



Theoretical study of Scattering of Electron Transport

Research Article

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Abstract. The effect of the scattering-direction of hot electrons in the drain of ballistic $n^+ - i - n^+$ diodes is studied by a semi-classical Monte Carlo method. At low doping concentrations, the ionized impurity scattering has a weak influence on hot electron transport, although it is an elastic scattering. At sufficiently high doping concentrations on the other hand, the ionized impurity scattering enhances the backward flow of hot electrons, and severely degrades the peak of mean carrier-velocity in the channel and also the steady-state current. We argue that the scattering direction of hot electrons is the main reason behind these results.

Keywords. Scattering; Monte Carlo method; Electron transport

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1. Introduction

Recently, advanced semiconductor devices have been scaled down to nanoscale size, and the device size is further shrinking [1]. If the channel length is further shortened to less than or comparable to the mean free path of carriers, frequency of scattering events in the device is diminished, so that near ballistic transport is expected even at room temperature [2]. In the conventional *metal oxide semiconductor filed-effect transistor* (MOSFET), the influence of scattering in the drain region on carrier transport is negligible because scattering is dominant in the channel. Carriers release their energy in the channel and “cold” carriers flow

into the drain [3]. If the channel is ballistic, carriers flow in the channel without losing energy and become hot electrons in the drain. The hot electrons are reflected back into the source-end, causing an increase in the injection barrier at the source edge [4]. The rebound of hot electrons from the drain back into the channel caused by scattering significantly reduces the drain current [5]. Kurusu and Natori studied the influence of elastic/inelastic scattering in the drain region on the hot electron transport. They pointed out that elastic scattering causes the backward flow of hot electrons from the drain into the channel, and seriously degrades the peak of the mean velocity of carriers in the channel and also the steady-state current. On the contrary, inelastic scattering can suppress the backward flow of hot electrons [6, 7]. However, they have not discussed the role of the scattering- direction in hot electron transport.

2. Simulation Method

The silicon $n^+ - i - n^+$ diode along [100] direction, as shown in Figure 1, is used in this work. The lengths of the source, channel and drain are 100, 40 and 100 nm, respectively. The diode width is 40 nm. The source and the drain are assumed to have ideal Ohmic contacts [9]. The lattice temperature is assumed to be $T = 300$ K. The analytical non-parabolic band model for the band structure of silicon is employed [9, 10]. We considered the intravalley acoustic, intervalley phonon and ionized impurity scatterings in our simulation. We employed the parameters for intervalley phonon scattering and the parameters for intravalley acoustic phonon scattering. The electron concentration profile is calculated by the cloud-in-cell method and the potential profile is calculated by the finite difference method scheme of the Poisson equation [11]. The steady-state current is computed using the Ramo-Shockley formula [12, 13].

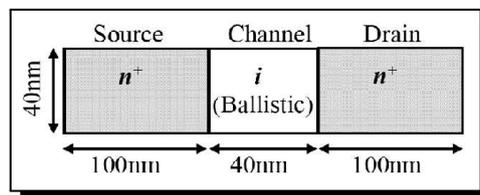


Figure 1. Schematic of structure of silicon ballistic channel $n^+ - i - n^+$ diode

The channel region is assumed to be intrinsic and ballistic. Electrons do not suffer any scattering throughout the channel. The different cases of scattering are studied in the drain region.

Case A: The drain region is ballistic. Electrons do not suffer any scattering throughout the drain.

Case B: Only intravalley acoustic phonon scattering is considered in the drain region.

Case C: Intravalley acoustic phonon and ionized impurity scatterings are considered in the drain region.

Case D: Intravalley acoustic and intervalley phonon scatterings are considered in the drain region.

Case E: Intravalley acoustic, intervalley phonon, and ionized impurity scatterings are considered in the drain region.

Intravalley acoustic, intervalley phonon, and ionized impurity scatterings are considered in the source region for all cases. Intravalley acoustic phonon scattering can be considered as an elastic scattering owing to the fact that the acoustic phonon energy is much lower than $k_B T$ at room temperature, where k_B is the Boltzmann constant and T is the lattice temperature. The intervalley phonon energy is comparable to the average thermal energy of carriers at room temperature and the intervalley phonon scattering is therefore regarded as inelastic. Ionized impurity scattering is treated as an elastic process.

