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Noise temperature reduction by doping in ballistic n⁺–n–n⁺ nanodiodes

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Abstract
We analyse the noise temperature versus applied voltage of ballistic n^+–n–n^+ nanodiodes. We show that by increasing the doping density of the ballistic channel the minimum of the noise temperature decreases. In particular, noise temperature values can be suppressed below the absolute minimum value predicted for undoped n^+–i–n^+ ballistic diodes. This result could be of interest for the development of low-noise ballistic devices.

1. Introduction

Ballistic devices are characterized by an active region where carriers, once injected by contacts, move from contact to contact without suffering any scattering process (i.e. the carrier mean free path is much longer than the device active region). In semiconductors, ballistic transport has been demonstrated in bulk materials [1, 2], point contacts [3] and two-dimensional electron gases [4]. Based on these results, a variety of ballistic electron devices with promising performances have been realized [5, 6] or proposed [7–9]. Among these last ones, we include dual-gate ballistic MOSFETs [7], ballistic heterojunction permeable base transistors [8] and negative effective mass ballistic field effect transistors [9].

The symmetric n^+–n–n^+ ballistic semiconductor nanodiode has received wide attention in past years being the simplest structure and, at the same time, offering some insights into the properties of more advanced devices, such as ballistic transistors. The transport properties of n^+–n–n^+ ballistic diodes have been well understood since the mid 1980s [10]. Concerning the noise properties, only very recently a complete theoretical description of these structures applicable to all current transport regimes has been developed [11]. In the present paper we report on the dependence of the noise temperature, T_n, of n^+–n–n^+ ballistic diodes on the doping density of the ballistic channel.

2. System under study

The ballistic n^+–n–n^+ nanodiode consists of a ballistic n-channel of length L sandwiched between two highly doped contacts which act as ideal carrier injecting reservoirs. The ballistic region is taken to be perfectly coupled with the contacts, thus no reflections take place at the interfaces. The voltage drop in the contacts is assumed to be negligibly small (ohmic contacts) and hence all band bending occurs in the ballistic region. The structure is assumed to be sufficiently thick in the transversal direction so as to allow for a 1D electrostatic treatment. We assume that carriers are injected into the active region in accordance with an equilibrium Fermi–Dirac distribution function and satisfy the corresponding binomial injection statistics. Finally, for simplicity a single spherical and parabolic band is assumed. The physical parameters describing the properties of the diode are the sample length L, cross sectional area A, effective contact chemical potential μ, lattice temperature T, static dielectric constant ε, electron effective mass m and carrier charge q. The independent variable is the applied voltage, V.

Within a semiclassical approach, the description of the transport and noise properties is given by means of the Vlasov equation self-consistently coupled to the Poisson equation and supplemented by appropriate boundary conditions, as detailed in [11, 12]. The boundary conditions fix the mean velocity distribution function and the statistics of injected carriers. This

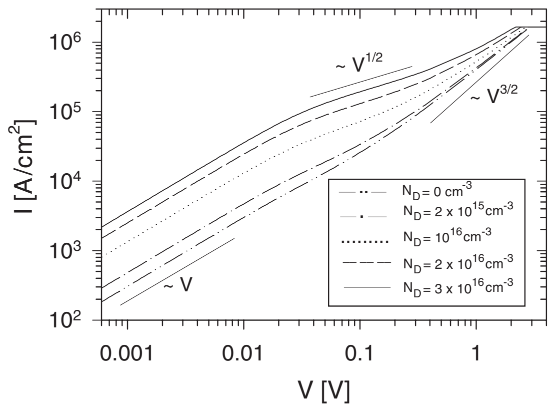

Figure 1. Current–voltage characteristics of a GaAs n⁺–n–n⁺ ballistic diode for five different channel doping densities. The sample length is 0.2 μm, the equilibrium contact doping density is 10^{18} cm^{-3} and the lattice temperature is 70 K.

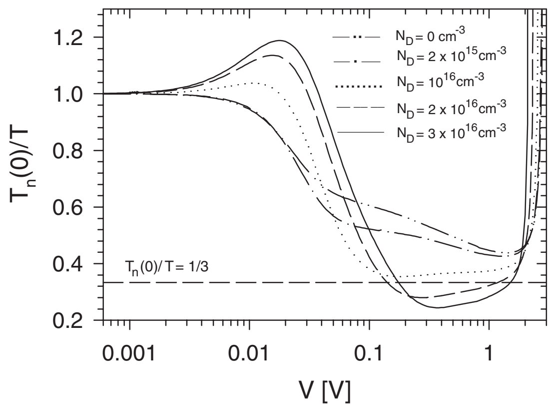

Figure 2. Noise temperature–voltage characteristics of a GaAs n⁺–n–n⁺ ballistic diode for five different channel doping densities. The noise temperature is normalized to the lattice temperature T. The sample length is 0.2 μm, the equilibrium contact doping density is 10^{18} cm^{-3} and the lattice temperature is 70 K.

