ELECTRON COOLING EFFECT IN QUANTUM WIRES AT LOW ELECTRIC FIELDS

V. Mitin and R. Mickevicius
Department of Electrical and Computer Engineering,
Wayne State University, Detroit, Michigan 48202

D. Jovanovic and J.P. Leburton
Beckman Institute for Advanced Science and Technology
and the Department of Electrical and Computer Engineering,
University of Illinois, Urbana, Illinois 61801

Abstract

The self-consistent simulation of electron transport and noise in GaAs V-groove quasi-1D quantum wire structures has been performed by a novel Monte Carlo technique. It is demonstrated that in the range of electric fields 1 to 10 V/cm the electron cooling effect takes place. This cooling effect is due to accumulation of electrons close to the subband bottom under conditions of their runaway from the distribution function tail and subsequent emission of optical phonons. The electrons close to the subband bottom are being held back from heating in electric fields by their intensive scattering by acoustic phonons at low energies. It is shown that electron noise decreases in the cooling regime. With the further increase of electric fields the electron streaming occures.

1 Introduction

The electron cooling effect, due to ionized impurity scattering, was predicted by Gribnikov and Kochelap [1] in 1970. Since that time this effect in bulk semiconductors has been experimentally observed [2] and studied in much detail [3,4]. The practical importance of the cooling effect is based on the fact that electron noise in the cooling regime essentially decreases [3]. The cooling effect in bulk materials exists only if three conditions are met: i) the total rate of elastic (say, ionized impurity) and quasi-elastic (say, acoustic phonon) scattering in the passive region (below the optical phonon energy) decreases with the increase of electron energy and at optical phonon energy it is much less than the rate of optical phonon emission; ii) the optical phonon absorption rate is negligible in the entire range of electron energies; iii) the electron-electron scattering is negligible so that the electron distribution function is strongly non-Maxwellian. The cooling effect occurs in the electric field range where electrons from the distribution function tail manage to runaway from the low energy passive region. They reach the optical phonon energy and then undergo optical phonon emission and get down to the conduction band bottom. Close to the band bottom electron scattering by ionized impurities is rather strong and this scattering holds back electrons from being heated by the electric field. As a result the electrons from the distribution function tail are being transferred down to the band bottom, they accumulate there, and the mean electron energy decreases.

In *bulk materials* the acoustic phonon scattering rate increases as a square root of electron kinetic energy, while the ionized impurity scattering rate decreases. Therefore, when the acoustic phonon scattering rate is high in comparison with the ionized impurity scattering rate the total scattering rate may increase with electron energy. That is why realization of the cooling effect is possible only in a highly doped material.

Favorable conditions for observing this phenomenon may occur in quasi-one-dimensional (1D) quantum wire (QWI) structures. Indeed, the rate of longitudinal-optical (LO) phonon emission in GaAs/AlAs QWIs is very high [5,6], the electron-electron interaction within the framework of a single subband model yields merely the exchange of electron momentum which has no physical consequencies since electrons are indistinguishable, and finally the *electron-acoustic phonon scattering rate dramatically decreases with electron energy*, reflecting the behavior of the 1D density of states. Therefore, *the role of electron back-holder at low energies in QWIs can be played by acoustic phonon scattering*. Altogether, it changes the picture of electron cooling in a QWI with respect to that in a bulk material and makes a QWI almost ideal structure for observing the cooling effect.

The goal of the present paper is to get an insight to the electron cooling dynamics through the study of velocity-field and energy-field characteristics as well as electron noise spectral density in GaAs QWI.

2 Model and Method

The model considered here is based on the V-groove quantum wire proposed by Sakaki [7] in which confinement is achieved via transverse triangular and square-well potentials [5]. Intersubband effects are ignored in our model as the confinement is assumed to be in the extreme quantum limit. LO phonon and acoustic deformation-potential scattering are the only processes taken into account in our model. Computationally, the main differences between 1D simulations and 2D and bulk models is that quantum-scale confinement lifts some of the complexities associated with angular scattering. For instance, due to the limited number of final scattering states, total rates can be stored in memory thereby eliminating lengthy computations during free-flight loops and final state selection. Quantized systems, however, introduce their own brand of difficulties in the treatment of singularities arising from the 1D density of states. A solution of the Fock equation by Briggs et al [8] demonstrates a substantial broadening in the LO phonon emission peak. For practicality, the golden-rule formalism can be retained by convolving a Gaussian broadening function containing a constant broadening factor, Γ, with the bare 1D density of states [5]. This method, with a proper choice of Γ, gives a good representation of the quantum corrections to the scattering rates.

