Influences of Elastic and Inelastic Scatterings on Ballistic Transport in MOSFETs

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1. Introduction
Si-MOSFETs have been scaled down to a sub-10nm channel length\(^1\), and a ballistic or quasi-ballistic transport is highly expected. Pioneering research on the ballistic transport in Si-MOSFETs has been performed by K. Natori, and he proposed that the elastic scattering degrades a ballisticity, while the inelastic scattering involving energy relaxation improves the ballisticity in contrast\(^2,3\).

We examine in this paper the Natori’s prediction using actual MOSFET structures based on a quantum-corrected Monte Carlo (QCMC) device simulator\(^4\). As a result, we found that the energy relaxation process in a channel indeed encourages the ballistic transport if the channel length is scaled down to the 10nm-scale, however, the mechanism is not so simple because the channel potential is fluctuated due to electric charges accumulated within the channel.

2. \(\hbar\omega\)–Layer Theory
First, we study a backscattering region where the carrier scattering reduces the drain current. Fig. 1 shows some characteristic aspects of scattering effects. According to Natori\(^2,3\), carriers are injected from source to channel with kinetic energy of the order of thermal energy \(kT\), and they suffer elastic and inelastic scatterings in the channel. Some carriers suffer the energy relaxation (ER) due to the inelastic optical phonon emission, which lose a few multiples of \(kT\) (61 meV for Si) and have little chance to return to source, and are eventually absorbed into drain.

Accordingly, the backscattering region is determined by a position where the potential decreases by the optical phonon energy of 61 meV. We refer to this region as \(\hbar\omega\)–layer. This is analogous to the \(\hbar\omega\)–layer discussed by Lundstrom\(^5\), except that the length \(L_{\hbar\omega}\) is controlled by the optical phonon energy.

A backscattering coefficient \(R\) is calculated by using \(R = L_{\hbar\omega}/(L_{\hbar\omega} + \lambda^{\text{back}})\) \(...\)(1)\(^5\), where \(\lambda^{\text{back}}\) is a mean free path for backscattering in \(L_{\hbar\omega}\). Fig. 2 shows the \(L_{\hbar\omega}\) dependencies of \(L_{\hbar\omega} \lambda^{\text{back}}\) and \(R\) computed for double-gate MOSFETs with ultrathin \((T_{\text{Si}} = 3\) nm) and undoped channels. It is found that the \(\hbar\omega\)–layer theory based on the ER principle agrees better than the \(kT\)-layer theory with the advanced QCMC approach\(^4\) and the recent experimental results\(^6\).

3. Influences of Elastic and Inelastic Scatterings
Next, we discuss the influences of each scattering mechanism. As shown in Fig. 3, we performed four kinds of simulations for the double-gate MOSFET, which include (I) no scattering processes, (II) elastic processes, (III) elastic + inelastic emission processes and (IV) elastic + inelastic emission and absorption processes. Note that all scattering processes are always considered in the source and drain regions. The quantum effects are considered by using a quantum correction of potential\(^4\), and the two-dimensional Poisson’s equation is self-consistently solved. Fig. 4 shows the average electron velocity profiles computed for (a) \(L_{\hbar\omega} = 10\) nm and (b) 30 nm. The lower figures summarize the source-end velocities \(v_x\). It is found that the elastic and inelastic absorption processes decrease \(v_x\) for both channel lengths. (see (II) and (IV)). On the other hand, the inelastic emission processes have the opposite effect on \(v_x\), depending on the channel length (see (III)). In short, the inelastic emission increases \(v_x\) for \(L_{\hbar\omega} = 10\) nm, which coincides with the Natori’s prediction, but it decreases \(v_x\) for \(L_{\hbar\omega} = 30\) nm.

To understand the effects of such inelastic emission processes, we computed the variations in \(v_x\) and \(L_{\hbar\omega}\) as a function of the left boundary of the ER region shown in Fig. 5, where the right boundary of the ER region is always set at the drain-end of channel. The results are shown in Fig. 6. For (a) \(L_{\hbar\omega} = 10\) nm, \(v_x\) increases by including the inelastic emission processes as shown in Fig. 4 (a), but \(v_x\) is found to decrease once when the ER region approaches and slightly overlaps the \(\hbar\omega\)–layer. This is due to the increase in \(L_{\hbar\omega}\) as shown in the dashed lines, which is owing to the potential uplift by the electric charges accumulated within the ER region. Next, for (b) \(L_{\hbar\omega} = 30\) nm, \(v_x\) slightly increases due to the ER region located close to the drain-end, and decreases significantly when the ER region approaches the \(\hbar\omega\)–layer. Consequently, the inelastic emission processes decrease \(v_x\) for \(L_{\hbar\omega} = 30\) nm as shown in Fig. 4 (b). It should be also noted that the \(\hbar\omega\)–layer becomes shorter as the ER region overlaps a wide range of the \(\hbar\omega\)–layer. This is because the potential drops more quickly due to the increased resistance caused by the inelastic emission scattering.

4. Conclusion
It has been found that the inelastic scattering involving energy relaxation improves the ballistic transport in the 10nm-scale Si channels, while it degrades the ballisticity in the longer channels. Furthermore, since the backscattering to source is governed by the \(\hbar\omega\)–layer, a potential profile engineering at the source-end of channel is expected to be a strategy for improving the ballisticity.

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References  
Fig. 1 Characteristic aspects of scattering effects on quasi-ballistic transport, and inelastic phonon energies $\hbar\omega$ and deformation potentials $D$. For Si, the g-LO type optical phonon with $\hbar\omega = 61\text{meV}$ is found to be dominant. Note that all six kinds of inelastic phonons are considered in the present QCMC simulation.

Fig. 3 Four kinds of simulations described above are performed for double-gate MOSFETs with ultrathin and undoped channels. In the source and drain regions, all scattering processes including plasmon scattering are always considered to activate the energy decay of hot electrons rapidly.

Fig. 5 Simulation model including the ER region, where the left boundary of the ER region is displaced from $y = 10$ or 30 nm to 0, while the right boundary is always set at the drain-end of channel.