kinetic model can be solved in closed analytical form for both the transport properties (stationary profiles and current voltage (*I*–*V*) characteristics) and the low frequency spectral density of current fluctuations, beyond $1/f$ noise

3. Results

The noise temperature T_{n} is one of the figures of merit in the noise characterization of two terminal electronic devices. It is defined as the equivalent temperature of a 'black body' under the condition that, within a given frequency bandwidth Δf centred on a frequency f, the thermal noise power generated by the black body coincides with the maximum noise power $P_{\mathrm{n,max}}(f)$ generated by the structure and extracted in a matched output circuit [13]. From a theoretical point of view, and in the low frequency plateau, it can be calculated as [13]

$$T_{\mathrm{n}}(0) = \frac{S_I(0)}{4k_{\mathrm{B}}G} \qquad (1)$$

where $S_I(0)$ is the spectral density of the current fluctuations in this frequency range, $G = \mathrm{d}I/\mathrm{d}V$ is the differential conductance and k_{B} is the Boltzmann constant. Since both $S_I(0)$ and G can be computed analytically [11], the noise temperature is obtained according to equation (1). The calculations have been performed for a 0.2 μm long GaAs n⁺–n–n⁺ ballistic diode with five different channel doping densities: $N_D = 0$ (undoped), 2×10^{15}, 10^{16}, 2×10^{16} and 3×10^{16} cm^{-3}. The contact equilibrium density is 10^{18} cm^{-3} and the temperature is 70 K. For the effective mass we have taken $m = 0.067m_0$ and for the dielectric constant $\varepsilon = 12.9\varepsilon_0$.

Figure 1 presents the calculated values for the *I*–*V* characteristics for the five values of the doping density listed above. We note that for the lowest value of the doping density (2×10^{15} cm^{-3}), for which $V_D \lesssim 3V_T$, with $V_D \equiv qL^2N_D/\varepsilon$ and $V_T = k_{\mathrm{B}}T/q$, the *I*–*V* characteristic is dominated by the action of the space charge associated with the carriers injected from the contacts, and its properties do not depart qualitatively from those observed in undoped structures (curve for $N_D = 0$ cm^{-3}) [12]. In particular, the *I*–*V* characteristic is linear for $0 < V \lesssim 3V_T$, with a resistance almost independent of the doping density, then it displays a $V^{3/2}$ dependence for $3V_T \lesssim V \lesssim V_{\mathrm{S}}$, V_{S} being the voltage at which current saturates, and finally it saturates to a constant value for $V_{\mathrm{S}} \lesssim V$. On the other hand, for higher doping densities such that $V_D \gtrsim 3V_T$, the *I*–*V* characteristic is dominated at low and intermediate bias by the action of the charge associated with the ionized donors and related free carriers. In this case, the *I*–*V* characteristic is linear for $0 < V \lesssim 3V_T$, with a resistance depending on the doping density; and then it displays a $V^{1/2}$ dependence for $3V_T \lesssim V \lesssim V_D$. At the highest voltages, injected carriers dominate the characteristic, which becomes again doping independent and similar to the undoped case [11]. Concerning the noise temperature–voltage characteristics, the calculated curves for the above doping densities are displayed in figure 2. Here, the qualitative behaviour of the curves depends again on whether the device is controlled by injected carriers or by donor-related carriers. In the former case (e.g. $N_D = 2 \times 10^{15}$ cm^{-3}) the values of T_{n} decrease continuously when increasing the bias, starting from $T_{\mathrm{n}} = T$ at equilibrium, down to a minimum value, $T^{\mathrm{inj}}_{n.\min}$, with $1/3 \leqslant T^{\mathrm{inj}}_{n.\min} < T$, before current saturation, in close analogy with the case of undoped ballistic diodes [14] (note that above current saturation the conductivity vanishes and hence T_{n} diverges). The value $T_{\mathrm{n}} = \frac{1}{3}T$ corresponds to the absolute minimum value attainable, for asymptotically long samples, in undoped structures [14]. On the other hand, for the latter case (behaviour dominated by donors and related carriers) T_{n} displays a non-monotonic behaviour, with an initial maximum followed by a minimum at intermediate voltages. The value of the maximum (resp. minimum) increases (resp. decreases) when the doping density increases. In this case, the most interesting result is that T_{n} can be suppressed below the absolute minimum value attainable in undoped ballistic diodes, as can be seen in figure 2. This result could be interesting from the point of view of potential applications.

4. Conclusions

We have analysed the noise temperature characteristics of ballistic n⁺–n–n⁺ nanodiodes. By means of an analytical theory recently developed, we have computed the noise temperature in all current regimes and for different values of the channel doping density. We have shown that for large enough doping densities, the qualitative features of the noise temperature characteristics depart significantly from those corresponding to undoped structures. In particular, they display a non-monotonic behaviour, with a maximum followed by a minimum at intermediate bias values. We have found that by increasing the doping density of the ballistic channel, the noise temperature can be suppressed below the absolute minimum value accessible in undoped diodes. The interplay between the Pauli principle and space charge effects is responsible for these features.

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