Extraction of Ballistic Parameters in 65 nm MOSFETs

Junsoo Kim, Jaehong Lee, Yongmin Kwon, Byung-Gook Park, Jong Duk Lee, and Hyungcheol Shin

***Abstract*—The channel backscattering coefficient and injection velocity have been extracted experimentally in 65 nm MOSFETs. Thanks to an experimental extraction methodology taking into account multi-subband population, we demonstrate that the short channel ballistic efficiency is slightly greater than long channel ballistic efficiency.**

***Index Terms*—Channel backscattering coefficient, injection velocity, ballistic efficiency, MOSFET**

I. INTRODUCTION

Channel lengths ($L_{channel}$) and supply voltages of MOSFETs are decreasing, and a key issue is to maximize the drain current (I_{ds}) for short-channel, low voltage devices. Identifying the limiting I_{ds} value as channel length approaches zero is an important issue that has been examined both experimentally and theoretically. As devices continue to shrink in size, they may become so small that carriers might traverse an active region without scattering. Under such conditions, carriers could move in a ballistic manner and cross a short, high-field region, a neutral region, or a thin, neutral region. Thus, we examine the ballistic parameter to determine whether ballistic transport is occurred in real devices.

Electrons are injected from a source into a channel across a potential barrier whose height is modulated by gate voltage. Carriers drift across such a channel and are collected by the drain. The source-channel barrier is well known, and routinely considered when treating drain-induced barrier lowering or weak inversion operations. The barrier also exists above threshold voltage, but the channel charge screens the gate voltage, so that the gate voltage has less influence on the surface potential and the transconductance drops below its bipolar limit. This analogy between MOSFETs and bipolar transistors is well known but is frequently ignored in contemporary MOSFET analysis. However, transport across the source-channel barrier increases in importance, and will ultimately limit I_{ds}, as $L_{channel} \rightarrow 0$. As illustrated in Fig. 1, the source may be treated as a reservoir of thermal carriers that inject a flux (a_s) to the source-channel barrier.

A fraction (t_s) of the source flux transmits across the source-channel barrier and enters the channel while a second fraction (t_c) of the flux injected into the channel transmits across the barrier and exits the drain, and a third fraction ($r = 1 - t_c$) backscatters from the channel and reenters the source.

From Fig. 1, we may write the steady-state flux entering the drain as

$$a_d = a_s t_s t_c \qquad (1)$$

At the entrance to the channel (x = 0), we can deduce the electron density from positively and negatively directed fluxes as

$$n(0,y) = \frac{a_S t_S + r a_S t_S}{v_{inj}} = \frac{a_S t_S (1+r)}{v_{inj}} \qquad (2)$$

$$a_D = n(0,y) v_{inj} \frac{t_C}{(1+r)} = n(0,y) v_{inj} \frac{(1-r)}{(1+r)} \qquad (3)$$

$$I_d = W Q_{inv} v_{inj} \frac{(1-r)}{(1+r)} \qquad (4)$$

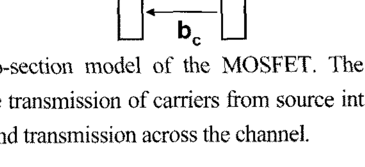

Fig. 1. Two-section model of the MOSFET. The first section describes the transmission of carriers from source into the channel and the second transmission across the channel.

Manuscript received Feb. 28, 2009; revised Mar. 11, 2009.
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Equation (4), the key product of this chapter, provides a simple expression for I_{ds} without invoking the use of mobility. In the ballistic limit ($r = 0$), the maximum current is controlled by the injection velocity at the thermal source. More generally, a key issue is to evaluate the channel backscattering coefficient (r). Fig. 2 shows a sketch of the lowest sub-band profile along a MOSFET channel. Channel backscattering takes place mainly in the kT-layer located at the source end of the channel. Reducing the channel backscattering coefficient (r) is desirable to achieve higher injection efficiency and therefore higher current drive. The channel backscattering coefficient can be determined from the kT-layer thickness (l) and the mean-free-path (MFP) for backscattering. Experimentally obtained backscattering parameters are summarized in Table 1 [5].

II. RESULTS AND DISCUSSION

To determine the origin of the drain current enhancement as channel length is decreased, we first extract the channel backscattering coefficient and the injection velocity at different gate lengths. Fig. 3 shows that, as channel length shrinks, the backscattering coefficient decreases, and the injection velocity increases. Fig. 4 exhibits extracted ballistic efficiency (BE = $1\text{-}r$ / $1\text{+}r$) as a function of gate length.

