Effect of Electron-Electron Scattering on the Energy Distribution in Semiconductor Devices

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Physical modeling of hot carrier degradation of semiconductor devices requires accurate knowledge of the carrier distribution function. Childs et al. predicted that the high energy tail of the distribution function is strongly affected by electron-electron scattering (EES) [1]. This has been shown by numerically solving the Boltzmann equation, which is nonlinear in the presence of EES, using an iterative method. The following approximations were made: 1) an energy-dependent formalism with the isotropic part of the distribution function (DF) as the unknown is adopted; 2) the phonon energy is assumed to be much smaller than the kinetic energy. The iterative method is thus not applicable in the low energy range, where instead a Monte Carlo method is used; 3) in the out-scattering rate the contribution of the EES rate is neglected.

While 1) is required to keep the problem numerically tractable, the purpose of approximations 2) and 3) is unclear since they do not significantly simplify the problem, but can greatly change the results.

In this work we employ instead of the Boltzmann equation a two-particle kinetic equation which has the advantage of being linear also in the presence of EES. In [2] a two-particle Monte Carlo method for uniform electric field has been presented, which calculates trajectory pairs to sample the six-dimensional **k**-space of the two particles. We have extended the stationary Monte Carlo algorithm so as to account for spatially varying electric fields.

The following numerical results were obtained assuming a single-valley band structure model and the material parameters of silicon. Fig. 1 shows the frequencies of different types of scattering events for uniform electric field. The frequencies of phonon absorption and emission do not change when EES is activated, despite EES being a dominant scattering process. A similar observation can be made in Fig. 2 and Fig. 3. Mean velocity, mean energy, and also the DF as functions of the electric field are virtually not affected by EES.

The situation is different for non-uniform electric fields. Fig. 4 shows a simplified potential profile in a channel of 50nm length, along with a colormap of the DF. At positions A and B the local potential is, respectively, 0.5eV and 1.0eV lower than the potential maximum. Without EES, the DF exhibits a thermal tail, whereas EES reduces the slope of the tail as shown in Fig. 5.

The potential profile in [1] is similar to that in Fig. 4 and characterized by a channel length of 150nm and a potential drop of 1.5V. The positions where the potential drops by 0.5/1.0/1.5eV are designated as A/B/C, respectively. Fig. 6 shows the DF at these positions in the channel. EES results in an enhanced high energy tail, which confirms Childs' results qualitatively. The main difference is that our results indicate the deviation from the thermal tail to occur at significantly lower energies. By comparing Fig. 5 and Fig. 6 we find that the enhancement of the tail is weaker if the potential drop along the channel is smaller.

Acknowledgment

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References

[1] P. Childs and C. Leung. *A one-dimensional solution of the Boltzmann transport equation including electron-electron interactions*, Journal of Applied Physics, **79**, 222 (1996).

[2] G. Indalecio and H. Kosina, *Monte Carlo Simulation of Electron-Electron Interactions in Bulk Silicon*, in Scientific Computing in Electrical Engineering, Mathematics in Industry **32**, G. Nicosia, V. Romano (ed); Springer International Publishing, 125 (2020)

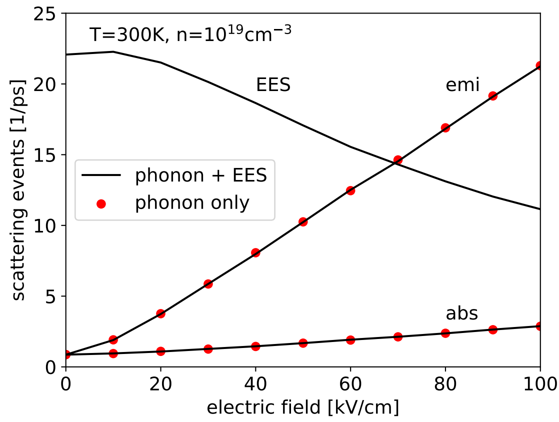

Fig. 1. Number of scattering events in a given time interval versus electric field for phonon emission, phonon absorption, and EES. Two simulations with and without EES are compared.

