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Simulation Study on Quasi-Ballistic Heat Transfer Effect in FinFETs

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1. Introduction

Growing heat dissipation is one of the main issues in today's IC chips limiting the reliability and performance. In the microscopic point of view, it has been pointed out that the nanoscale *hot spot* is generated in the MOSFET drain [1, 2], which may degrades the current drivability and also worsen the negative bias temperature instability [3]. In this study, we have analyzed the fundamental processes of the hot spot creation by using a Monte Carlo (MC) simulation technique to solve the Boltzmann transport equation for the electrons and/or phonons in nanoscale Si devices [4, 5].

2. Phonon Transport Simulation

To estimate the thermal properties in small dimensions, the concept of the thermal resistance has been widely used. The conventional analysis based on Fourier's law suggests that it is described as $R_{\rm th} = L/S\kappa$, where L and S are the length and cross sectional area of the heat conduction path, respectively, and κ the thermal conductivity. However, $R_{\rm th}$ does not actually scale like this. Firstly, κ itself decreases with the size due to the frequent phonon boundary scattering at the interface; Fig. 1 shows the simulated κ in Si films and wires together with the experimental data, both showing κ reduction in proportion to the characteristic dimension. In the MC simulation, the phonon diffuse boundary scattering was taken into account in addition to the Umklapp phonon-phonon scattering process. Moreover, in the nanoscale regime, the quasi-ballistic phonon transport effect becomes obvious [6]; Fig. 2 shows the simulation results for the point contact structure, indicating the potential underestimation of $R_{\rm th}$ predicted by the conventional approach. The mechanisms to understand such behavior are illustrated in Fig. 3. Note that, in the ballistic limit, $R_{\rm th}$ is less dependent on L, and asymptotically expressed as $R_{\rm th} = 4\lambda/3S\kappa$, where λ is the phonon mean free path.

To investigate the impact of such effects, we have analyzed the steady-state heat conduction in FinFET structure [5]; the acoustic phonon transport between the heat source placed at the drain edge (based on the results of electron's MC simulator as Fig. 4 [4]) and the heat sinks set at the source/drain contacts and the substrate was simulated. Our simulation suggested that the Fourier-based approach significantly underestimates $R_{\rm th}$ particularly at the exit from the Fin area in the heat flow path due to the ballistic phonon transport effect [5]. This gives rise to the underestimation of the hot spot temperature created around the drain edge (Fig. 5).

3. Discussion: Impact on Electron Transport

The simulation results in Fig. 4 also suggests that the hot electrons dissipates their excess energies mainly through the optical phonon emission in the drain of the nanoscale FETs ($L = 10$ nm). However, the contribution of the optical phonons to the heat transport is expected to be negligible because of the small group velocity, and hence the thermal energy stored in the optical phonons can only be dissipated through the conversion into the acoustic modes via phonon-phonon scattering [7]. It has thus been pointed out that higher temperature rise would be expected inside the hot spot [2]; Fig. 6 schematically illustrates this picture using the equivalent thermal circuit model [4]. If we use the specific heat of optical phonons in Si of ~ 0.3 J/gK at 300 K and the heat source volume as in Fig. 5, then $C_{\rm op} = 3.4$ aJ/K is obtained, which yields $R_{\rm op} = \tau_{\rm op}/C_{\rm ph} = 3$ MK/W, where $\tau_{\rm ph} \sim 10$ ps [1] is the time constant of the optical phonon decay into the acoustic modes. Note that this additional thermal resistance is not negligible compared to that obtained from the MC simulation for the acoustic phonon conduction throughout the FinFET device.

How this RC component affects the drain current? It has been suggested that the inelastic phonon emission processes help achieve ballistic current when the channel length is scaled down to 10 nm [8]. If so, the local heating of the drain edge would worsen the relaxation efficiency of the hot electrons and eventually reduces the current drivability in the steady-state condition. Compared to the device heating time constant ($\sim>$ 1 ns [9]), $\tau_{\rm ph}$ is so small that $C_{\rm op}$ is more easily warmed up but just as easily cooled down. In the pulsed bias conductions with a limited average power (as in digital circuits), the time-averaged temperature would not be raised so much certainly, but instantaneous creation of the hot spot may reduce the drain current. This would become prominent in the ultimately scaled FETs, in which the higher power densities per unit volume are projected [2].

4. Conclusions

We have analyzed the hot spot creation in the drain edge of the nanoscale Si devices using the MC method. The quasi-ballistic transport of phonons and electrons quantitatively and qualitatively influences the self-heating effect, and the presented simulation and modeling approach is useful for understanding the microscopic processes of the heat transfer from the hot electrons via optical phonons to acoustic phonons.

References

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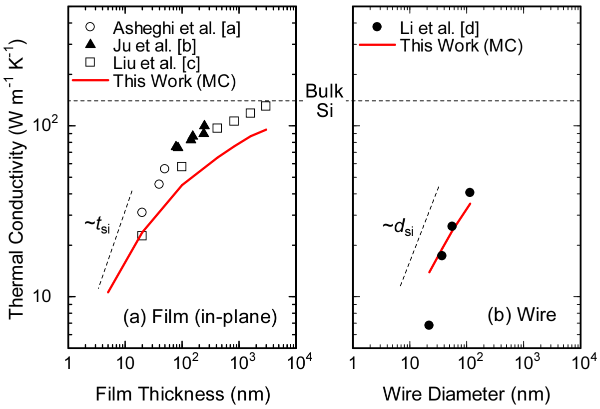

Fig. 1 Thermal conductivities of (a) Si films and (b) Si nanowires at room temperature. Simulated results (lines) are compared with the experimental data (symbols); [a] Asheghi et al., APL **71** (1997) 1798. [b] Ju et al., APL **87** (2005) 153106. [c] Liu et al., APL **84** (2004) 3819. [d] Li et al., APL **83** (2003) 2934.

