Non-Parabolicity and Non-Maxwellian Effects on Gate Oxide Tunneling

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ABSTRACT

Simulation of gate oxide tunneling currents in sub-quartermicron devices requires correct modeling of the electron energy distribution function in the channel region. However, the common assumption of a heated Maxwellian distribution function leads to a dramatic overestimation of the high-energy tail of the distribution function near the drain region which leads to spurious gate currents for short-channel devices. Our approach is based on a recently presented transport model which accounts for six moments of the Boltzmann transport equation. Using this model, the shape of the distribution function can be reproduced more accurately and the gate current behavior of short-channel devices shows a more reasonable behavior.

Keywords: tunneling, moment equations, BOLTZMANN equation, distribution function model.

1 INTRODUCTION

For the design of sub-micron devices with gate oxide thicknesses around or below 2 nm, the proper simulation of gate oxide tunneling currents is of increasing importance. Thermionic emission based models are frequently used for this purpose [1]. For an accurate evaluation of such models, the assumptions of a parabolic dispersion relation $\mathcal{E}(k)$ and a heated Maxwellian electron energy distribution are too simplistic approximations and lead to erroneous results.

2 TUNNELING MODEL

Following [1], the gate current density is given as

$$J_\mathrm{g} = \int_0^\infty f(\mathcal{E})\, g(\mathcal{E})\, v_\perp(\mathcal{E})\, T(\mathcal{E})\, d\mathcal{E} \tag{1}$$

where $f(\mathcal{E})$ is the electron energy distribution function, $g(\mathcal{E})$ the density of states, $v_\perp(\mathcal{E})$ the electron velocity perpendicular to the interface, and $T(\mathcal{E})$ the tunneling probability. The integration is performed starting from the conduction band edge energy which is the reference energy.

2.1 Tunneling coefficient

A simple model for the tunneling probability can be derived using the WKB approximation [2] for trapezoidal and triangular barriers:

$$T(\mathcal{E}) = \exp\left\{-4\frac{\sqrt{2m_\mathrm{ox}}}{3\hbar q F_\mathrm{ox}}\,\phi\right\} \tag{2}$$

with the barrier ϕ being

$$\phi = \begin{cases} (\Phi-\mathcal{E})^{3/2} & \text{for} \quad \Phi_0 < \mathcal{E} < \Phi \\ (\Phi-\mathcal{E})^{3/2} - (\Phi_0-\mathcal{E})^{3/2} & \text{for} \quad \mathcal{E} < \Phi_0 \end{cases}$$

where Φ and Φ_0 are the upper and lower barrier height, m_ox is the electron mass, and F_ox is the electrostatic field in the oxide layer. Fig. 1 shows the transmission coefficient as a function of the electron energy for different oxide thicknesses. In the inset the shape of the energy barrier together with the definition of Φ and Φ_0 can be seen.

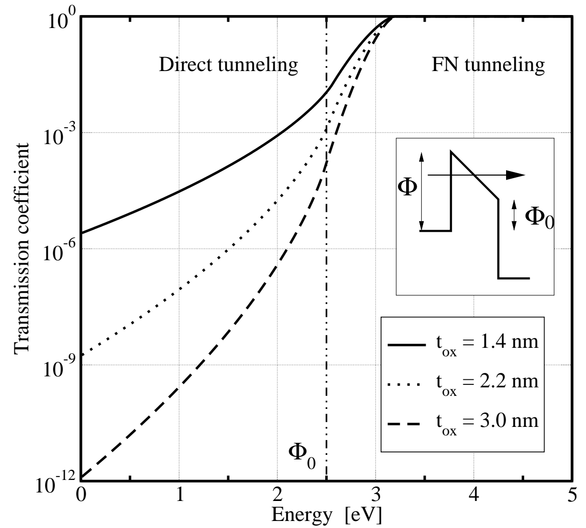

Figure 1: Transmission coefficient as a function of the electron energy for different oxide thicknesses. Φ_0 is 2.5 eV and Φ is 3.2 eV.

