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Noise Current Spectrum in Submicrometer Samples

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Abstract. The noise current spectral density in submicrometer samples is computed using the Monte Carlo method. The normalized spectral density is found to decrease with sample length and increase with the field. The high-field noise is like shot noise and increases with current in agreement with experimental results.

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Electron transport in samples of submicrometer length is of current interest as the feature length of devices is fast approaching such dimensions. Studies on GaAs samples at 300 K indicate that the transport is nearly ballistic for lengths smaller than 0.7 μm [1–6]. Experiments have been mostly conducted on the voltage-current characteristic in submicrometer samples to explore the nature of the electron motion. The interpretation of the conduction characteristics is, however, difficult as the contacts produce significant effect [7].

The study of noise current may be expected to help the understanding of submicron transport. An experiment has been reported [8] in which the noise current spectral density in n^+-n-n^+ devices with 0.47 μm long n layers has been measured. The results are not, however, properly understood as detailed theory of noise in submicrometer devices has not yet been worked out. We present results of Monte Carlo calculations of the noise current spectrum in submicrometer samples, which explain the observed noise characteristic.

1. Model for Calculation

Electrons were assumed to enter the sample from the two ends at random. The time of entrance was calculated by using random numbers so that the distribution followed the Poisson distribution [9] over the simulation time. The velocity vectors of the electrons at the time of entrance were chosen by random numbers according to the Maxwellian distribution law at the lattice temperature (assumed to be 300 K). Electrons were assumed to drift in a uniform electric field and their instantaneous velocities were recorded at intervals of 0.004 ps. The electron trajectories were followed by the Monte Carlo method assuming an energy-independent collision time of 0.2 ps and an effective mass ratio of the electrons of 0.068 with a nonparabolicity factor of 0.61. The effective mass value was chosen to correspond to GaAs [10] and the collision time was chosen to be of the same order as that for GaAs in the high-field region [11]. The velocity of a simulated electron was recorded till it reached an end of the sample or till the simulation time was over. The trajectories of a large number of electrons were recorded to obtain statistically meaningful results. It was found that about 2000 electrons with a simulation time of 40 ps gave results with less than 10% statistical fluctuations.

The noise current spectral density was calculated from the recorded velocity-time data using the formula [12, 13]

$$S_{\Delta I} = (4Ne^2/L^2)D\,, \tag{1}$$

$$D = \int_0^S c(s)\,ds\,, \tag{2}$$

where

$$c(s)=(1/NT)\int_0^T\left[\Delta\sum_{i=1}^{N_s}v_i(t)\right]\left[\Delta\sum_{i=1}^{N_s}v_i(t+s)\right]dt. \quad (3)$$

N_s is the total number of simulated electrons, N is the average electron content of the sample, T is the total simulation time, S is lag time upto which $c(s)$ has significant values, e is the charge of the electron, L is the sample length, $v_i(t)$ is the velocity of the ith electron at time t, s is the lag time and Δ indicates the fluctuation from the average value. It should be noted that N and N_s are related as

$$N=\sum_{i=1}^{N_s}T_i/T, \quad (4)$$

where T_i is the time spent by the ith electron in the sample, which was also computed.

2. Results and Discussion

Calculations were done for sample lengths of 0.1, 0.2, 0.5, and 1 μm and for the field of 10^{-3}, 10^{-1}, 3, and 10 kV/cm. The computed values of the normalized noise current spectral density $S_{\Delta I}(Ne^2/L^2)^{-1}$ ($=D$) are presented in Table 1.

We note that the low-field value of D should be identical in all samples if the transport is collision dominated. The expected value of D for collision dominated transport is 135 cm²/s (obtained by using the value of collision time of 0.2 ps, the effective mass ratio of 0.068, lattice temperature of 300 K and the Einstein relation).

We find that the value of D increases from 33 cm²/s for a length of 0.1 μm and approaches the collision dominated long-length value, as the length increases. The dependence of D on the sample length may be understood considering that as the sample length decreases, the transit time becomes comparable to the collision time. The velocity of the electron is decorrelated by collisions as well as when it reaches an end of the sample. Hence, when the transit time is comparable to the collision time, the correlation time becomes smaller causing a decrease in the value of D.

Table 1. Normalized spectral current density D in submicrometer samples

Field [kV/cm⁻¹] ↓ \ Length → [μm]	0.1	0.2	0.5	1.0
10^{-3}	30	66	87	117
10^{-1}	33	–	90	–
3	44	94	232	561
10	92	247	763	1054

Table 2. Noise current spectral density in submicrometer samples (comparison of theoretical shot noise and computed noise)

Length [μm]	Field = 3 kV/cm			Field = 10 kV/cm		
	(a)	(b)	(c)	(a)	(b)	(c)
0.1	0.78	39	44	1.61	80	92
0.2	0.86	86	94	2.4	240	247
0.5	1.07	267	232	2.73	682	561
1.0	1.15	575	561	2.52	1260	1054

a: Average velocity $\bar{v}$ in units of 10^7 cm/s
b: Theoretical normalized shot noise, $(\bar{v}L/2)$ in units of cm²/s
c: Calculated normalized noise in units of cm²/s

The field-dependence of D is similar in all the samples. It is independent of the field for low values of the field but increases rapidly for high fields. It was, in fact, found that the increase is significant when the voltage across the sample is comparable to or larger than $k_BT_L/|e|$ (k_B is the Boltzmann constant and T_L is the lattice temperature). The increase in the value may be explained to be due to the predominance of shot noise in submicron conduction. The shot noise spectral density is given by [12]

$$S_{\Delta I}=2|e|I=(4Ne^2/L^2)(\bar{v}L/2), \quad (5)$$

where $\bar{v}$ is the average value of electron velocity. We computed values of D using (5), and these are compared with the calculated values in Table 2. It is seen that the two sets of values are in agreement within the statistical errors in the calculations. The noise for sample voltages exceeding $(k_BT_L/|e|)$ is thus essentially shot noise. Since shot noise is independent of the details of scattering mechanisms, this conclusion even though reached from calculations based on a constant collision time model should be applicable when more realistic scattering models are used.

No experimental results are available about the dependence of noise spectral density on the sample length, with which the present results may be compared. Schmidt et al. [8] have, however, measured the noise spectral density at 300 K in 0.47 μm long GaAs samples as a function of current. The spectral density was found to increase with current. The currents up to which the measurements were carried out was not sufficiently high for the predominance of shot noise. Nevertheless, the increase of noise spectral density with current is in agreement with the conclusion of the present paper.

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