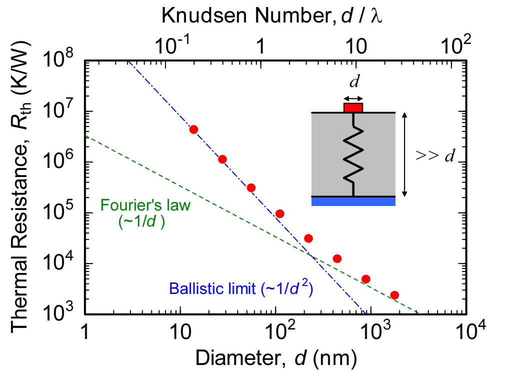

Fig. 2 Simulated equivalent thermal resistance of the point contact structure as depicted in the inset. In this simulation, the phonon mean free path λ was assumed to be 70 nm.

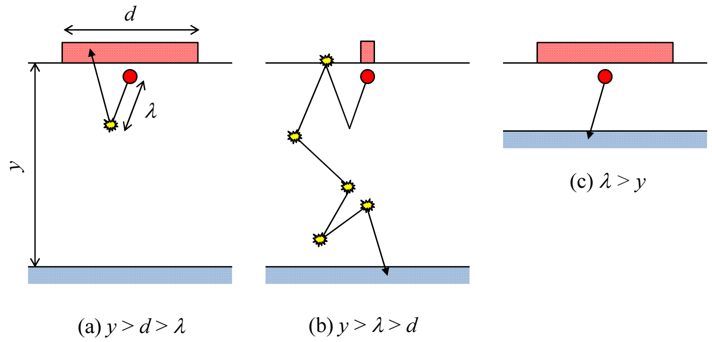

Fig. 3 Schematic illustration showing the phonon ballistic transport effect. (a) If $y > d > \lambda$, the phonon emitted from the top contact easily returns back by the scattering. (b) If $\lambda > d$, it has less chance to return and instead is likely to reach the bottom contact. R_{th} is then limited by the phonon radiative flux from the top contact ($\propto \pi d^2/4$). This is also the case for (c) $\lambda > y$.

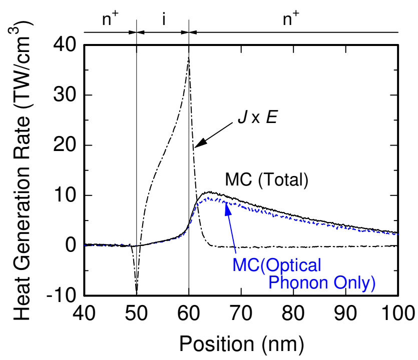

Fig. 4 The spatial distribution of heat generation rate simulated with the MC simulator for the electron transport[4]. For comparison, the results estimated with the Joule heating formula ($J \times E$) are also plotted.

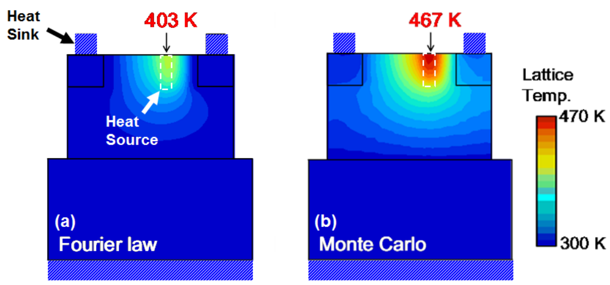

Fig. 5 Steady-state temperature distribution in FinFET (L_{ch} = 22 nm, T_{fin} = 8 nm) calculated with (a) the heat conduction equation solver based on the Fourier law, and (b) the MC simulator developed for solving the Boltzmann transport equation for acoustic phonons [5]. Heat source was placed at the drain edge with a power of 42 μW, and heat sinks were set on the source/drain (S/D) pads as well as at the bottom of the substrate.

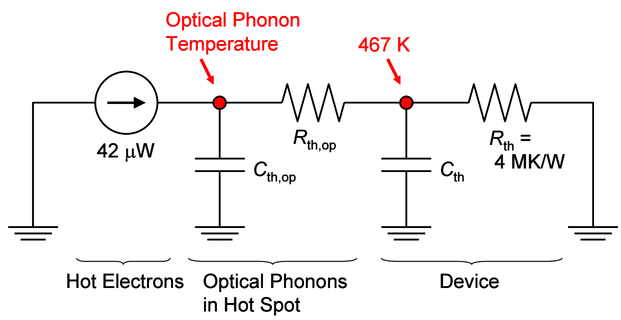

Fig. 6 Equivalent thermal circuit model to describe the self-heating in the device [4]. The heat generation source (42 μW) is modeled as a constant current source, and the node voltages correspond to the temperature rise. If we suppose that the hot electrons dissipates their energies mainly through the optical phonon emission, and finite time is needed for optical phonons to relax into the acoustic modes, an additional component ($R_{\mathrm{th,op}}$ and $C_{\mathrm{th,op}}$) should be considered.