The doping concentrations of the source/drain are set to be $N_D = 10^{18}$ and 10^{20} cm^{-3} , respectively. The scattering rate of ionized impurity scattering is computed by the Brooks-Herring approach [14] when $N_D = 10^{18} \text{ cm}^{-3}$ and using Kosina's model [15, 16] when $N_D = 10^{20} \text{ cm}^{-3}$. Kosina's model has been shown to be adequate for doping concentrations up to 10^{20} cm^{-3} .

3. Results and Discussion

In all cases, the channel is completely ballistic. Electrons injected from the source flow into the drain and then become hot electrons, because electrons do not suffer any scattering and do not lose their energy in the channel region.

Figure 2(a) shows the distribution of the mean velocity of all electrons along the x-axis for bias voltage of 0.3 V, and Figure 2(b) shows the current-voltage characteristics of a ballistic $n^+ - i - n^+$ diode for Cases A, B and C with $N_D = 10^{18} \text{ cm}^{-3}$.

For all cases, the mean velocity of electrons is decreased in the drain region, because there are many "cold" electrons with low velocity in the drain region.

When the drain region is ballistic (Case A), all hot electrons are absorbed in the drain region and are not transported in the backward direction since scattering does not occur. Therefore, Case A has the largest peak of the mean velocity of electrons in the channel as well as the largest steady-state current.

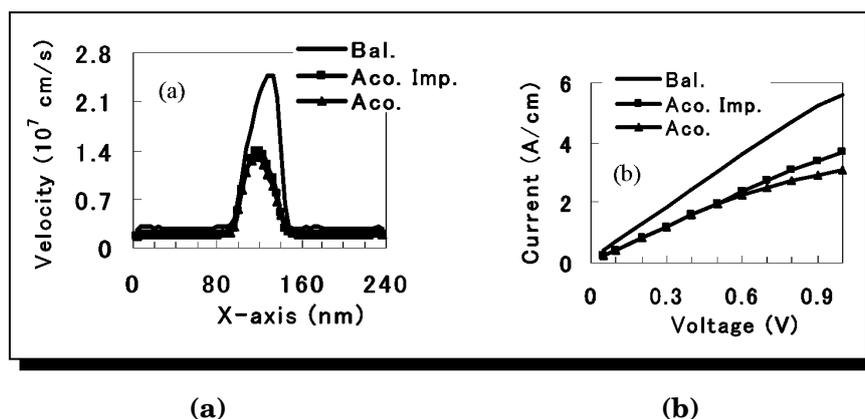


Figure 2. (a) Distribution of mean velocity of electrons along X-axis at $V_D = 0.3 \text{ V}$, and (b) $I - V_D$ characteristics of ballistic channel $n^+ - i - n^+$ diode, for cases in which the drain region is ballistic (Case A, solid line), only acoustic phonon scattering is considered (Case B, triangles line) and both of acoustic phonon and ionized impurity scatterings are considered (Case C, squares line). Here, the doping concentration of source/drain is $N_D = 10^{18} \text{ cm}^{-3}$

When only the intravalley acoustic phonon scattering is considered in the drain region (Case B), results are in accordance with the theory of elastic/inelastic scattering as described by Kurusu and Natori [17]. The intravalley acoustic phonon scattering can be considered as elastic scattering and moreover the scattering motion is random. Therefore, some hot electrons can rebound from the drain back into the channel; some of them even have sufficient energy to return to the source region with high energy and velocity. For these reasons, intravalley acoustic phonon scattering can sufficiently increase the backward flow of hot electrons and decrease the peak of the mean velocity of electrons in the channel as well as the steady-state current.

