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Role of Source/Drain Electrodes in Ballistic Transport

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1. Introduction

In an investigation of the ballistic transport device (Fig.1), analysis is usually focused on the channel part, where the efficient transport of the carrier is the main concern. The source and drain electrodes are simply assumed to be of ideal characteristics. The source emits as much carriers as the channel requests, and the drain accepts whole of the transmitted carriers without reflection. However, can we really expect these ideal characteristics to the down-sized source/drain electrodes of nanoscale MOSFETs ?

In this paper, we have developed a simplified formalism of transport analysis based on the flux equation, and applied it to the carrier transport in the source/drain electrodes. The source/drain electrodes are usually regarded as an Ohmic conductor that causes only a potential drop across. But we have also considered the carrier scattering inside with the use of the one-dimensional flux model, and examined the flux coupled to the transport in the channel.

2. Analysis

In a transport analysis within the Ohmic conductor, the one-dimensional equations of continuity for the positive velocity flux component, $j_+(x)$, and the negative velocity flux component, $j_-(x)$, are separately introduced, with the scattering terms representing the carrier exchange between these two components. These scattering terms are given by the carrier density of flux, $j_\pm(x)/v_\pm$, multiplied by the scattering probability $(1/\tau)$, where $v_\pm$ are the drift velocity of the positive and the negative velocity components, and τ is the mean scattering time to the opposite velocity state. Then the pair of the equation of continuity for the two flux components is described as in Fig. 2. Note that this expression is equivalent to the McKelvey's flux equation[1], and yields the drift diffusion current model. If the transport in the conductor is free of hot carrier generation, the carrier energy fully relaxes along the path. The magnitude of mean carrier velocity just after the scattering is reduced to the thermal velocity $v_0 \sim 10^7 cm/s$ for the both flux components. The electric field E applied in the current direction accelerates (decelerates) the positive (negative) velocity flux carrier by the amount $qE\tau/m$ during the scattering time τ. This amount is usually much less than the thermal velocity. Thus the drift velocity $v_\pm$ for the both flux components, which is the mean velocity during the time τ, is given as in Fig.3. The net flux in a uniform system is given by $j = j_+ - j_- = n_0 q\tau E/m$ in accordance with the conventional result of Drude law. Here n_0 is the doping concentration. The source/drain electrodes are modeled as the one-dimensional Ohmic conductor (Fig. 4) applied with the electric field in x-direction, and carriers are injected and drained at each edge. For the source electrode, the flux equation in Fig. 2 is solved with the boundary condition that the positive velocity flux of $j_+(0) \equiv j_{+0} = (n_0/2)v_+$ is injected from the left-and edge facing the contact, and no negative velocity flux is injected from the right-hand edge facing the ballistic channel. The solution of the flux equation with the boundary condition for source is given as in Fig. 5. For the drain electrode in contrast, the boundary condition that $j_{+0} = (n_0/2)v_+$ is injected, and $j_{-L} = (n_0/2)v_-$ is drained both at the right-hand edge facing the contact is applied, so as to yield the net flux equal to $n_0 q\tau E/m$. The solution of the equation for drain is given in Fig. 6.

3. Result

We assume the source/drain electrodes have the doping concentration $n_0=10^{20}/cm^3$, the length L=100nm, $\tau=2.8\times10^{-14}$s in accordance with the value of mobility, and is applied with the electric field E=6570V/cm leading to the potential drop of 66meV within. In Fig. 5, we can see the positive velocity flux and the negative velocity flux have almost the same magnitude showing that carriers are in quasi-equilibrium close to the contact at x=0. The small difference between $j_+(x)$ and $j_-(x)$ shows net current flow within the source. The magnitude of flux components exponentially decays toward the channel entrance at x=100nm, where the negative velocity flux vanishes showing the ballistic injection into the channel without back-scattering. The Ohmic conductor is shown to function as an emitter of carriers. The situation is different for the drain electrode. In Fig. 6, carriers are in quasi-equilibrium in the region close to the contact at x=100nm. But we can find no solution only with the inflow and without the outflow at the left-hand edge, x=0, facing the channel. It shows that the drain electrode cannot accept the carrier flow from the channel without backscattering into the channel. The figure suggests that the steady state outflow and inflow are comparable to each other. Presence of a large backscattered steady flow from drain into channel is serious, because it contradicts the ballistic transport from source to drain.