2.2 Density of states

As a first order correction to the single parabolic band model, we use Kane's dispersion relation [3]

$$\frac{\hbar^2 k^2}{2m_{\mathrm{ox}}} = \mathcal{E}(1+\alpha\mathcal{E}) \tag{4}$$

which is frequently used to describe non-parabolicity effects. For this expression the density of states $g(\mathcal{E})$ is

$$g(\mathcal{E}) = 6\frac{\sqrt{2m^3}}{\pi^2\hbar^3}\sqrt{\mathcal{E}(1+\alpha\mathcal{E})}\,(1+2\alpha\mathcal{E}) \tag{5}$$

with the non-parabolicity factor α being 0.5 eV^{-1} for Si. Six valleys of the silicon conduction band are taken into account.

2.3 Perpendicular velocity

The electron velocity perpendicular to the interface $v_\perp(\mathcal{E})$ can be derived from the normal component of the k-vector as described in [4], where the expression

$$v_\perp(\mathcal{E}) = \frac{1}{4\hbar}\frac{\partial\mathcal{E}}{\partial k} \tag{6}$$

was given. This leads to the following results for a parabolic and Kane's dispersion relation:

$$\text{Parabolic}: \quad v_\perp(\mathcal{E}) = \sqrt{\frac{\mathcal{E}}{8m_{\mathrm{ox}}}}$$

$$\text{Kane}: \quad v_\perp(\mathcal{E}) = \sqrt{\frac{\mathcal{E}(1+\alpha\mathcal{E})}{8m_{\mathrm{ox}}(1+2\alpha\mathcal{E})^2}}.$$

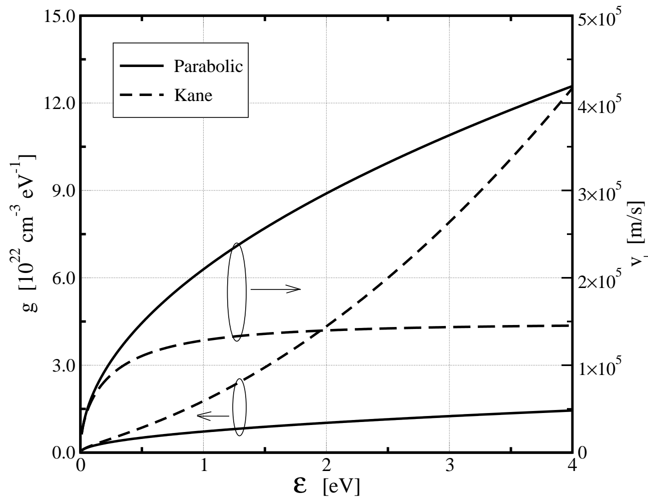

Figure 2: Density of states $g(\mathcal{E})$ (left) and the resulting normal velocity $v_\perp$ (right) for a parabolic and Kane's dispersion relation.

Fig. 2 shows a comparison of the density of states and the resulting normal velocity for a parabolic and the Kane dispersion relation. It can be seen that Kane's dispersion relation leads to a density of states which exceeds the density of states using the parabolic dispersion relation, while Kane's perpendicular velocity saturates well below the perpendicular velocity from the parabolic dispersion relation. However, the total effect on the gate current density which depends on the product of perpendicular velocity and density of states will be small which explains why good results have been achieved using the parabolic dispersion approximation.

3 DISTRIBUTION FUNCTION MODEL

Several works deal with the problem of distribution function modeling for hot carriers in the channel region of a MOSFET [5], [6]. The problem arises from the fact that the assumption of a cold Maxwellian distribution function inevitably overestimates the amount of carriers near the source region where electrons have to surmount an energy barrier and the population of high-energy electrons is low. At the drain end, however, electrons have gained energy and the cold Maxwellian distribution underestimates this high-energy tail. The straightforward approach is to use a heated Maxwellian distribution function

$$f(\mathcal{E}) = A\exp\left(-\frac{\mathcal{E}}{\mathrm{k_B}T_\mathrm{n}}\right) \tag{8}$$

with T_n being the electron temperature, $\mathrm{k_B}$ the Boltzmann constant, and A a normalization constant. This model, however, overestimates the high-energy tail all along the channel because it cannot account for the curvature of the distribution function at high energies. Thus, to account for the electron energy distribution function of hot carriers in the channel region an expression has been presented in [7] which makes use of a six moments transport model:

$$f(\mathcal{E}) = A\exp\left[-\left(\frac{\mathcal{E}}{\mathcal{E}_{\mathrm{ref}}}\right)^b\right]. \tag{9}$$