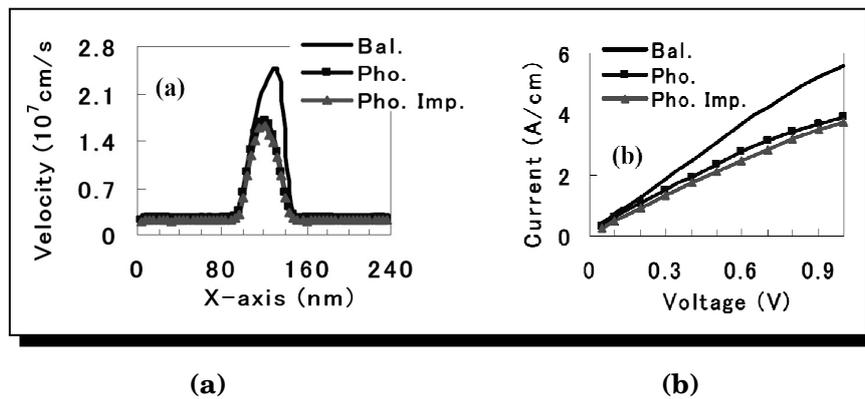


Figure 3. (a) Distribution of mean velocity of all electrons along X-axis at $V_D = 0.3$ V, $N_D = 10^{18}$ cm $^{-3}$ and (b) $I-V_D$ characteristics of ballistic $n^+ - i - n^+$ diode, for cases in which the drain region is ballistic (Case A, solid line), intravalley acoustic and intervalley phonon scatterings are considered (Case D, squares line) and intravalley acoustic, intervalley phonon, and ionized impurity scatterings are considered (Case E, triangles line). Here, the doping concentration of source/drain is $N_D = 10^{18}$ cm $^{-3}$

Figure 3(a) shows the mean velocity for bias voltage of 0.3 V and Figure 3(b) shows the current-voltage characteristics for Cases A, D and E with $N_D = 10^{18}$ cm $^{-3}$.

When the intravalley acoustic phonon and ionized impurity scatterings are considered in the drain region (Case C), the results, however, cannot be explained on only the basis of the theory of elastic scattering as for Case B, although ionized impurity scattering is elastic. Indeed, the peak of the mean velocity of electrons in the channel is slightly larger than that in Case B. In addition, when the drain voltage is high, the steady-state current of Case C is also obviously higher than that in Case B.

We argue that the scattering direction plays a significant role in the results of Case C. Since more than 90% of scattering events are ionized impurity scattering that is a strongly anisotropic process with a high probability for forward-scattering events, ionized impurity scattering occurs more frequently than intravalley acoustic phonon scattering, the occurrence of which is suppressed. Eventually, the rebound of hot electrons in the backward direction is suppressed and most hot electrons are absorbed in the drain. Therefore, Case C has a slightly larger peak of the mean velocity of electrons in the channel and a higher steady-state current at a high drain voltage relative to Case B.

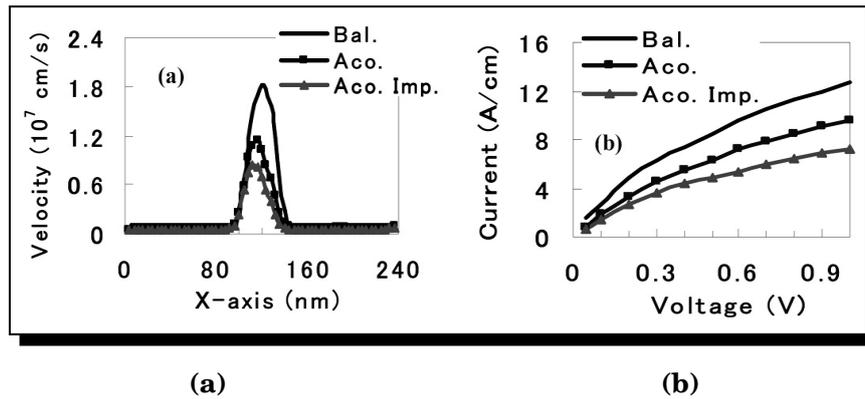


Figure 4. (a) Distribution of mean velocity of all electrons along X-axis at $V_D = 0.3$ V and (b) $I - V_D$ characteristics of ballistic $n^+ - i - n^+$ diode, for Case A (solid line), Case B (squares line) and Case C (triangles line) with $N_D = 10^{20}$ cm^{-3}

When both intravalley acoustic and intervalley phonon scatterings are considered in the drain region (Case D), the results are also in accordance with the theory of elastic/inelastic scattering. If hot electrons are scattered by inelastic phonon scattering, most of them will release their energy and will be unable to return to the channel or the source. Eventually, they are absorbed by the drain. This will decrease the backward flow of hot electrons. Therefore, Case D has a larger peak of the mean velocity of electrons in the channel and higher steady-state current relative to Case B.

