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Monte Carlo simulation of ballistic transport in high-mobility channels

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Abstract. By means of Monte Carlo simulations coupled with a two-dimensional Poisson solver, we evaluate directly the possibility to use high mobility materials in ultra fast devices exploiting ballistic transport. To this purpose, we have calculated specific physical quantities such as the transit time, the transit velocity, the free flight time and the mean free path as functions of applied voltage in InAs channels with different lengths, from 2000 nm down to 50 nm. In this way the transition from diffusive to ballistic transport is carefully described. We remark a high value of the mean transit velocity with a maximum of 14×10^5 m/s for a 50 nm-long channel and a transit time shorter than 0.1 ps, corresponding to a cutoff frequency in the terahertz domain. The percentage of ballistic electrons and the number of scatterings as functions of distance are also reported, showing the strong influence of quasi-ballistic transport in the shorter channels.

1. Introduction

Modern technology allows the reduction of the dimensions of electronic devices deeply into the nanometric scale, thus reducing the electron transit time inside the structures. The increase of the operation speed obtained by downsizing the device dimensions can be boosted by the use of very high mobility materials such as InGaAs and, more recently, InAs. For instance, recent studies showed that High Electron-Mobility Transistors (HEMT) with InGaAs channels can be used as emitters or detectors in the THz domain [1]. On the other hand, despite its small gap, InAs has attracted recent interest for advanced electronic applications because it presents a higher mobility. The so-called Quantum Hot Electron Transistor (QHET) is an example of an innovative high-speed transistor using the attractive properties of InAs [2]. By means of Monte Carlo (MC) simulations coupled with a two-dimensional Poisson solver, we can evaluate the possibility to use this semiconductor as the active zone of ultra fast devices exploiting ballistic transport. In particular, we have calculated specific microscopic physical quantities such as the transit time, the transit velocity, the free flight time and the mean free path as functions of applied voltage in InAs channels with different lengths, from 2000 nm down to 50 nm. The percentage of ballistic electrons and the number of scatterings as functions of length are also reported. In this way the transition from diffusive to ballistic transport is carefully described.

2. Model description

We consider different InAs semiconductor channels at room temperature with two contacts at both ends. The width W is fixed to 200 nm and the length L can be shorter (longer) than the carrier mean free path so that ballistic (diffusive) regimes can be analysed. The carrier concentration N_D is equal to 10^{16} cm^{-3}. Electrons are injected in the channel at a constant rate from contacts treated as thermal reservoirs according to the model detailed in Ref. [3], which is well adapted to the case of mesoscopic conductors.

The MC model here used to simulate transport at room temperature has been previously validated by comparison with experimental data [4]. For the conduction band we have used three non-parabolic spherical valleys. The scattering mechanisms which are included are the collisions with ionized impurities, the transitions due to absorption and emission of polar and nonpolar optical phonons, the collisions with acoustic (elastic) phonons, and the intervalley scatterings. Carrier-carrier interaction is neglected. Impact ionization is not taken into account even if, because of the small InAs gap, it could influence the results mainly for the ballistic channels and when the applied voltage is above 0.4 V.

3. Transport analysis

To evaluate the ballistic or diffusive character of transport and the possibility for this type of devices to work at THz frequencies we have simulated different channels of various lengths, from 2000 nm to 50 nm. First of all we have calculated two basic parameters: the average number of collisions S and the average transit time of an electron which moves from cathode to anode T_t. In our model we consider the exit of an electron from the device as a scattering event.

We remark that, for shorter channels, S decreases (Fig. 1(a)). For low voltages S is practically constant and varies from 1 for $L = 50$ nm to 30 for $L = 2000$ nm. Therefore for 50 and 100 nm-long devices under ohmic conditions the majority of electrons are completely ballistic. On the other hand, when the voltage reaches a value of approximately 1.0 V, intervalley transfer is activated and the number of scatterings increases very fast. A similar behavior is found for T_t (Fig. 1(b)) where we notice a first region (quasi-ballistic region) where T_t decreases with voltage, typical of a ballistic behavior, and a second region, after intervalley onset (diffusive region), where it increases with voltage. In the case impact ionization mechanisms were considered, a similar effect (but less significant) would be found for lower applied voltages (around 0.4 V).