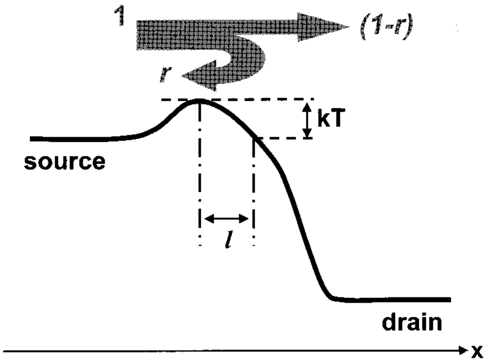


Fig. 2. Schematic diagram of carrier channel backscattering in MOSFETs.

Table 1. Summary of ballistic parameters extraction method [5].

Drain current expression for short channel devices in the quasi-ballistic regime.	$I_{DS} = WQ_i v_{inj}\left(\frac{1-r}{1+r}\right)$
Carrier injection velocity at the channel entrance.	$v_{inj} = \sqrt{\frac{2kT}{\pi m^*}}\frac{F_{1/2}(\eta_F)}{F_0(\eta_F)} = \left(\frac{4}{3}\sqrt{\frac{2}{q\pi}}\frac{\hbar}{m_t}\right)\sqrt{\frac{1}{1+r}}\sqrt{Q_i}$
Expression for the backscattering coefficient	$\frac{1-r}{(1+r)^{3/2}} = \frac{I_{ds}}{B(Q_i)^{3/2}}$

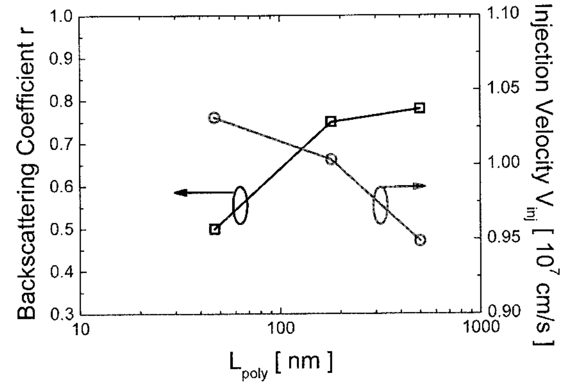


Fig. 3. The channel backscattering coefficient and the injection velocity for different gate lengths.

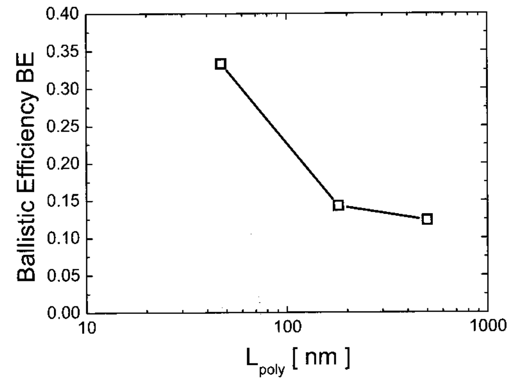


Fig. 4. The ballistic efficiency as a function of gate length.

A short channel device is more ballistic than a long channel device, and the ballistic change is evidence of drain current gain. Channel region band structure determines the extension of the kT layer, and Fig. 5 shows the channel backscattering coefficient as a function of $V_{gs} - V_{th}$ with different V_{ds}. A small backscattering coefficient is observed at higher V_{ds}, because increasing the V_{ds} produces an increase in the underlying channel potential drop so that l becomes smaller. The I_{ds} in Table 1 represent intrinsic drain current.

Thus, source/drain resistance is corrected by measured

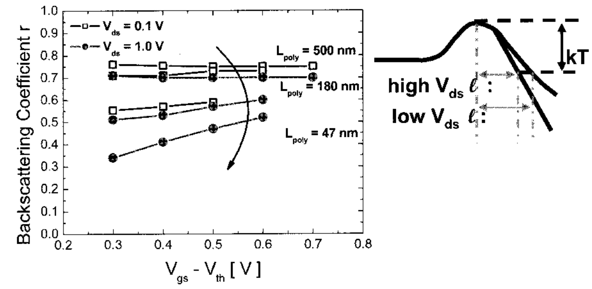


Fig. 5. The channel backscattering coefficient as a function of $V_{gs} - V_{th}$ with different V_{ds}.

drain current to extract accurate ballistic parameters. However, Fig. 6 shows that errors were less than 5 percentage between corrected and uncorrected values. The source/drain resistance effect can be ignored in the channel backscattering coefficient. A λ / l ratio is plotted versus L_{poly} in Fig. 7. A λ / l ratio is extracted from backscattering coefficnet. As gate length shrinks, a sharper potential profile is observed and therefore a small l is obtained under the same V_{ds}. Temperature dependence of ballistic parameters is indicated in Fig. 8. Notice that injection velocity increases with temperature because the population of the energetic carriers is increased. However, ballisticity is degraded at high temperature due to enhanced scattering probability in the channel. Thus, occupation of states when $k_x < 0$ is enhanced and the backscattering coefficient increases. A λ / l ratio is plotted versus temperature in Fig. 9. The increases in λ / l at low temperatures are mainly to the result of low temperature increases in mean-free-path.

