Low-field mobility and carrier transport mechanism transition in nanoscale MOSFETs

Liu Hongwei(刘宏伟)†, Wang Runsheng(王润声), Huang Ru(黄如), and Zhang Xing(张兴)

(Institute of Microelectronics, Peking University, Beijing 100871, China)

Abstract: This paper extends the flux scattering method to study the carrier transport property in nanoscale MOSFETs with special emphasis on the low-field mobility and the transport mechanism transition. A unified analytical expression for the low-field mobility is proposed, which covers the entire regime from drift-diffusion transport to quasi-ballistic transport in 1-D, 2-D and 3-D MOSFETs. Two key parameters, namely the long-channel low-field mobility (μ_0) and the low-field mean free path (λ_0), are obtained from the experimental data, and the transport mechanism transition in MOSFETs is further discussed both experimentally and theoretically. Our work shows that λ_0 is available to characterize the inherent transition of the carrier transport mechanism rather than the low-field mobility. The mobility reduces in the MOSFET with the shrinking of the channel length; however, λ_0 is nearly a constant, and λ_0 can be used as the "entry criterion" to determine whether the device begins to operate under quasi-ballistic transport to some extent.

Key words: mobility; low-field mean free path; transport mechanism transition
DOI: 10.1088/1674-4926/31/4/044006 **EEACC:** 2520

1. Introduction

With the continuous downscaling of CMOS devices, a new carrier transport mechanism, namely quasi-ballistic transport, has been recognized in nanoscale devices[1], and has attracted much attention recently[2–4]. However, the transition region from traditional drift-diffusion transport to quasi-ballistic transport has rarely been discussed. In addition, it is not clear in which dimension a device with a given structure will operate under quasi-ballistic mode. In the conventional transport theory, the effective mobility has been widely used as a parameter to determine or predict the carrier transport in MOSFETs and is believed still available in nanoscale devices[2]. However, recently, it has been observed by different techniques that the measured low-field mobility degrades in short-channel MOSFETs[4–6]. The physical mechanism for this phenomenon has not been well studied. It is not clear yet whether mobility is still a reliable parameter for carrier transport in nanoscale MOSFETs.

This paper studies the low-field mobility in MOSFETs using the flux scattering method. A close-form expression of the low-field mobility is presented, which is valid for 1-D, 2-D, and 3-D MOSFETs. The low-field mean free path λ_0 is extracted in the 1-D, 2-D, and 3-D MOSFETs and the transition of transport mechanism is then discussed in detail. The experimental data show that λ_0 can be used as the "entry criterion" to characterize the carrier transport mechanism transition from drift-diffusion transport to quasi-ballistic transport in nanoscale MOSFETs.

2. Mobility using the flux scattering method

Flux scattering theory has provided a clear conceptual view of quantum transport in mesoscopic structures and guided much of the experimental work in that field[7]. The flux scattering method, based on McKelvey's flux method[8] and revised by Lundstrom's group, has been used to investigate the driving current for nanoscale MOSFETs in the saturation region[1, 2]. In this paper, the flux scattering method is adopted, with the emphasis on the carriers' transport in the low-field limit.

As schematically shown in Fig. 1, the positive coordinate direction is from the source to the drain in the MOSFET, and the origin is located at the top of the potential barrier near the source. The flux scattering method can be extended for the case of no absorption[9],

$$\frac{\mathrm{d}J^+}{\mathrm{d}x} = -R^+J^+ + R^-J^-, \tag{1}$$

$$\frac{\mathrm{d}J^-}{\mathrm{d}x} = -R^+J^+ + R^-J^-, \tag{2}$$

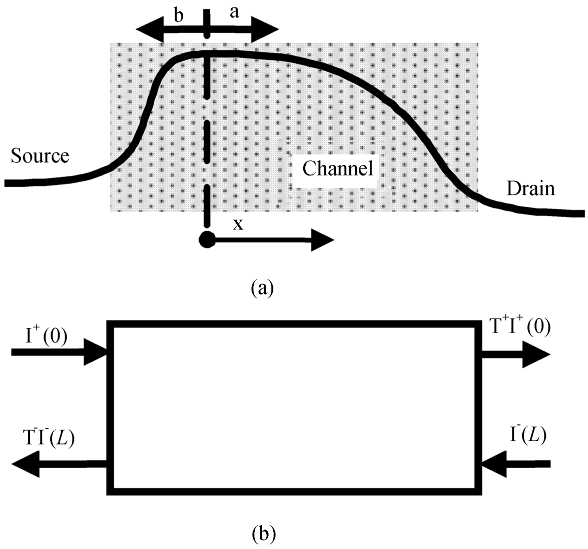

Fig. 1. Schematic diagram of a MOSFET in the flux scattering method. (a) The simple energy band. (b) The two-port network.

