thus giving rise to a shot noise spectrum. On the other hand, at higher applied bias the nearly uniform carrier density profile induces considerable screening effects, which introduce correlation between the diffusion and thermionic emission process. The resulting thermal noise spectrum is thus the result of the suppression of the intrinsic shot noise of the device. The main ideas developed in this article can be extended to other devices, like $p-n$ diodes, tunneling diodes, ballistic devices or mesoscopic devices, thus offering new perspectives on what concerns the understanding of the noise properties of semiconductor devices.

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⁹Indeed, above flat band conditions the electric field inside the sample can be assumed to be nearly constant, thus we can approximate $\int_0^L E(x') dx' \approx (\bar{V} - V_{bi})x/L$. By substituting this expression into Eq. (11), one obtains $\bar{v}_D = \mu(\bar{V} - V_{bi})N_D / (n^{eq}L) \exp(-q\beta\bar{V})$, where we have used the expression for V_{bi} , Einstein's relation and the fact that $\exp[q\beta(\bar{V} - V_{bi})] \gg 1$. This last condition also implies $\bar{v}_D \ll v_r$, thus giving $I_s \approx qA\mu N_D / L(\bar{V} - V_{bi}) \exp(-q\beta\bar{V})$.