HYDRODYNAMIC AND MONTE CARLO SIMULATION OF AN ELECTRON SHOCK WAVE IN A ONE MICRON SEMICONDUCTOR DEVICE

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Abstract

Hydrodynamic model simulations of a steady-state electron shock wave [1] in a one micron Si semiconductor device at 77 K are presented. The hydrodynamic simulations are compared with a Monte Carlo simulation of Laux using the DAMOCLES [2] program. Excellent agreement between the two different methods for simulating the electron shock wave can be obtained by adjusting the amount of heat conduction in the hydrodynamic model.

1 Introduction

In Ref. [1], I presented two parameter regimes for the $n^+ - n - n^+$ diode in which a shock profile develops in the channel as the supersonic flow on entering the channel breaks to a subsonic flow, in analogy with gas dynamical flow in a Laval nozzle. The electron shock wave is a new nonlinear wave analogous to the gas dynamical shock wave in the Laval nozzle, but in a very different physical setting. Here the $n^+ - n - n^+$ doping of the diode corresponds to the converging/diverging geometry of the Laval nozzle.

The steady-state upwind shock simulations presented in Ref. [1] were reproduced in Ref. [3] using a time-dependent "essentially non-oscillatory" (ENO) upwind scheme [4], a higher-order Godunov method.

The one-dimensional shock computations imply that the electron shock waves are an integral part of the hydrodynamic model. The shock waves allow for higher electron velocities in the diode channel and thus faster switching times, and provide a richer space charge structure in the diode channel.

Ref. [5] presented numerical simulations of a family of steady-state electron shock waves (parametrized by the amount of heat conduction) in a one micron Si semiconductor device at 77 K. The electron shock wave has a finite width which scales linearly with the amount of heat conduction. I presented numerical evidence that the shock width goes to zero as the amount of heat conduction in the model goes to zero.

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2 Comparison of Hydrodynamic and Monte Carlo Computations

In this section I present the confirmation of the original prediction of the 77 K electron shock wave in Si by the DAMOCLES [2] simulation of the Boltzmann equation by Steven Laux of the IBM Thomas J. Watson Research Center.

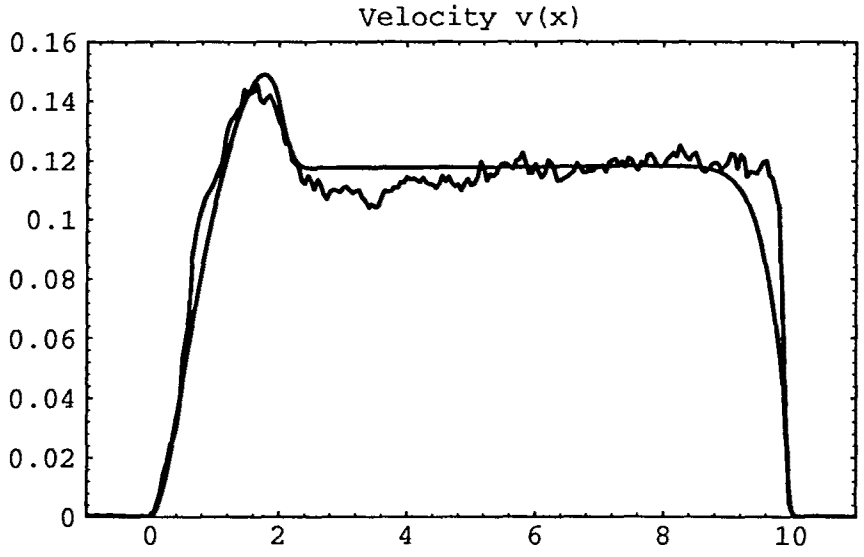

Figure 1: Hydrodynamic and Monte Carlo electron velocity in 10^8 cm/s for $V = 1$ volt, 1 micron channel, 77 K. x is in 0.1 microns. The jagged curve is the DAMOCLES result.