† Corresponding author. Email: hw_liu@ime.pku.edu.cn

Received 8 November 2009, revised manuscript received 17 December 2009

where the backscattering probabilities per length in the channel of the MOSFET are

$$R^{+} = R_0 + \frac{qE_x}{2k_{\mathrm{B}}T_{\mathrm{L}}},\ E_x < 0, \tag{3}$$

$$R^{-} = R_0 - \frac{qE_x}{2k_{\mathrm{B}}T_{\mathrm{L}}},\ E_x < 0. \tag{4}$$

The backscattering coefficients, R^+ and R^-, consist of two terms due to the actual scattering R_0 and the electric field. The low-field backscattering probability per length R_0 is related to the low-field mean free path λ_0 by $R_0 = 1/2\lambda_0 = 0.5k_{\mathrm{B}}T_{\mathrm{L}}\mu_0/qc$, where $c = \sqrt{2k_{\mathrm{B}}T_{\mathrm{L}}/\pi m}$ is the average velocity of hemi-Maxwellian distribution for the non-degenerate case or $c = \sqrt{2k_{\mathrm{B}}T_{\mathrm{L}}/\pi m}\left[F_{1/2}(\eta_{\mathrm{F}})/F_0(\eta_{\mathrm{F}})\right]$ for the degenerate case (here, $F_j(\bullet)$ is the Fermi–Dirac integral of order j)[2] and T_{L} is the lattice temperature. It is worth noting that c and λ_0 can be treated as parameters and that the same derivation can be followed in this work, though they may have different expressions in 1-D, 2-D, and 3-D MOSFETs.

The net flux can be defined by

$$J = J^{+} - J^{-}, \tag{5}$$

and the effective carrier concentration is defined by

$$n^{*} = \left(J^{+} + J^{-}\right)/c. \tag{6}$$

From Eqs. (1)–(6), the conventional-like expression can find

$$J = -\mu^{*}E_x n^{*} - D^{*}\left(\mathrm{d}n^{*}/\mathrm{d}x,\right), \tag{7}$$

where $\mu^{*} = (q/k_{\mathrm{B}}T_{\mathrm{L}})\,D^{*} = (q/k_{\mathrm{B}}T_{\mathrm{L}})\,c/2R_0$. Here, all parameters (in superscript) are effective values, which are usually different from the corresponding parameters in the traditional transport theory. However, the effective values can become the corresponding conventional ones under the low-field limit.

When the potential barrier between the source and drain is given, the flux's scattering matrix is independent on the incoming fluxes[9]. To derive a reasonably simplified expression for the transmission coefficient, simple boundary conditions have been introduced in the flux's scattering matrix method[9]. The boundary conditions are bounded by the planes $x = 0$ and $x = L$ as $J^{+}(0) = 1$ and $J^{-}(L) = 0$.

As far as the low field limit is concerned, the net carrier transport current is given by

$$J = \frac{q\phi}{k_{\mathrm{B}}T_{\mathrm{L}}} n_0^{+} c \frac{2\lambda_0}{2\lambda_0 + L}, \tag{8}$$

where ϕ is the potential difference between the top of the potential barrier and the drain, n_0^{+} is the positive component of carrier concentration per unit area at the top of the potential barrier, which is approximately half of the total carriers per unit area, $n_0 = 2n_0^{+}$, in the case of transport dominated by scattering-limited mechanisms under the low-field limit. That is, in the derivation in Eq. (8), emphasis is only laid on the influence of electric field on the carrier transport.