III. CONCLUSIONS

Applying an experimental extraction methodology, to short channel MOSFETs, we have obtained the channel backscattering coefficient and injection velocity. And we can observe no significant channel backscattering coefficient difference between R_{SD} corrected and uncorrected values.

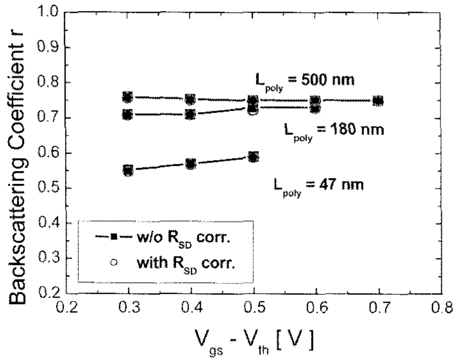


Fig. 6. The channel backscattering coefficient as a function of $V_{gs} - V_{ds}$. We can neglect R_{SD} effect.

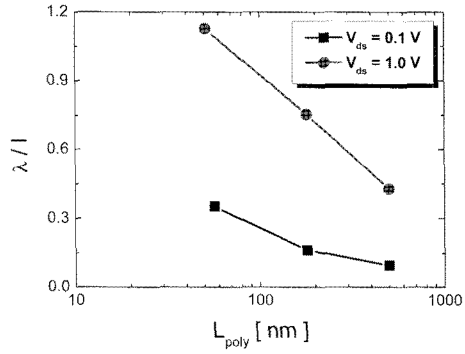
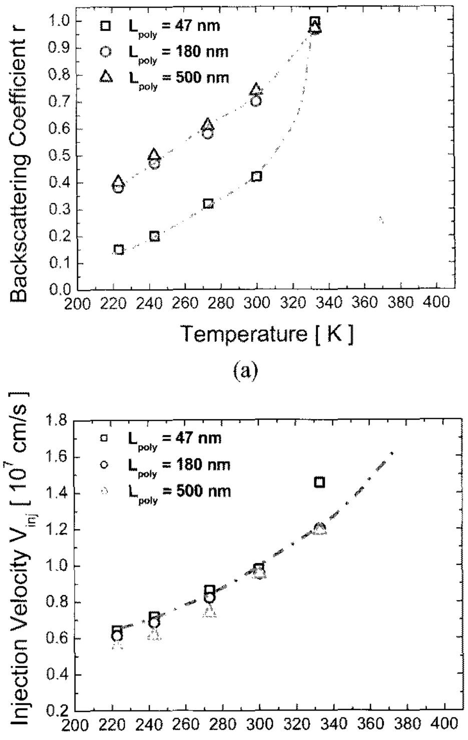


Fig. 7. λ / l ratio is plotted versus gate length.



(a)

(b)

Fig. 8. The temperature dependence of ballistic parameters.

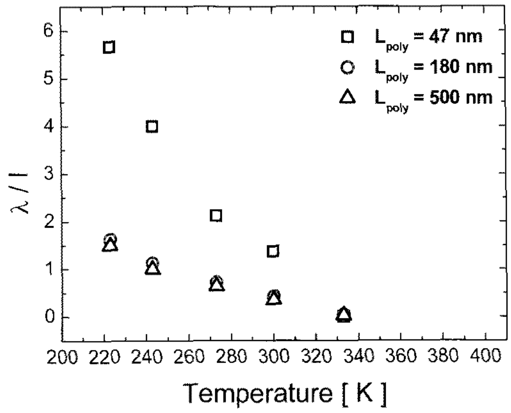


Fig. 9. λ / l ratio versus temperature.

ACKNOWLEDGMENTS

This work was supported Samsung Electronics Ltd. and Nano Systems Institute.

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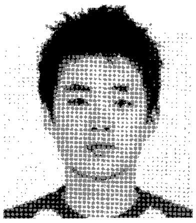

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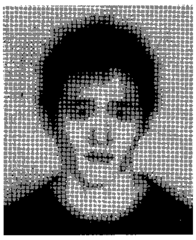

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