INTRINSIC LIMITATIONS OF GaAs DEVICE COOLING FOR MICROWAVE LOW NOISE APPLICATIONS

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ABSTRACT

A simulation at microscopic level of the microwave noise temperature associated to a GaAs resistance at different physical temperatures and far from equilibrium conditions has been performed. The dependence of the noise temperature on the electric field, doping level and physical temperature has been investigated.

INTRODUCTION

The subject of this work is to investigate how the high frequency noise temperature in an homogeneous resistance of GaAs varies as a function of the physical temperature when the resistance is far from equilibrium conditions.

Semiempirical modeling of the noise temperature based on circuital techniques has demonstrated to be the best way to simulate the noise performance of different microwave devices, such as Schottky diodes [1-4] and low noise transistors [5-7]. Monte Carlo techniques have also been applied to calculate the noise temperature at microscopic level in these devices [8-11], but the requirements of computing power and memory storage demanded by the Monte Carlo method have reduced the simulation at microscopic level to one and two dimensional devices. In addition, strong assumptions need to be made when setting the boundary conditions and degeneracy effects, and these assumptions limit the simulation at microscopic level to a description of the device performance from just a qualitative point of view. Despite these limitations, a strong interest has recently been shown by Monte Carlo researchers for a direct comparison of calculations with available experimental data [12]. Furthermore, the fast developments in the microprocessor technology have made the simulation at microscopic level in reasonable CPU times with affordable computers possible [13].

An important advantage of the simulation with Monte Carlo techniques is that it enables us to differentiate between noise temperature and electron temperature. These two temperatures may have quite different values [14], although it is a common practice to equate them in the simulation of noise at circuital level.

This paper illustrates how the dynamics of the carriers in the material may play a major role in the calculation of the noise temperature. We have calculated this temperature under different conditions of doping concentrations, physical temperature and applied field. These simulations have enabled us to investigate under which conditions the cooling of the material may lead to an efficent reduction of the noise temperature.

COMPUTING NOISE TEMPERATURES

The noise temperature $T_N(f)$ may be calculated at microscopic level in an homogeneous semiconductor from the spectral density of velocity fluctuations $S_V(f)$ and the differential mobility $\mu_D(f)$,

$$T_N(f) = \frac{qS_V(f)}{4k\mu_D(f)},$$

where q is the electron charge and k the Boltzmann constant. The Monte Carlo scheme enables us to follow the carrier movement through the

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semiconductor, and the sampling of the velocity at different times provides us the spectral density of velocity fluctuations via any spectral estimator.

Although the well known Wiener-Khintchine theorem may serve for the calculation of the noise spectrum, we have made use of a novel procedure based on the Maximum Entropy Method. This procedure enables us to estimate the spectrum with a fairly high degree of efficiency, especially when the carrier population at the satellite valleys is negligible and therefore the spectrum is nearly lorentzian [13].

We have performed different simulations of the noise temperature at microwave frequencies in n-type samples of GaAs doped at levels which are typical of microwave devices, from 10^{15} to 10^{17} cm^{-3}. The results are depicted in figure 1, which shows that it is possible to reach a threshold electric field (3.5 to 4 KV/cm, depending on the doping level) above which the cooling of a resistance makes the latter noisier. The increase of the noise temperature that one obtains by cooling the material is particularly noticeable at the lowest doping levels, where at 3 KV/cm the noise temperature nearly duplicates its value when the physical temperature of the material is reduced from 300 K to 77 K.

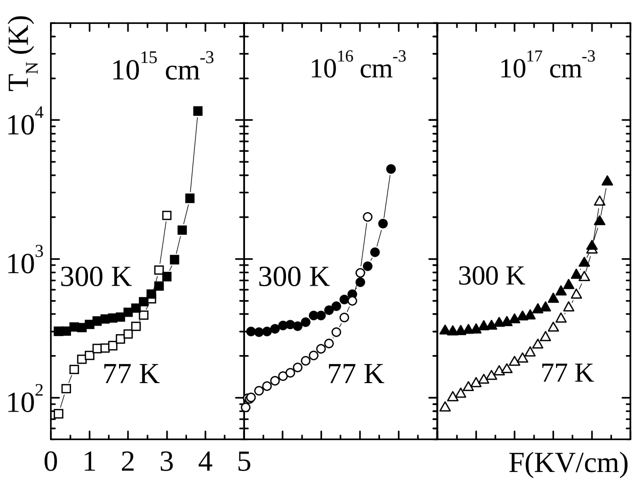

Figure 1. Microwave noise temperature as a function of electric field for different doping levels.

Furthermore, the performance of the noise temperature at 300 K is qualitatively different from the performance at low temperatures.

At 300 K the carriers have enough energy to emit polar optical phonons even under equilibrium conditions, and this results in a smooth noise temperature increase as a function of the field. However, at 77 K the carriers need to be heated by an external field in order to reach energies that enable them to emit phonons with a non negligible probability. If the doping level is low, there are nearly no scattering mechanisms at this temperature and the carriers suffer an strong heating even at the lowest fields. The electron heating noticeably increases the noise temperature under these conditions. This increase reaches a saturation when phonon emission is possible with a non negligible probability, as it is shown in figure 1 for the lowest doping level. However, the phonon emission is not able to saturate the noise temperature at the highest fields, where the transitions between the main and satellite valleys generate a strong partition noise.

The effect of cooling by phonon emission is noticeable in low doped materials but it is hidden by ionized impurity scattering at higher doping levels, where phonon emission is no longer the dominant scattering mechanism. Therefore, a complex dependance of the noise temperature on the physical temperature, electric field and doping level results.

Figure 2 shows an excellent agreement between the simulations presented in this paper with pulsed noise measurements at 10 GHz, which have been performed by the research group of Lituania [15].

Since the scattering mechanisms that operate in GaAs have time constants of the order of ps, we expect that these simulations may be considered valid from frequencies at which 1/f noise becomes negligible up to about 100 GHz.

Our simulator runs in a personal computer. The total simulation time spent in the calculations shown in figure 1 was 10 hours per curve using a personal computer with a first generation 200 MHz processor.

We believe that these calculations may be helpful for the investigation of an accurate physical model of noise in cooled Schottky diodes and low noise transistors. In addition, a deep understanding of the noise processes in bulk semiconductors is essential to stablish microwave noise measurements as a valuable tool for the qualification of semiconductor fabrication processes.

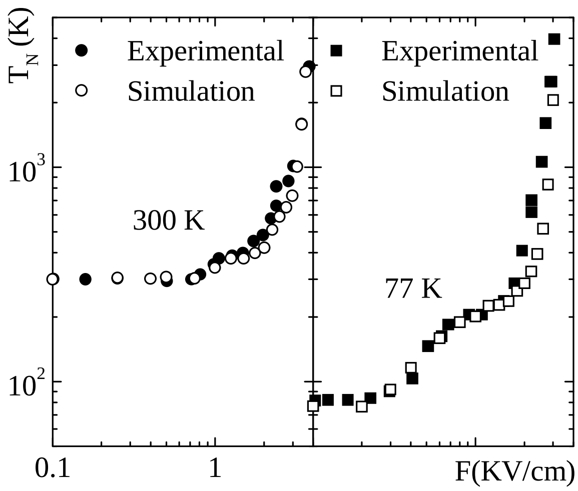

Figure 2. Comparison between pulsed noise measurements at 10 GHz and simulation. The doping concentration is 10^{15} cm^{-3}.

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