Non-local Effects on the Electron Energy Distribution in Short Devices under high-field conditions.

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ABSTRACT

In this paper we show by means of Monte Carlo calculations that the electron energy distribution function (EED) in finite length devices under high electric fields presents a tail with effective temperature equal to the lattice temperature T_L. This thermal tail (TT) characterizes the EED at energies larger than that corresponding to the voltage drop and therefore it is of relevant interest in short length devices with relatively low applied voltages: in this case the TT is found at energies corresponding to important threshold phenomena. In the case of equilibrium distribution at the injecting electrode, phonon absorption is the dominant mechanism for the electrons to gain energy beyond that given by the field and the TT shows the lattice temperature. If, instead, electrons are injected with effective temperature $T_{e\_in} \gg T_L$, they carry a memory of the initial distribution, and the high energy tail exhibits a temperature in between that of the initial distribution and T_L. As a practical example the case of a 75nm long silicon MOSFET is presented.

INTRODUCTION

Recent papers [1,2,3] have reported that the high energy tail of the electron energy distribution (EED) in short silicon MOSFETs is affected by strong non-local effects which make questionable the modeling of energy threshold phenomena, such as impact ionization, hot carrier injection into the MOSFET gate oxide, and hot-carrier induced degradation, based on local (i.e. electric field **F**) or average (i.e. average kinetic energy $< E_{kin} >$) quantities. In this paper we show that the EED at any position of a short device is strongly modulated by the applied bias and features two well defined regions: at kinetic energies (E_{kin}) larger than qV_d, (V_d is voltage drop from the injecting electrode up to the point under analysis) the EED shows a thermal tail (TT) with a well defined, constant electron temperature T_{e_0} coincident with that of the lattice T_L. On the contrary, at $E_{kin} \ll qV_d$, the EED assumes a higher electron temperature (T_{e_hot}, possibly a function of E_{kin} as well) determined by the field distribution. In between these two extremes, a transition region is present where the temperature drops gradually towards T_0. This behavior has been observed at high fields and tentative explanations have been given by solving analytically Boltzmann's equation [4,5].

Experiments have been performed with a Monte Carlo (MC) device simulator [1] applied to exploratory one-dimensional device structures, different bias conditions and semiconductor models, always neglecting electron-electron (e-e) interaction. The results of these simulations show the influence of the lattice interactions and of the initial condition of the injected carriers on the EED shape. The example of a short-channel MOSFET is also presented.

RESULTS AND DISCUSSION

Monte Carlo simulations of electron transport at room temperature were performed in one-dimensional, $0.5\mu m$ long $n^+ - n - n^+$ Si diode with doping concentrations 2×10^{20}, 1×10^{18}, and

2×10^{20} respectively. The high doping value of the n region allows to obtain a constant value of the electric field F in this region. Several transport models were adopted (simple parabolic, non-parabolic, multi-band models [6]), but, because we found their influence limited to the portion of the EED at $E_{kin} \ll qV_d$, here we report the results obtained with a parabolic model which results in a well defined electron temperature (T_{e_hot}) for the low energy portion of the EED. The scattering mechanisms included in the simulations were acoustic and optical phonons only, for a simple interpretation of the results. The applied voltage was $5V$, corresponding to F= $100kV/cm$ in the n region. Fig.1 shows the total energy, along the $n^+ - n - n^+$ diode. In the inset we show the EED at a channel point: it is clear the presence of a knee corresponding to zero total energy.

Fig.2 shows the EED evolution along the n region. For each EED the distance from the injecting electrode and the corresponding V_d is given. The distributions of Fig.2 present two well-defined values of $T_e(E)$: at E_{kin} larger than the corresponding qV_d, the $EED's$ shows the TT with a well defined, constant electron temperature T_{e_0} coincident with that of the lattice $T_L = 300K$. On the contrary, at $E_{kin} \ll qV_d$, the EED assumes a higher electron temperature determined by F. Travelling from source to drain, the EED thermalizes at an energy value which increases with the voltage drop qV_d. An interesting feature of the $EED's$ in Fig.2 is the presence of a transition region around $E_{kin} = qV_d$ where the electron temperature drops gradually from T_{e_hot} to T_{e_0}; the width of the transition region depends on the voltage drop and increases with it.

The same results have been obtained if electrons were injected with effective temperature $T_{e\_in} < T_L$. In all these cases, electrons at $E_{kin} \gg qV_d + KT_{e\_in}$ must have acquired the energy above qV_d only through interactions with the lattice (in particular phonon absorption) and therefore their distribution assumes the lattice temperature.

