Extended Abstracts of the 2004 International Conference on Solid State Devices and Materials, Tokyo, 2004, pp. 728-729

A-9-2

Nanoscale Quasi-Ballistic MOSFETs in Reflection-Transmission Model

Kenji Natori and Takashi Kurusu

Institute of Applied Physics, University of Tsukuba, Tsukuba, Ibaraki 305-8573, Japan
Phone: +81-298-53-5311, Fax: +81-298-53-5205, E-mail: natori@hermes.esys.tsukuba.ac.jp

1. Introduction

Recently, silicon MOSFETs have been down-sized to nanometer scale, and a ballistic or quasi-ballistic transport is highly expected (Fig. 1). Actually, the famous 70nm MOSFET by IBM showed a performance close to ballistic limit at 77 K[1]. However, recent nanoscale MOSFETs in 20-30 nm range show poorer performance of around 50 % of the limit (index of ballisticity)[2]. Elucidation of quasi-ballistic transport considering carrier scattering is essential for search of the background.

In this paper, a new and straightforward analysis based on reflection-transmission(R-T) probabilities of scattering is presented, and a novel viewpoint on mutually competing role of the elastic scattering and the energy relaxation(ER) due to inelastic optical phonon emission(OPE) is proposed. To improve ballisticity of MOSFETs, the suppression of elastic scattering as well as the encouragement of ER due to OPE is crucial. The Monte Carlo simulation is known to be an efficient method for analysis of devices. But the procedure is complicated and the usual result of analysis does not necessarily provide a clear-cut and cogent view on physics of the transport.

2. Procedure of Analysis

Figure 2 depicts some characteristic aspects of transport in nanoscale MOSFETs. (1) Carriers are injected from source to channel with the kinetic energy of the order of thermal energy kT. (2) Carriers suffer elastic and inelastic scattering in the course from source to drain. Some are back-scattered and some transmitted. (3) Some suffer ER and those that have lost a few multiple of kT by inelastic scattering have little chance to recover the energy to return to source, and so are eventually absorbed to drain. (4) The steady device current consists of the injected flux to channel minus the back-scattered flux to source.

We assume that a single one-dimensional scattering (Fig. 3) causes a carrier to be back-scattered with the reflective coefficient r, forward-scattered with the transmission coefficient t, both without serious loss of energy. Some carriers are energy-relaxed with the probability $(1\text{-}r\text{-}t)$, presumably due to OPE. The OPE causes an ER of 2.44 kT at room temperature. The absorption is rare. The scattering event is expressed in a matrix which we call the R-T matrix. The multiple scattering in a one-dimensional uniform region[3] of length L with scatterer density n are analyzed by successively multiplying the R-T matrix to give the reflection, the transmission and the ER probability of the whole region. (Fig. 4) In actuality, these parameters of the region are computed if only the mean free path λ for elastic scattering, the one μ for inelastic scattering (OPE) and the length L are given. Fig. 5 shows the reflection probability of such a uniform region as a function of the mean free path ratio $(2\mu/\lambda)$ for various values of L. Note that the elastic scattering and the ER perform opposite functions in enhancement of back scattering. The conduction channel of a MOSFET is divided into three regions as in Fig. 6. Region I adjacent to source includes the potential maximum. Here we assume carriers suffer elastic scatterings but the ER due to OPE is forbidden due to lack of carrier energy. Region II covers the rest of channel and both the elastic and the inelastic scattering are present. Region III is the drain electrode in which also the both scatterings are present. Providing specific values of λ and μ for each region and successively multiplying the R-T matrix, we can analyze carrier flux from region to region, and obtain the carrier back-scattering ratio $\Re$ to source. In terms of $\Re$, the index of ballisticity, $b=(I_{sat.exp}/I_{sat.bal})$, showing the ballistic efficiency of the device is expressed as $r=(1-\Re)/(1+\Re)$. The kT-layer effect[4] due to the longitudinal momentum relaxation is not considered in this one-dimensional analysis. Values of λ and μ are evaluated as follows. The mean free path of impurity scattering is estimated based on the Brooks-Herring model[5]. The one for phonon scattering is estimated referring to the analysis by Fischetti[6]. As for surface roughness scattering, we referred to the result of Nayfeh[7]. The device is assumed to be operated at $(V_G\text{-}V_T)=V_D=0.6$ V in saturation, and the energy dependence of mean free paths is considered.

3.Results

First the Super-Halo[8] nanoscale MOS is analyzed. Fig. 7 shows four parameters of b and $\Re$ above mentioned, the ratio of equi-energy transport to drain designated by Te, as well as the rebound ratio from drain, Rb as a function of channel length. The scaling-down causes gradual decrease of $\Re$ and so the increase of b leading to increase of current. A sharp rise of Te shows that carriers increasingly tend to reach drain without losing energy as the channel length is decreased. Fig. 8 shows the relative magnitude of carrier flux between regions for the 5 nm MOSFET with intrinsic channel. Note that 78 % of the flux injected to channel escapes ER and reach drain, but one eighth of that is rebound to channel again and is carried back to source. Fig. 9 is a similar result for a large 50 nm MOSFET with a low concentration channel operated at 77 K. Here a near ballistic transport of b = 0.9 is obtained by the suppressed elastic scattering which enhances ER within channel.