When intravalley acoustic, intervalley phonon, and ionized impurity scatterings are all considered in the drain region (Case E), ionized impurity scattering suppresses the occurrences of both intravalley acoustic and intervalley phonon scatterings, which is similar to what happened in Case C. Therefore in Case E, the final effect of ionized

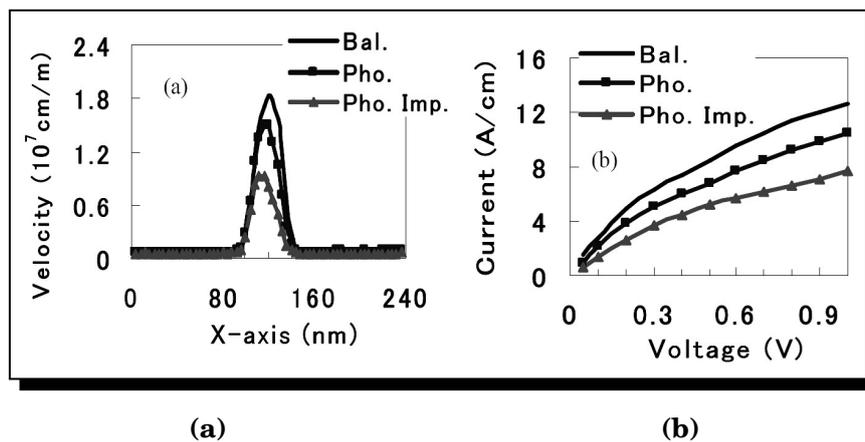


Figure 5. (a) Distribution of mean velocity of all electrons along X-axis at $V_D = 0.3$ V and (b) $I - V_D$ characteristics of ballistic $n^+ - i - n^+$ diode, for Case A (solid line), Case D (squares line) and Case E (triangles line) with $N_D = 10^{20}$ cm^{-3}

Impurity scattering leads to a minor change in the peak of the mean velocity of electrons in the channel and the steady-state current.

It must be mentioned that ionized impurity scattering approaches the isotropic state and obviously increases the rebound of hot electrons in the backward direction at sufficiently high doping concentrations. These effects will severely degrade the peak of the mean velocity of electrons in the channel and the steady-state current. Figure 4(a,b) and Figure 5(a,b) show that both the peak of the mean velocity of electrons in the channel and the steady-state current are substantially reduced when the ionized impurity scattering is considered in the drain region when the doping concentration is $N_D = 10^{20} \text{ cm}^{-3}$. Impurity scattering leads to a minor change in the peak of the mean velocity of electrons in the channel and the steady-state current.

4. Conclusion

Intravalley acoustic phonon scattering within drain severely degrades peak of the mean velocity of electrons in the channel and the steady-state current of the device, because the scattering substantially increases the backward flow of hot electrons. The reason is that the intravalley acoustic phonon scattering is not only an elastic scattering, but is an isotropic scattering and has a random scattering direction. At low doping concentrations, the ionized impurity scattering has a weak influence on hot electron transport because of its anisotropic characteristics with a high probability for forward-scattering events. On the other hand, the scattering assumes an isotropic character at sufficiently high doping concentrations, and increases the scattering of hot electrons in the backward direction, severely degrading the peak of the mean velocity of electrons in the channel and also the steady-state current. It is concluded that the scattering direction is an important factor for the hot electron transport within drain of semiconductor devices. Both the peak of the mean velocity of electrons in the channel and the steady-state current are decreased if the rebound of hot electrons in backward direction is increased in the drain region.

Competing Interests

The authors declare that they have no competing interests.

Authors' Contributions

All the authors contributed significantly in writing this article. The authors read and approved the final manuscript.

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