4. Conclusion

The carrier transport within the source/drain electrode, which are assumed to be an Ohmic conductor, is analyzed by flux equations. The source electrode connected to the quasi-equilibrium reservoir works as the carrier emitter into the channel, yielding a ballistic carrier flow. The drain electrode, on injection from the channel, backscatters a large carrier flow into the channel, destroying the one-way ballistic transport in the channel. It seems critical to work out a measure to counter the backscattering or rebound[2,3] in order to improve the ballistic transport in the channel.

Reference

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[3] T. Kurusu and K. Natori, Jpn. J. Appl. Phys. vol. 45, pp. 1548, (2006).

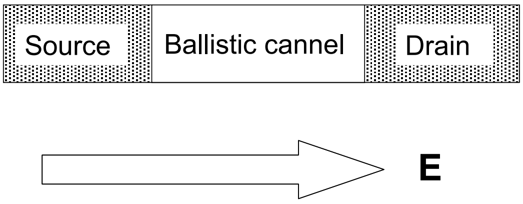

Fig. 1. The ballistic transport device is modeled by a diode structure with a constant applied field.

$$\frac{dj_+(x)}{dx} + \frac{1}{\tau}\left(\frac{j_+(x)}{v_+} - \frac{j_-(x)}{v_-}\right) = 0$$

$$-\frac{dj_-(x)}{dx} + \frac{1}{\tau}\left(\frac{j_-(x)}{v_-} - \frac{j_+(x)}{v_+}\right) = 0$$

Fig. 2. A pair of flux equations that describes an Ohmic conductor.

$$v_0 = \sqrt{\frac{k_B T}{m}}, \qquad v_\pm = v_0 \pm \frac{qE\tau}{2m}$$

$$j = j_+(x) - j_-(x)$$

Fig. 3. v_0 is the thermal velocity. The electric field modulates the carrier velocity to yield the drift velocity of the positive velocity flux, v_+, and that of the negative velocity flux, v_-.

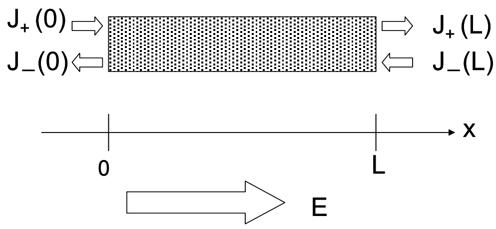

Fig. 4. The source/drain electrodes are modeled by an Ohmic conductor, with the inflow and the outflow of carriers at edges facing the contact/channel as the boundary conditions.

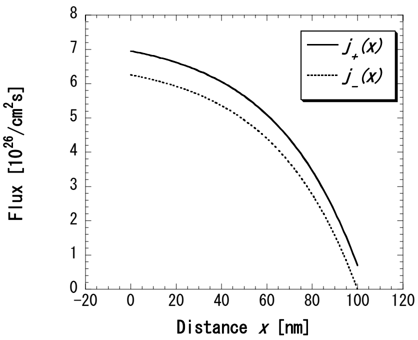

Fig. 5. Carrier flow distribution within the source connected to a contact at x=0. $j_+ \neq 0$ as well as j_-=0 at x=100nm shows that a ballistic injection of carriers into the channel is possible.

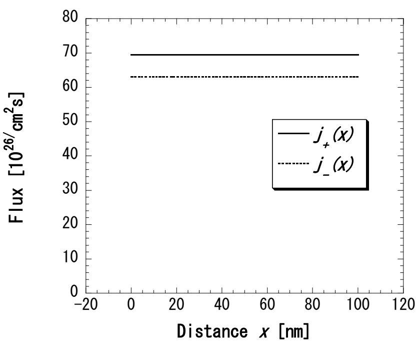

Fig. 6. Carrier flow distribution within the drain connected to a contact at x=100nm. Both j_+ and j_- are non-zero at x=0, showing that the carrier injection into drain inevitably induces a large backscattering of carriers into the channel.