4. Conclusion

A quasi-ballistic nanoscale MOSFET is analyzed by a simple R-T model. The crucial role of ER by OPE is newly pointed out as a factor to improve efficiency of ballistic transport. For $\lambda < \mu$, elastic scattering is dominant and carriers are back-scattered to source to have a degraded ballisticity. For $\lambda > \mu$ on the contrary, the OPE is dominant and the ballisticity is improved (shown in Fig.5). When the device is so much down-sized that the size is smaller than both of λ and μ, the channel region is transparent to ballistic transport, and the competition of λ and μ inside drain dominates $\Re$.

References

[1] K.Natori, IEEE Electron Device Letters, **23**, 655 (2002).
[2] K.Natori et al., Jpn. J. Appl. Phys. **42**, 2023, (2003).
[3] For R-T formalism of elastic scattering, see S.Datta, *Electronic Transport in Mesoscopic Systems*, 1995, Cambridge, p.62. Also S.Datta etal., Superlattices and Micro-structures, **23**, 771, (1997).
[4] M.Lundstrom, IEEE Trans. ED, **49**, 133, (2002).
[5] H.Brooks and C.Herring, Phys. Rev. **83**, 879, (1951)..
[6] M.V.Fischetti and S.E.Laux, Phys. Rev. **B48**, 2244, (1993).
[7] H.M.Nayfeh et al., IEDM 03, 475, (2003).
[8] Y.Taur et al., IEDM 98, 29.4, (1998).

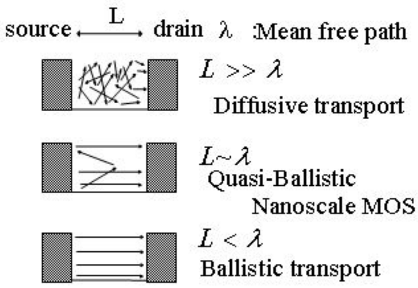

Fig. 1. Classification of transport in nanoscale devices.

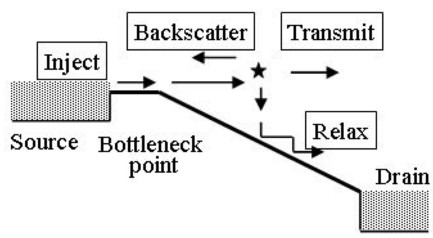

Fig. 2. Characteristic aspects of carrier transport in nanoscale MOSFET.

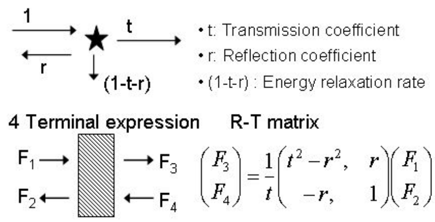

Fig. 3. Reflection-transmission formalism of scattering with energy relax.

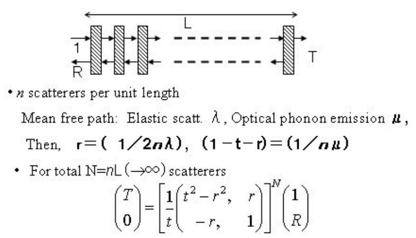

Fig. 4. R-T formalism to include multiple scattering in a homogeneous region.

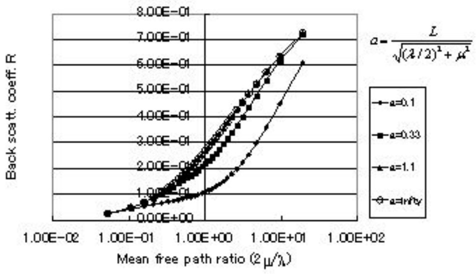

Fig. 5. Reflection probability of the region of length L.

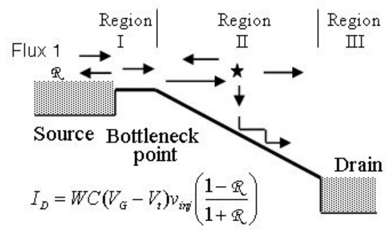

Fig. 6. MOSFET is divided into three characteristic regions.

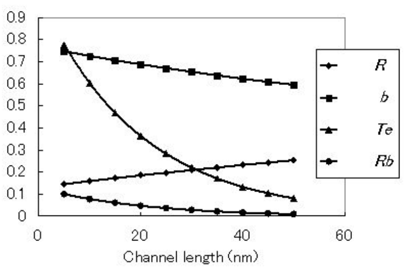

Fig. 7. R: Backscatt. Coeff. b: Ballisticity. Te: Elastic transport ratio to drain. Rb: Rebound ratio from drain to channel.

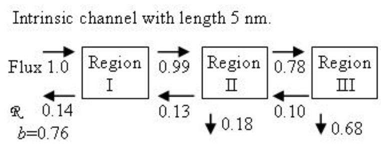

Fig. 8. Relative value of carrier flux from region to region. The rate of energy relaxation is also shown. L=5nm.

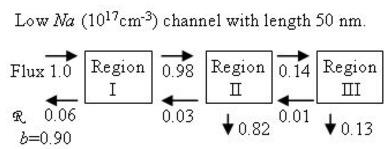

Fig. 9. Similar diagram as Fig. 8 for the 50nm MOSFET on low Na substrate in low temperature operation.