For the momentum and energy relaxation times in the hydrodynamic model I use modified Baccarani-Wordemann models [6, 5]:

$$\tau_p = \tau_{p0}\frac{T_0}{T} \tag{1}$$

$$\tau_w = \frac{\tau_p}{2}\left(1 + \frac{\frac{3}{2}T}{\frac{1}{2}mv_s^2}\right) \tag{2}$$

where the low-energy momentum relaxation time τ_{p0} is set equal to 1.65 picoseconds from the DAMOCLES data [7] for 0.009975 eV electrons[1] in homogeneous Si, T is the electron temperature, T_0 is the ambient device temperature, m is the effective electron mass, and $v_s = v_s(T_0)$ is the saturation velocity. Good agreement between the two different methods for simulating the electron shock wave can be obtained by adjusting the amount of heat conduction in the hydrodynamic model. The best fit for the thermal

[1]The equilibrium electron average energy at 77 K.

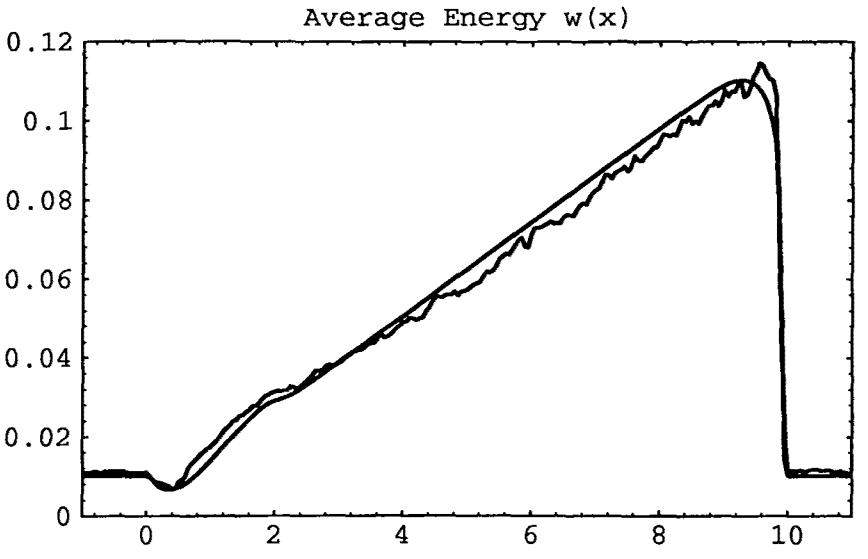

Figure 2: Hydrodynamic and Monte Carlo electron average energy in eV for $V = 1$ volt, 1 micron channel, 77 K. The jagged curve is the DAMOCLES result.

conductivity κ in the law for heat conduction

$$\mathbf{q} = -\kappa \nabla T, \quad \kappa \approx \kappa_0 \tau_{p0} n T_0 / m \tag{3}$$

where n is the electron density, is given by $\kappa_0 = 0.05$.

For the shock computations, I take an $n^+ - n - n^+$ diode consisting of a 0.1 micron source, a 1.0 micron channel, and a 0.1 micron drain. In the n^+ region, the doping density $N = 10^{18}$ cm^{-3}, while in the n region $N = 10^{15}$ cm^{-3}.

Figs. 1 and 2 present the hydrodynamic and DAMOCLES simulations of the 77 K electron shock wave at $V = 1$ volt. DAMOCLES calculates a current of 4500 amps/cm^2, in agreement with the hydrodynamic value of 4463 amps/cm^2. The shock profile is most clearly visible in the velocity plot (Fig. 1). The flow is supersonic at the velocity peak just inside the channel, and subsonic at the end of the wave where the velocity makes a "bend" to the plateau in the channel.

The DAMOCLES velocity exhibits a Mach 2.2 shock profile (slightly spread out due to heat conduction) based on both internal evidence[2] and comparison with the hydrodynamic simulations. Thus the hydrodynamic prediction of an electron shock wave [1] in Si at 77 K has been confirmed by Monte Carlo simulation of the Boltzmann equation.

[2]The electron temperature $T \approx 77$ K at the shock wave. Using the effective electron mass approximation, the electron Mach number $M = v/c = v/\sqrt{T/m} \approx 2.2$.

References

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