The values of $\mathcal{E}_{\mathrm{ref}}$ and b are derived from the solution variables T_n and β_n using a two-dimensional Newton procedure as described in [7]. There it has been shown that (9) accurately reproduces Monte Carlo results inside the channel. In the drain region, however, hot electrons from the source mix with the pool of cold electrons of the drain region which leads to an additional population of cold electrons. An improved model which is able to reproduce this behavior is given in [8] which, however, does not influence the results given here.

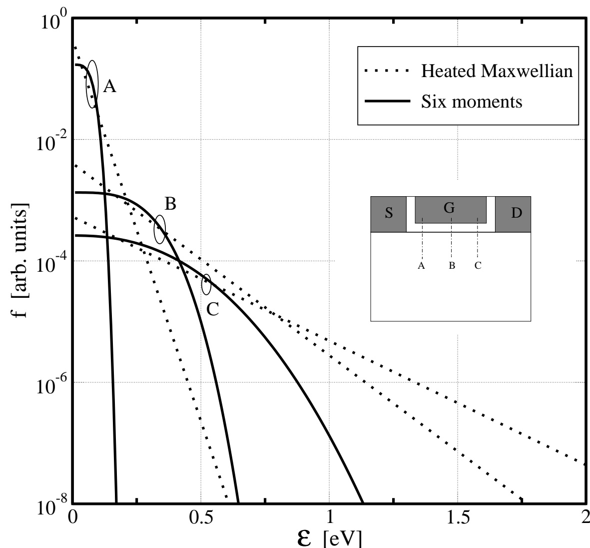

Figure 3: Comparison of the heated Maxwellian distribution and the six moments distribution function (9) as a function of the electron energy at different points in the channel of a $0.35\,\mu$m device.

The value of the normalization variable A is calculated from the carrier concentration using the normalization

$$n = \int_0^\infty f(\mathcal{E}) g(\mathcal{E})\, d\mathcal{E} \tag{10}$$

where the carrier concentration n is taken from the transport model. Thereby consistency of the model is assured. Fig. 3 shows a comparison of the six moments electron energy distribution function with a heated Maxwellian distribution at the points A (near the source contact), B (in the middle) and C (near the drain contact) in the channel of a $0.35\,\mu$m device. The heated Maxwellian distribution overestimates the high-energy tail at all of these points, giving rise to a considerable amount of erroneous gate currents.

4 RESULTS

For the evaluation of the tunneling model we solved our six moments transport model [9] for several MOS transistors with varying gate lengths and oxide thicknesses. The expressions have been implemented into the general purpose device simulator MINIMOS-NT in a self-consistent manner. We assumed an nMOS device in on-state with $V_{\text{gs}} = 0.8\,\text{V}$ and $V_{\text{ds}} = 1.2\,\text{V}$. Gate lengths of $0.5\,\mu$m, $0.35\,\mu$m, $0.25\,\mu$m, $0.18\,\mu$m, and $0.1\,\mu$m with oxide thicknesses of 4 nm, 3 nm, and 2 nm have been taken into account. It has been shown in Fig. 3 that the heated Maxwellian distribution overestimates the high-energy tail of the distribution function. However, due to the shape of the transmission coefficient, the correct modeling of the distribution function in the high energy regime is crucial for the calculation of hot carrier gate currents. The effect of this overestimation is clearly visible in Fig. 4 which shows the integrand of (1). While the incremental gate current density for the six moments distribution function strongly decreases for increasing energies, it peaks around the upper edge of the energy barrier for the heated Maxwellian distribution. This spurious peak can be seen in the lower part of Fig. 4. The overestimation finally results in a peak of the gate current density near the drain side of the channel, as seen in the upper part of Fig. 5 which shows the resulting normalized gate current density along the channel for devices with different gate lengths.