In the conventional transport theory, the current is

$$J = \mu_{\mathrm{LF}} n_0 \phi / L. \tag{9}$$

Compared with Eq. (8), we obtain the analytical expression of the low-field mobility in a MOSFET as

$$\mu_{\mathrm{LF}} = \frac{q}{k_{\mathrm{B}}T_{\mathrm{L}}} c \frac{\lambda_0}{2\lambda_0/L + 1} \cong \frac{\mu_0}{2\lambda_0/L + 1}, \tag{10}$$

where μ_0 is the long-channel low-field mobility.

Equation (10) shows that the low-field mobility is directly related to the channel length of MOSFETs. Equation (10) evidently predicts that the measured mobility in a MOSFET decreases with the shrinking of the channel length. Furthermore, compared with the experimental data, the carrier low-field mean free path λ_0 can be extracted as follows in the 1-D, 2-D and 3-D MOSFETs.

3. Experimental verification and key parameters

For the 1-D transport case, the low-field mobility in gate-all-around twin Si nanowire MOSFETs (SNWTs) was characterized in this work. The nanowire diameter is 10 nm, and the gate oxide thickness is 3.5 nm. Fabrication details were given in an earlier work[10]. The mobility is measured by the Y-function method[11]. Equation (10) gives a reasonable description of the low-field mobility of n-SNWTs and p-SNWTs, as shown in Figs. 2(a) and 2(b). For the 2-D (UTB SOI MOSFETs[6]) and 3-D (planar bulk MOSFETs[6]) cases, Figures 3 and 4(a)–4(b) also demonstrate the validity of Eq. (10).

Because of the fact that the low-field mobility reduces with the shrinking of the channel length, it is often confusing whether the transport property in the nanoscale MOSFETs degrades to some extent. However, our work demonstrated that, in most cases, λ_0 was a constant and hardly changed with decreasing channel length. Compared with the experimental data, λ_0 has been extracted for the SNWTs, UTB SOI and bulk MOSFETs, which are shown in the corresponding captions of the figures respectively. Based on the flux scattering method, the low-field mean free path λ_0 is the key parameter in determining the driving current in nanoscale MOSFETs[2]. Therefore, the transport property almost does not degrade in the nanoscale MOSFETs with the shrinking of the channel length, though the low-field mobility reduces with the continuous downscaling of MOSFETs. In other words, the mobility can only be regarded as apparent mobility, which is hard to maintain supremacy and to characterize the transport property in the nanoscale devices. Yet actually λ_0 can play an important role in identifying the carrier transport characteristics in MOSFETs with different lengths. The issue will be discussed in the following section on how to use λ_0 to characterize the carrier transport mechanism transition: from drift-diffusion to quasi-ballistic transport.

4. Discussion on the transition region

Based on the Lundstrom backscattering theory, the channel backscattering, taking place in the critical length l_0 near the virtual source, mainly determines the driving current in MOSFETs [2]. The driving current $I_{\mathrm{D,\,sat}}$ is given by:

$$I_{\mathrm{D,\,sat}} = WC_{\mathrm{eff}}v_{\mathrm{inj}}\left(\frac{1 - r_{\mathrm{sat}}}{1 + r_{\mathrm{sat}}}\right)(V_{\mathrm{G}} - V_{\mathrm{T,\,sat}}), \tag{11}$$