Starting from the previous parameter we have extracted the longitudinal transit velocity $V_t = L/T_t$. As we can see in Fig. 1(c) V_t at equilibrium is different from zero, because it corresponds to the mean velocity of electrons which from the cathode arrive to the anode. The shorter the channel the higher the velocity because of the more ballistic character of transport. As long as the applied voltage is low, the number of the scatterings undergone by an electron decreases and so the longitudinal transit velocity increases. We also remark that the shape of velocity shows a maximum just before the onset of intervalley transfers. In the diffusive region, contrary to the ballistic one, the velocity decreases with voltage. If we take into account impact ionization mechanisms, by avoiding intervalley scattering, the electron velocity should increase [5]. We have also reported in Fig. 1(d) the free flight time $T_f = T_t/S$. At equilibrium T_f tends towards the transit time for the ballistic channels , while when L increase, and the transport becomes more diffusive, T_f tend toward the same value. When biasing the channels, we first observe a slow decrease of T_f and then a sharp drop around V = 1V, again due to the onset of intervalley mechanisms. To better understand the behavior of electrons in these channels we have also extracted the longitudinal mean free path $L_p = L/S$ reported on Fig. 1(e). At equilibrium and in the quasi-ballistic channels L_p increases with L. As expected for the ballistic channels, L_p coincides with L since there is practically no scattering. Moreover, at low voltages it is practically constant because the increase of V_t is balanced by the reduction of T_f. For higher voltages intervalley transfer leads to a strong reduction of L_p.

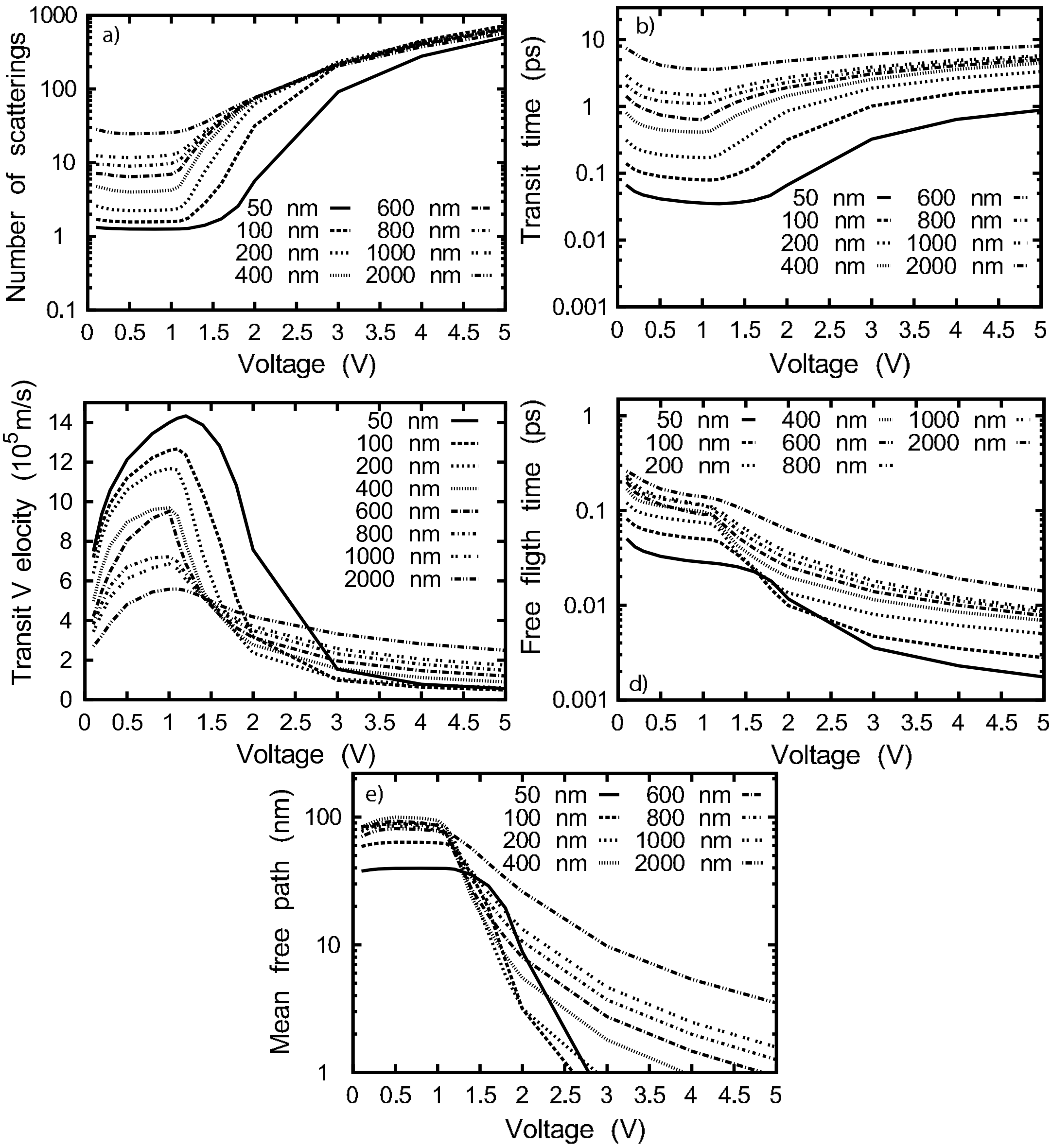

Figure 1. Number of scatterings from cathode to anode S (a), transit time T_t (b), longitudinal transit velocity V_t (c), free flight time T_f (d) and longitudinal mean free path L_p (e) as functions of applied voltage in InAs channels of different lengths L from 50 nm to 2000 nm.