To prove this point we have calculated the number of optical phonons emitted (N_e) and absorbed (N_a) by the electrons during the travel from the injecting electrode to a certain point in the channel, as a function of their final kinetic energy. Only optical phonons were considered because they represent the dominant mechanism of energy loss and gain. We also plotted the net number $|N_e - N_a|$ which is proportional to the quantity $|qV_d - E_{kin}|$ by the factor $\hbar\omega_{opt}$ (the energy of the optical phonon) for the whole energy range. The data are shown in Fig.3 for $V_d = 2.2V$ (thus the EED at $0.22\mu m$ from the source). It must be noticed that we represent *average* values, for example electrons reaching the point with $E_{kin} = 1eV$ *on the average* emit 30 phonons and absorb 5.

Fig.3 carries several important information: the perfect agreement between $|N_e - N_a| \times \hbar\omega_{opt}$ and $|qV_d - E_{kin}|$ indicates electrons get to the TT because of lattice interaction; as a consequence the N_e and N_a curves intersect at $E_{kin} = 2.2eV$ because at this energy electrons reach the point of interest with an even energy balance; the small number of phonon interactions at this energy (≈ 3) indicates that electrons experience quasi-ballistic transport. Electrons reaching the point with $E_{kin} \ll 2.2eV$, instead, experience many phonon emissions and much less phonon absorptions Because of the dominant role played by phonon emission the electrons assume an electron temperature $T_{e\_hot} > T_L$ which is a unique function of F due to the parabolic band model adopted. This situation holds until phonon emission is dominant over absorption, that is for electrons with $E_{kin} \ll qV_d$. Phonon absorption dominates over emission, instead, for electrons with $E_{kin} \gg qV_d$: here the EED temperature cannot be T_{e_hot} (determined by F) but must be that of the lattice (T_L) from which electrons absorb phonons. Notice also that the EED features one well defined temperature in the range where absorption (emission) dominates while emission (absorption) is relatively low: it is therefore reasonable that only one mechanism determines T_e. The data in Fig.3 help also to understand the presence of a transition region in the EED where T_e drops gradually from T_{e_hot} to T_L: this corresponds to electrons which have experienced a comparable number of phonon emissions and absorptions in their motion from the source to the point of interest while neither mechanism dominates. As shown in Fig.3 the transition region extends for a wide energy range and the corresponding EED values drop by several orders of

magnitude compared to the ideal EED with T_{e_hot}.

In order to check the effect of different initial conditions, we have performed simulations at $T_L = 300K$ but injecting electrons with effective temperature $T_{e\_in} \gg T_L$. The results, not shown in the figures, indicate that the high energy tail exhibits a temperature in between that of the initial distribution and T_L. We think this is because electrons in this case carry a memory of the initial distribution, as shown also by the model in Ref.[5].

It is likely that the inclusion of e-e interaction will affect these results only quantitatively and lead to a larger transition region and therefore to a smoother EED shape. The presence of this transition region is particularly important in real devices as MOSFETs with applied voltages $\leq 5V$: in this case in fact the transition region extends at energies comparable to those related to important threshold phenomena as impact ionization, gate current injection and device degradation, making questionable any 'a priori' assumption on the EED shape. This point is illustrated in Fig.4, showing the EED at a channel point of a $75nm$ long MOSFET biased at $V_{gs} = V_{ds} = 1.9V$ and whose technological parameters are given in [7]. The voltage drop from the source to the point of interest is $V_d = 1.6V$. The MOSFET EED (solid line) is compared with that (dotted line) corresponding to the local value of $< E >$ in the homogeneous case. In this latter case the temperature T_{e_hot} is not uniquely defined because the simulation was performed using a realistic band model [6] which results in non maxwellian $EED's$. The transition region exteds for about $1eV$ around $E_{kin} = qV_d$.

CONCLUSIONS

We have shown that the EED in finite length devices under high electric fields presents a tail with effective temperature equal to the lattice temperature at energies larger than the corresponding applied voltages. The physical explanation of this phenomenon can be summarized as follows. At a finite distance d from the injection terminal, F can supply to the carriers a maximum kinetic energy equal to $qV_d = \int_0^d q\mathrm{F}dx$. Beyond this energy value, only carrier-lattice interaction can provide the extra energy to the carriers. It is therefore reasonable that the EED part below qV_d reflects the interaction of carriers with the field and the lattice, while the lattice interaction alone determines the behavior of EED above qV_d. If, instead, electrons are injected with effective temperature $T_{e\_in} \gg T_L$, they carry a memory of the initial distribution, and the high energy tail exhibits a temperature in between that of the initial distribution and T_L.