$$r_{\mathrm{sat}} = l_0/(l_0 + 2\lambda_0), \tag{12}$$

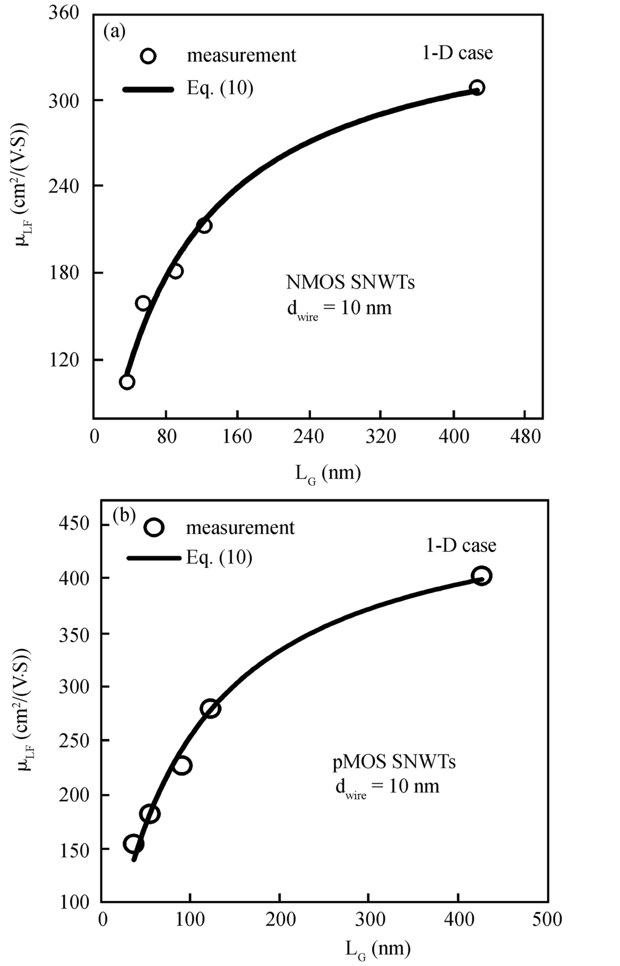

Fig. 2. (a) Low-field mobility ($\mu_{\rm LF}$) as a function of the channel length ($L_{\rm G}$) in n-SNWTs: λ_0 = 43.3 nm, μ_0 = 369.9 cm^2/(V·s). (b) Low-field mobility ($\mu_{\rm LF}$) as a function of the channel length ($L_{\rm G}$) in p-SNWTs: λ_0 = 45.3 nm, μ_0 = 485.4 cm^2/(V·s).

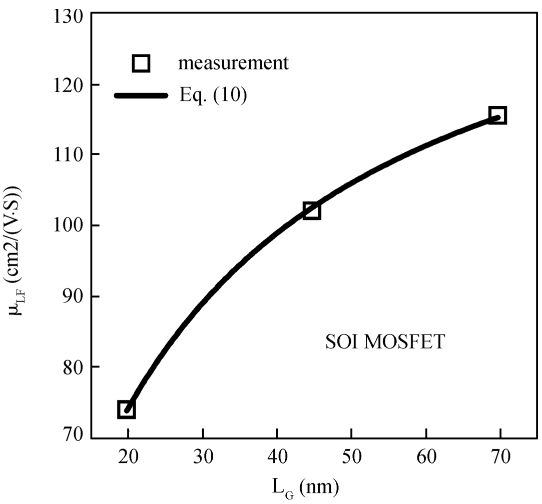

Fig. 3. Low-field mobility ($\mu_{\rm LF}$) as a function of the channel length ($L_{\rm G}$) in SOI MOSFETs: λ_0 = 10.3 nm, μ_0 = 148.4 cm^2/(V·s).

