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Joule Heating and Phonon Transport in Silicon MOSFETs

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INTRODUCTION

Joule heating is caused by emission of phonons as electrons traverse through a semiconductor device. In silicon MOSFETs, most of the emission is concentrated in the small region where the channel meets the drain. It has been noted in the literature that this causes a hot-spot in the device where strong non-equilibrium conditions exist [1]. The emission of phonons has previously been examined, but the resulting non-equilibrium temperature conditions in a typical device have never been established. This work aims at using full-band Monte Carlo simulation coupled with phonon transport to quantify the extent and the location of Joule heating in a silicon MOSFET.

NUMERICAL APPROACHES

Data on scattering events in a device can be obtained from a Monte Carlo simulation. In this work we use a three-dimensional full-band simulator with a self-consistent non-linear Poisson solver. In order to insure accuracy of results for phonon events, a full phonon dispersion is included. It is calculated from an Adiabatic Bond Charge model and tabulated for lookup [2]. An iterative algorithm was devised in order to make all scattering events involving phonons energy and momentum conserving with the full phonon dispersion relationship. This gives us a more accurate value for the phonon momentum and energy.

Once the simulation run is complete, data on all phonon events that occurred is tabulated. Then phonon velocity is looked up from the dispersion relationship for each phonon, and each phonon is allowed to move without scattering until the end of the simulation time-frame. Finally, the entire simulation region is divided into small cubes, and the total phonon energy in each cube is computed. A curve relating lattice energy $U(T)$ and temperature T is pre-computed by integrating the phonon density-of-states (DOS) $D(\omega)$ with the phonon occupation probability $\langle n(\omega)\rangle$, as given by (1).

$$U(T) = \int d\omega D(\omega)\langle n(\omega)\rangle \hbar\omega \qquad (1)$$

The phonon DOS is calculated numerically from tabulated dispersion data using the algorithm proposed in [3]. Using these results, the non-equilibrium temperature in each location of the device can be found.

RESULTS

The computed phonon DOS is shown in Fig. 1. It was found that transitions between opposite equivalent valleys dominate the scattering statistics, as shown in Fig. 2. The reduced momenta of the phonons resulting from such transitions are near the Brillouin zone edge and rest on the longitudinal optical branch. The direction of propagation of these phonons is perpendicular to the energy isosurface, shown in Fig. 3, so most of the phonons emitted continue to travel in the direction of the flow of electrons. This means very little heat actually flows towards the substrate, as in Fig. 4. Future work is planned to enable coupled electro-thermal simulation in order to probe this process in more detail.

REFERENCES

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[3] G. Gilat and L. J. Raubenheimer, *Accurate Numerical Method for Calculating Frequency-Distribution Functions in Solids*, Physical Review **144**, 2 (1966).

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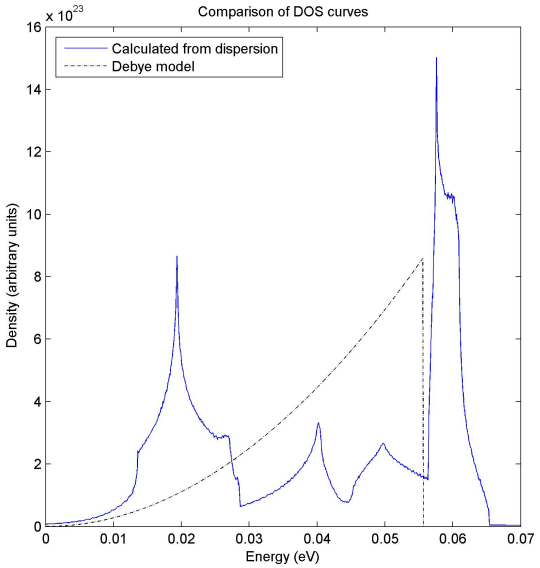

Fig. 1. Phonon DOS computed numerically. The dashed line is the standard Debye approximation, for comparison.

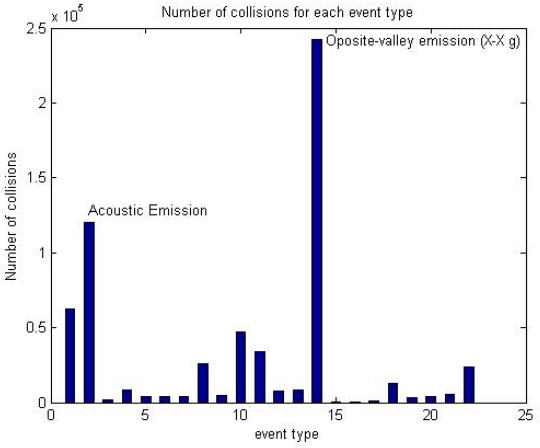

Fig. 2. Number of phonons emitted for each event type. Opposite equivalent valley and acoustic intravalley transitions are marked. Opposite equivalent valley transitions dominate.

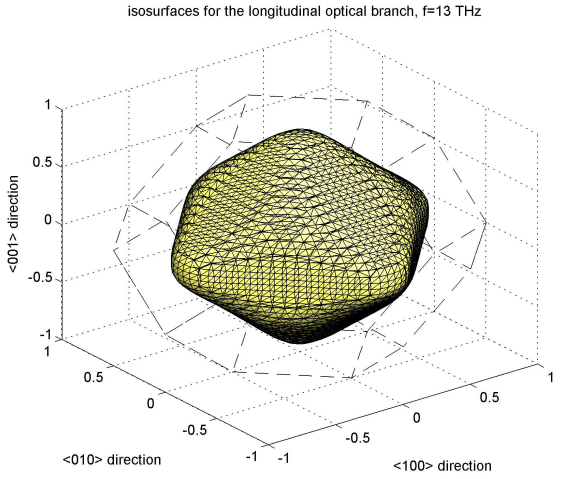

Fig. 3. Surface of equal phonon energy in momentum space for the longitudinal optical branch. Direction of phonon propagation is perpendicular to this surface.

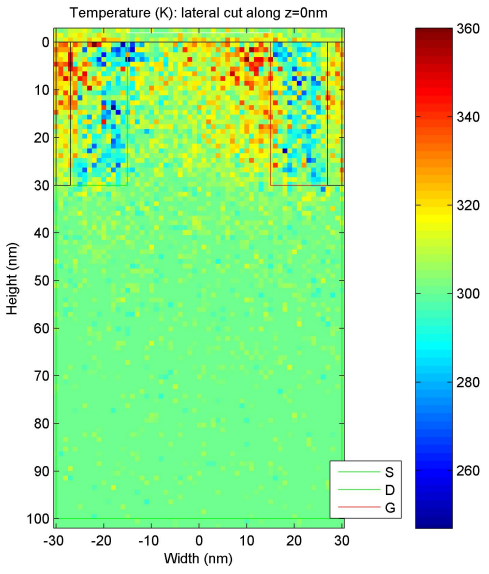

Fig. 4. Map of temperature distribution in an example short channel MOSFET device after 20ps. The clouds of elevated temperature have moved to the left of the source and drain regions.