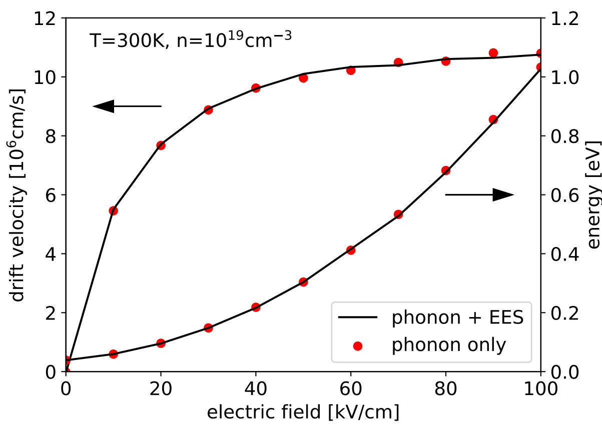

Fig. 2. Mean velocity and mean energy versus electric field. EES has no visible influence on the mean values.

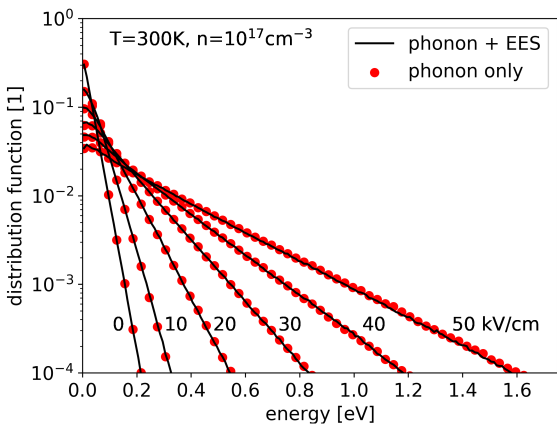

Fig. 3. Distribution functions for uniform electric field at different field strengths. EES has no visible influence.

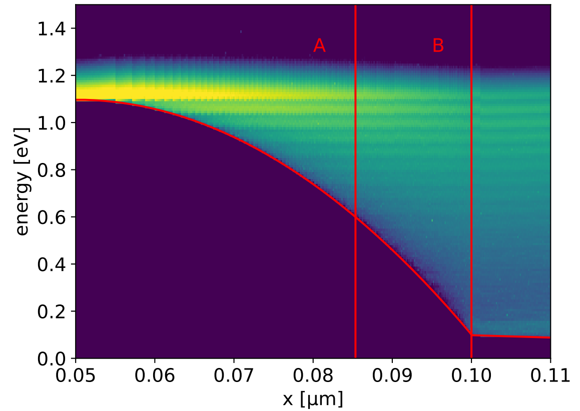

Fig. 4. Potential profile in a 50nm channel. The distribution function shown is calculated assuming phonon scattering only.

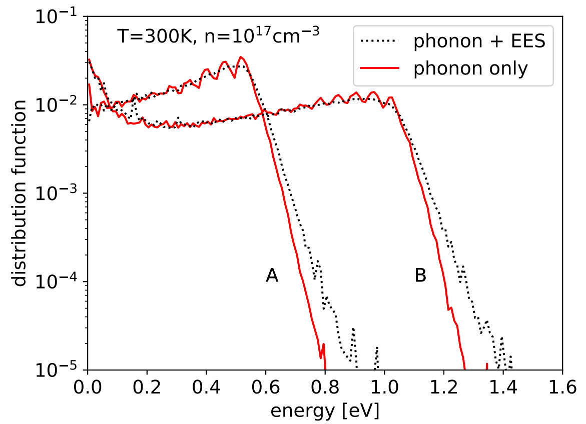

Fig. 5. Distribution functions at positions A and B in a 50nm channel, calculated with and without EES.

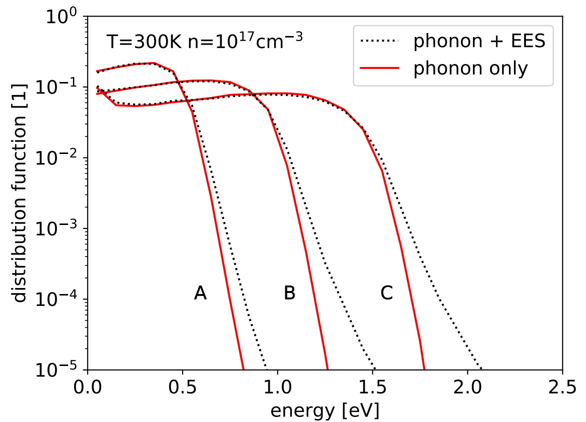

Fig. 6. Distribution functions at positions A, B, C in a 150nm channel, calculated with and without EES.