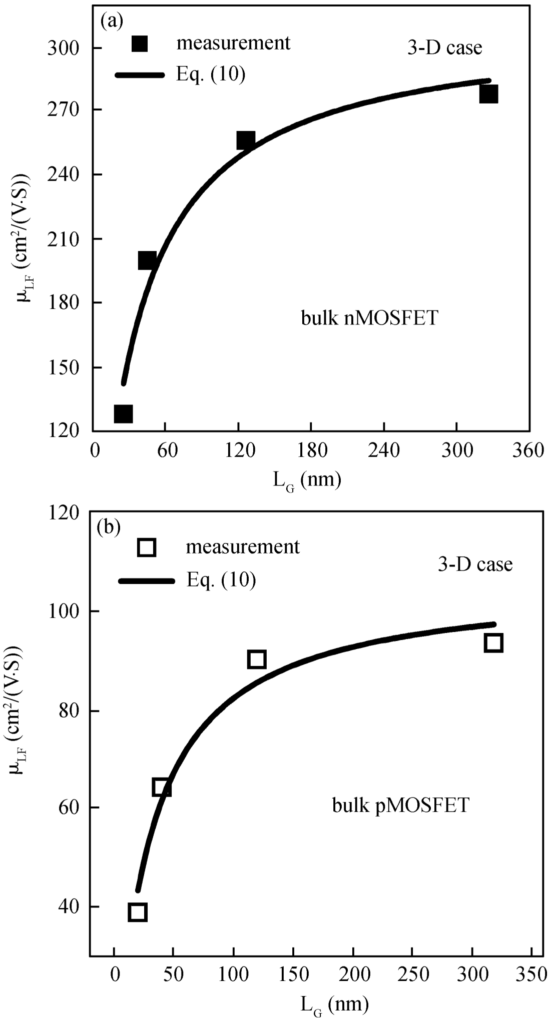

Fig. 4. (a) Low-field mobility ($\mu_{\rm LF}$) as a function of the channel length ($L_{\rm G}$) in bulk n-MOSFETs: λ_0 = 30.2 nm, μ_0 = 311.6 cm^2/(V·s). (b) Low-field mobility ($\mu_{\rm LF}$) as a function of the channel length ($L_{\rm G}$) in bulk p-MOSFETs: λ_0 = 14.5 nm, μ_0 = 106.2 cm^2/(V·s).

where $v_{\rm inj}$ is the carrier injection velocity, $r_{\rm sat}$ is the channel backscattering ration, λ_0 is the mean free path for backscattering, W is the transistor width and $C_{\rm eff}$ is the effective gate capacitance. Note that, due to the different definitions, we use $2\lambda_0$ in Eq. (12). Here, the ballistic efficiency $B_{\rm sat} = (1 - r_{\rm sat})/(1 + r_{\rm sat})$ can be regarded as the extracted parameter, which is beneficial to characterize the carrier transport mechanism transition[3].

We have extracted the ballistic efficiency $B_{\rm sat}$ of SNWTs as a function of the channel length, as shown in Fig. 5. It is clear that a kink occurs in the experimental data. We propose that this is the transition region, which is the critical dimensional range to identify the carrier transport mechanism: from drift-diffusion transport to quasi-ballistic transport.

Let us focus on this transition region. Figure 5 shows that the dimensional range of the kink region approximately covers λ_0 to $2\lambda_0$ (around 40 to 100 nm) for n-SNWTs (the similar situation found in p-SNWTs is not shown here). The slopes for the curve relating the ballistic efficiency to the channel length are different on both sides of the kink region. When the channel length in the n-SNWTs is larger than $2\lambda_0$, the slope is relatively small and the ballistic efficiency increases slowly. On the other side, a distinctly different picture occurs in the n-SNWTs with channel length shorter than λ_0, where the slope is

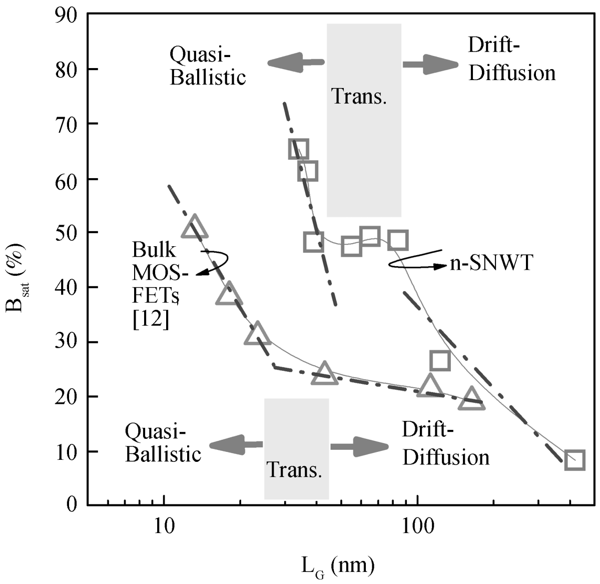

Fig. 5. Ballistic efficiency B_{sat} of the n-SNWTs and bulk MOSFETs as a function of the channel length (L_G).

larger than the previous one. The ballistic efficiency increases rapidly when the channel lengths continue to be scaled down. The physical causes for this experimental phenomenon can be explained as follows.