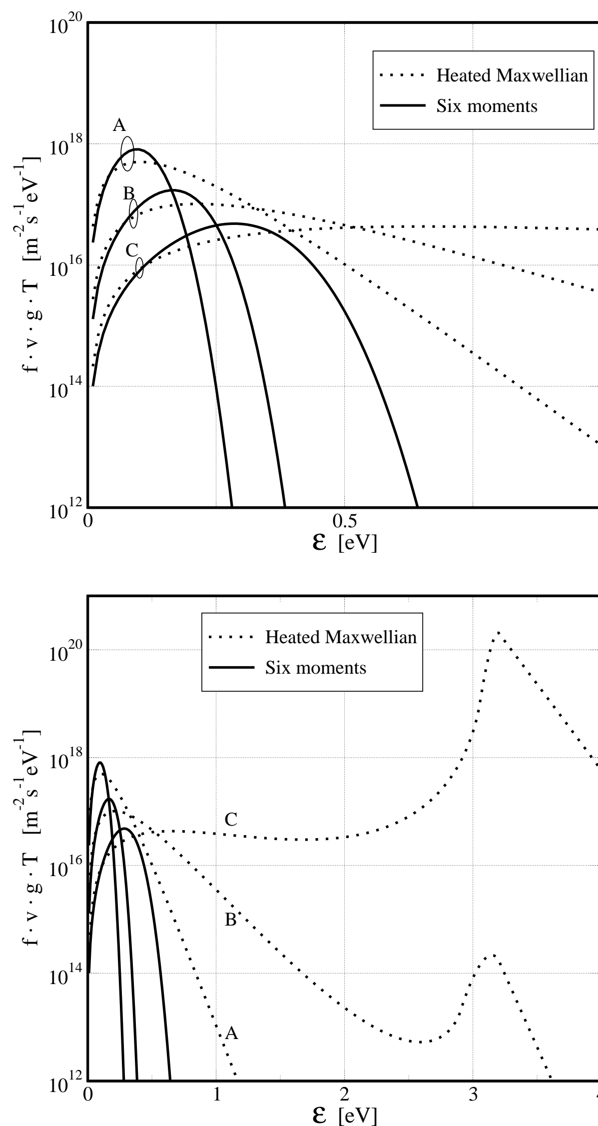

Figure 4: Integrand of expression (1) for a heated Maxwellian distribution and the six moments distribution function (9) as a function of the electron energy at different points in the channel of a $0.35\,\mu$m device.

The spurious gate current density in the upper part of Fig. 5 is clearly visible and it becomes even more pronounced for smaller devices. The effect on the total gate current is shown in the lower part of Fig. 5 where the gate current is given for different gate oxide thicknesses as a function of the gate length and normalized to the gate length. It can be seen that the heated Maxwellian approximation leads to increasingly wrong results for reduced gate length. I_g/L_g becomes even independent of the oxide thickness for the heated Maxwellian distribution at $L_g = 0.1\,\mu$m which seems at least questionable. The new distribution function, however, delivers reasonable results and can thus safely be used for the evaluation of gate currents in sub-0.1μm devices.