As in bulk simulations, the computation of the scattering rates is essential for the stochastic determination of free-flight durations and the selection of a particular scattering event from the background of phonons. The reduced degrees of freedom in quantum wires makes direct integration of the Monte Carlo free-flight equation extremely efficient for the quasi-1D problem [5].

The transient process under streaming conditions lasts very long, far exceeding any other characteristic time. We have employed a recently developed ensemble Monte Carlo technique which permits a quick relaxation to steady state in the presence of long lasting transient processes. The essence of this technique is in the choice of the initial electronic state. We choose every next electron randomly from the trajectory of the previous electron so approaching the stationary initial distribution function in a few iterations.

3 Results and Discussion

The results presented here are obtained at 30 K temperature. Figure 1 demonstrates the field dependences of electron mean energy and drift velocity. After initial electron heating the cooling occurs within the field range of 1 to 10 V/cm. In the field range preceding electron cooling the drift velocity almost linearly depends on the electric field (Fig.1b). In QWIs in the absence of ionized impurity scattering electrons with the energy of the order of or higher than kT easily escape from acoustic phonon scattering which dramatically decreases with electron energy increase, and runaway up to LO phonon emission threshold. Further increase of electric field leads to the increase of electron energy and near-saturation of the drift velocity. This is related to electron transition from cooling to streaming regime. Under streaming conditions acoustic phonon scattering can no longer hold back low energy electrons and they reach LO scattering threshold, then emit phonons and go the subband bottom and repeat this process again and again.

A powerful technique to reveal electron cooling dynamics is the analysis of the current density autocorrelation function [4]. The fluctuations of current density for the conservative electron system arise merely from the fluctuations of electron velocity. In the general case the velocity autocorrelation function is given by: $C(T) = \langle \delta v(t)\, \delta v(t+T) \rangle$, where angular brackets stand for an average over time t, $\delta v(t) = v(t) - v_d$ is the deviation of the drift velocity at time t from its time-average value v_d.

Figure 2 shows some autocorrelation functions plotted versus delay time and calculated for different electric fields. The negative autocorrelator which appears at 10 V/cm turns to few oscillations seen at 20 V/cm and finally exhibits well pronounced damping oscillations when electrons reach regime close to streaming (100 V/cm). The oscillation period obviously coincide with the period of electron motion in **k**-space (which is equal to the time of electron acceleration from zero to the LO phonon energy, t_s, if electron penetration into the active energy region can be neglected). The characteristic oscillation decay time is mainly defined by the acoustic phonon scattering rate since electron penetration into the active region where they can emit LO phonons is negligible at these electric fields.

The autocorrelation functions have been used to calculate the frequency dependences of electron diffusion coefficient related with autocorrelation function through Wiener-Khintchine theorem and given by

$$D(\omega) = \int_0^\infty dT e^{-i\omega T} C(T). \quad (1)$$

Some of the results are presented in Figure 3. On the ordinates we plot the normalized diffusion coefficient which in fact is the normalized noise power spectral density, S, of conservative electron system [10]: $S(\omega) = 4D(\omega)$. At very low electric fields electron diffusivity is close to equilibrium and can be employed to evaluate low-field electron mobility in the QWI. The obtained mobility is of the order of $2 \times 10^6\, cm^2/Vs$, i.e. far exceeding the bulk material values. It should be noted, however, that the mobility dramatically decreases with the increase of either field or temperature (it is of the same order as bulk mobility at 300 K [11]). The frequency dependences of diffusion coefficient have almost the same Lorenzian shape: constant value up to some critical frequency, and then the rapid step-like decrease. Figure 3 shows that the critical frequency is shifted up with the increase of electric field. The critical frequency is related to electron scattering rate which increases effectively with the onset of LO phonon scattering. The effective time of electron scattering by LO phonons is determined mainly by the electric field, i.e. is equal to the streaming time, t_s, because electron penetration into the active region is still negligible. At higher electric fields when electron streaming takes through electron diffusive motion and cooling, the peak related to the streaming frequency separates from the step-like diffusivity-frequency dependence (see Fig.3). Referring back to Figure 1 one can see that this field (20 V/cm) corresponds to the beginning of mean electron energy increase. With the further increase of electric field the peak related to the streaming increases while the plateau of constant diffusivity is going down. Electron low-frequency diffusion coefficient decreases with the increase of electric field since the streaming coheres electron motion (see Fig. 4). As the electron penetration into the active region becomes significant the diffusion coefficient should start growing.