As shown in Fig. 5, for the long-channel n-SNWTs, because sufficient carrier scattering events occur in the channel, drift-diffusion transport will dominate the carriers' flux and can even hold under the existence of velocity saturation. This is the classical transport picture, where the mobility has been used as the basic parameter for evaluating the performance of MOSFETs. The carrier transport remains predominantly scattering-limited in the long-channel MOSFETs; therefore, the ballistic efficiency increases very slowly, and is even almost unchanged under the velocity saturation region (the kink region in Fig. 5). On the other hand, when the channel length of n-SNWTs is shorter than λ_0, the carriers scarcely suffer scattering events in the channel (Fig. 5). Quasi-ballistic transport begins to dominate the flux of carriers and the ballistic efficiency increases rapidly with the downscaling of MOSFETs. Figure 5 shows the carrier transport mechanism transition from drift-diffusion transport to quasi-ballistic transport, and the dimensional range of the kink region is surely related to the low-field mean free path λ_0. This experimental phenomenon is consistent with the physical picture to some extent; therefore, our work proposes that λ_0 is a key parameter in determining the carrier transport, especially the transport mechanism transition from drift-diffusion transport to quasi-ballistic transport in nanoscale MOSFETs.

In order to backup the proposal presented above, Figure 5 plots the extracted data of planar bulk MOSFETs[12]. It is clear that different slopes for the curve of the ballistic efficiency versus the channel length also occur even in bulk MOSFETs due to the different carrier transport mechanisms. Though the kink region is hardly identified, this is probably caused by insufficient experimental data in the transition region[12]. We suggest that the low-field mean free path, λ_0, can be used as the "entry criterion" to determine whether the device begins to operate under quasi-ballistic transport. More experimental work is expected to be done in the future on this transition region.

5. Conclusion

In this paper, we present an analytical expression for the low-field mobility in nanoscale MOSFETs by the flux scattering method. Based on the analytical expression, an inherent mobility reduction in MOSFETs with the shrinking of the channel length is predicted, which agrees well with the experiments. Different slopes are observed in the curves of the ballistic efficiency as a function of the channel length on both sides of the kink region and this phenomenon is directly related to the transition of carrier transport mechanisms: drift-diffusion transport is dominant in the long-channel MOSFETs, but quasi-ballistic transport feature clearly occurs in MOSFETs with channel lengths shorter than λ_0. It is suggested that the low-field mean free path, λ_0, can be used as the "entry criterion" to characterize the carrier transport mechanism transition from drift-diffusion transport to quasi-ballistic transport in nanoscale MOSFETs.

References

[1] Lundstrom M. Elementary scattering theory of the Si MOSFET. IEEE Electron Device Lett, 1997, 18: 361

[2] Lundstrom M. On the mobility versus drain current relation for a nanoscale MOSFET. IEEE Electron Device Lett, 2001, 22: 293

[3] Wang R, Zhuge J, Huang R, et al. An experimental study on carrier transport in silicon nanowire transistors: how close to the ballistic limit. 9th International Conference on Solid-State and Integrated-Circuit Technology, 2008: 46

[4] Lusakowski J, Knap W, Meziani Y, et al. Electron mobility in quasi-ballistic Si MOSFETs. Solid State Electron, 2006, 50: 632

[5] Widiez J, Poiroux T, Vinet M, et al. Experimental comparison between sub-0.1 μm ultrathin SOI single- and double-gate MOSFETs: performance and mobility. IEEE Trans Nanotechnol, 2006, 5: 643

[6] Cros A, Romanjek K, Fleury D, et al. Unexpected mobility degradation for very short devices: a new challenge for CMOS scaling. IEDM Tech Dig, 2006: 663

[7] Datta S. Electronic transport in mesoscopic systems. Cambridge University Press, 1995

[8] McKelvey J P, Longni R L, Brody T P. Alternative approach to the solution of added carrier transport problems in semiconductors. Phys Rev, 1961, 123: 51

[9] Gildenblat G. One-flux theory of a nonabsorbing barrier. J Appl Phys, 2002, 91: 9883

[10] Cho K H, Suk S D, Yeoh Y Y, et al. Observation of single electron tunneling and ballistic transport in twin silicon nanowire MOSFETs (TSNWFETs) fabricated by top-down CMOS process. IEDM Tech Dig, 2006: 695

[11] Ghibaudo G. New method for the extraction of MOSFET parameters. Electron Lett, 1988, 24: 543

[12] Jeon J, Lee J, Kim J, et al. The first observation of shot noise characteristics in 10-nm scale MOSFETs. Symposium on VLSI Technology, 2009: 48