4. Evolution of ballistic electrons

We investigate now the evolution of the number of interactions undergone by electrons on a channel of length L with an applied average electric field of 1 kV/cm. Here the exit from the channel is not considered as a collision. Figure 2(a) shows the percentage of carriers as a function of the scatterings undergone from cathode to anode for several channel lengths. In the case of a long channel (beyond 400 nm) the curve exhibits a bell shape. This is typical of a stationary diffusive transport where the maximum is centered on a non-zero average number of scatterings. The shorter the channel is the more the maximum of the distribution approaches to zero. The distribution is tightened and decreases exponentially, which is typical of non-stationary transport where the majority of carriers undergoes a maximum of one interaction, or

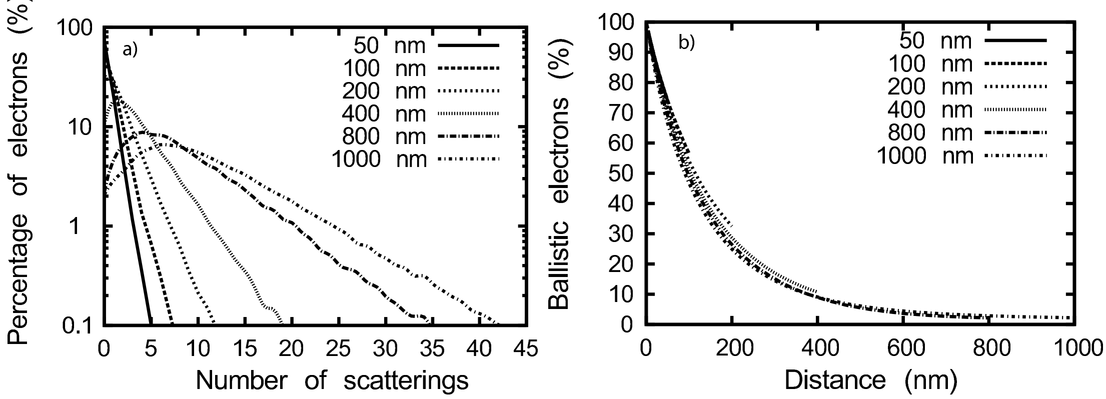

Figure 2. Percentage of electrons going from cathode to anode as a function of the number of scatterings (a) and percentage of ballistic electrons going from cathode to anode as a function of the distance from the cathode (b) for an average electric field of 1 kV/cm, in channels of different lengths L from 50 nm to 2000 nm.

are completely ballistic. For $L = 100$ nm, we have 54% of ballistic electrons and 73% for a 50 nm-long channel. In Fig. 2 (b) we show the number of strictly ballistic electrons, as a function of the distance from the cathode for the same average electric field of 1 kV/cm. We remark the high quantity of ballistic electrons in the shorter structures, equal, for example, to 35% at the end of a 200 nm-channel, sign of non-stationary quasi-ballistic transport. For the shorter lengths ($L \leq 400$ nm) the percentage of ballistic electrons depends slightly on the length of the channel while for the longer lengths the different curves coincide. For the longer channels transport is pratically stationary and there is only a negligible quantity of ballistic electrons at the end of the channel.

5. Conclusions

To investigate the diffusive or ballistic character of transport and to evaluate the possibility of InAs channels to work at THz frequencies, we have calculated different microscopic parameters. The transit time, in the case of 50 nm or 100 nm channels can be equal or lower than 0.1 ps, that in frequency corresponds to 10 or more terahertz. In fact for these lengths we remark that already at low voltages there is a great number of ballistic electrons equal, for example, to 73% for a 50 nm-long channel. The limit of length to have a cut off frequency in the THz range (transit time lower than 1 ps) is between 600 nm and 800 nm. We remark also that the mean longitudinal transit velocity is very high with a maximum value of 14×10^5 m/s for the shortest channel. However, to have the best performances the applied voltage must be kept under the limit imposed by intervalley scattering. In the case impact ionization mechanisms were considered, avoiding intervalley scattering, the electron velocity should further increase [5].

6. References

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