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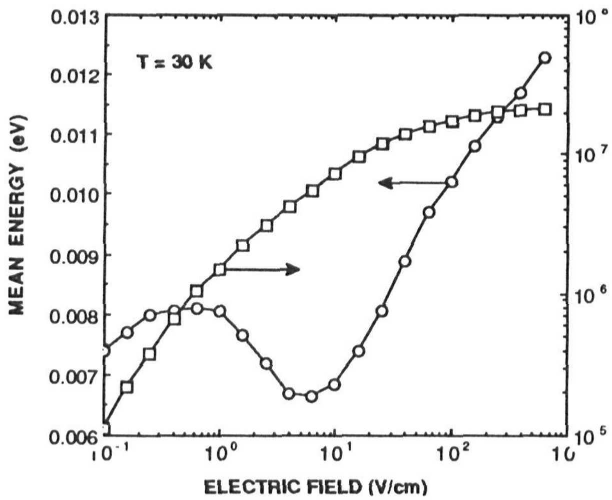

Fig.1 Mean electron energy (left) and drift velocity (right) as a function of applied electric field.

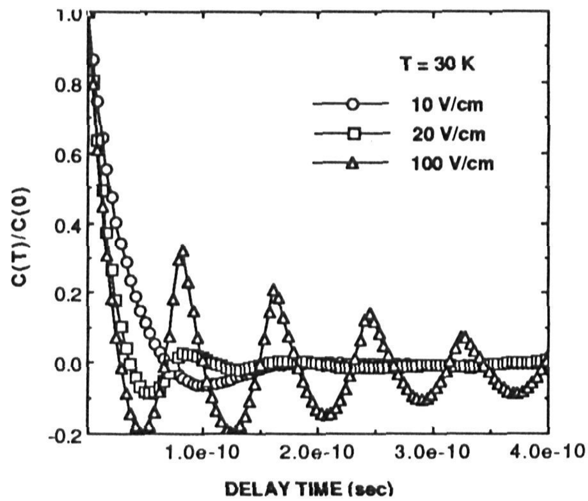

Fig.2 Electron velocity autocorrelation function versus delay time at different electric fields.

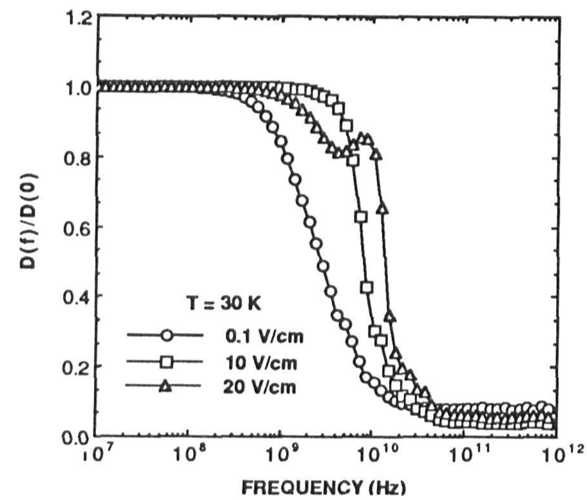

Fig.3 Electron diffusion coefficient as a function of frequency.

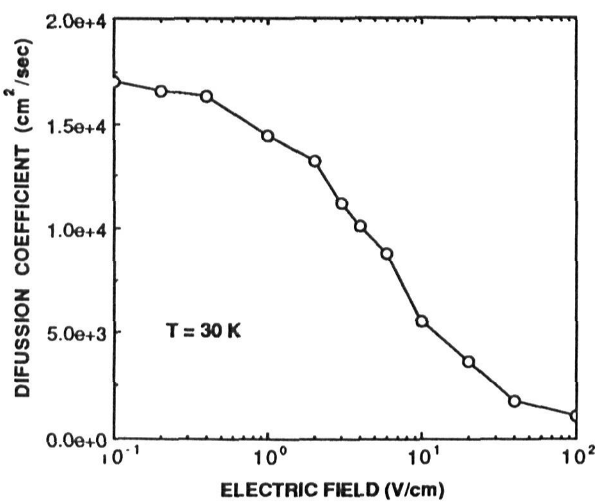

Fig.4 Electron diffusion coefficient at zero frequency as a function of electric field.