A practical example of a $75nm$ long silicon MOSFET is presented. showing that the presence of the TT is of relevant interest in short length devices with relatively low applied voltages: in this case the TT is found at energies corresponding to important threshold phenomena as hot-carrier induced degradation.

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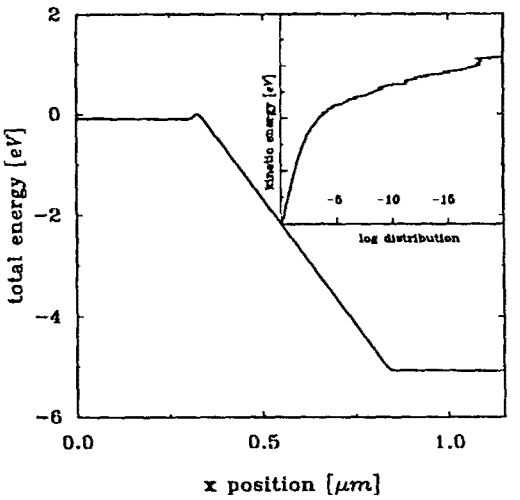

Fig.1 EED along Si n-i-n diode; F=100kV/cm. EED at a channel point is reported in the inset

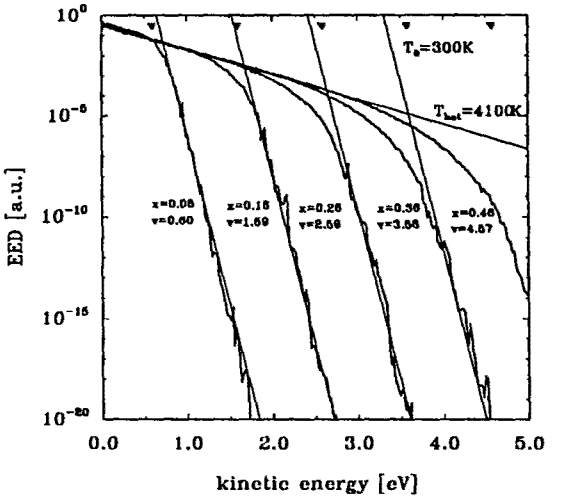

Fig.2 EED along a Si n-i-n diode; correspond to different points and voltage drops; ▼: voltage drop

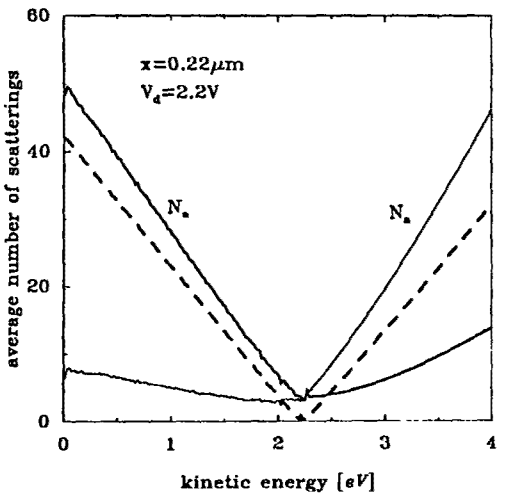

Fig.3 Average number of optical; phonons emitted (N_e, thick solid) and adsorbed (N_a, thin solid) by electrons travelling from source to $x = 0.22\mu m$ ($V_d = 2.2V$) dashed line: $\mid N_e - Na \mid \propto qV_d - E_{kin}$.

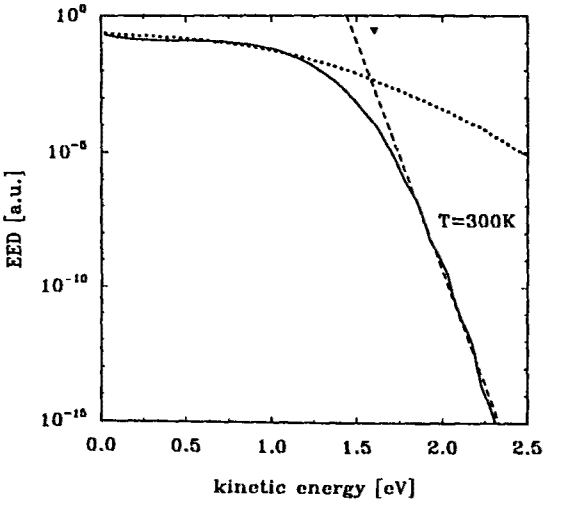

Fig.4 n-MOSFET case, $L_{eff} = 75nm$, $V_{gs} = V_{ds} = 1.9V$: EED at a channel point where $V_d = 1.6V$ ▼: voltage drop