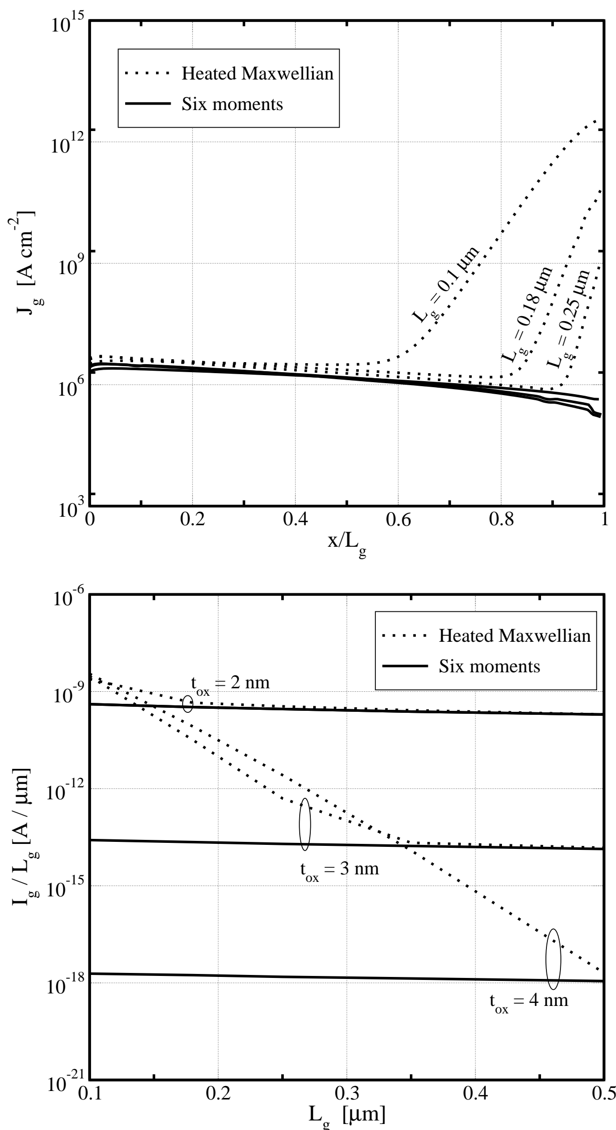

Figure 5: Spatial distribution of the gate current density along the channel for different gate lengths L (upper figure) and the resulting gate current normalized to the gate length (lower figure).

5 CONCLUSIONS

We presented a new model for the hot-electron gate tunneling current by taking the non-Maxwellian shape of the electron energy distribution function and a non-parabolic dispersion relation into account. We showed that the commonly used heated Maxwellian shape assumption for the distribution function can deliver correct results for the case of cold carrier tunneling, but it fails to reproduce hot carrier tunneling. We used a recently developed six-moments transport model to deploy an expression which correctly reproduces the shape of the distribution function in the channel region. Using this model reasonable results even for short channel devices could be achieved.

REFERENCES

[1] K. Hasnat, C.-F. Yeap, S. Jallepalli, S. A. Hareland, W.-K. Shih, V. M. Agostinelli, A. F. Tasch, and C. M. Maziar, "Thermionic Emission Model of Electron Gate Current in Submicron NMOSFETs," *IEEE Trans.Electron Devices*, vol. 44, no. 1, pp. 129–138, 1997.

[2] R. Shankar, *Principles of Quantum Mechanics*. Plenum Press, New York, 1994.

[3] E. O. Kane, "Band Structure of Indium Antimonide," *J.Phys.Chem.Solids*, vol. 1, pp. 249–261, 1957.

[4] C. Fiegna, F. Venturi, M. Melanotte, E. Sangiorgi, and B. Riccó, "Simple and Efficient Modeling of EPROM Writing," *IEEE Trans.Electron Devices*, vol. 38, no. 3, pp. 603–610, 1991.

[5] D. Cassi and B. Ricco, "An Analytical Model of the Energy Distribution of Hot Electrons," *IEEE Trans.Electron Devices*, vol. 37, no. 6, pp. 1514–1521, 1990.

[6] N. Goldsman and J. Frey, "Electron Energy Distribution for Calculation of Gate Leakage Current in MOSFETs," *Solid-State Electron.*, vol. 31, no. 6, pp. 1089–1092, 1988.

[7] T. Grasser, H. Kosina, and S. Selberherr, "Influence of the Distribution Function Shape and the Band Structure on Impact Ionization Modeling," *J.Appl.Phys.*, vol. 90, no. 12, pp. 6165–6171, 2001.

[8] T. Grasser, H. Kosina, C. Heitzinger, and S. Selberherr, "An Impact Ionization Model Including an Explicit Cold Carrier Population," in *Modeling and Simulation of Microsystems (submitted)*, (San Juan, Puerto Rico), 2002.

[9] T. Grasser, H. Kosina, M. Gritsch, and S. Selberherr, "Using Six Moments of Boltzmann's Transport Equation for Device Simulation," *J.Appl.Phys.*, vol. 90, no. 5, pp. 2389–2396, 2001.