Electron Transport in MOSFET's Inversion Layer under High Electric Field

Masayasu Tanaka, Hiroaki Ueno, Osamu Matsushima and Mitiko Miura-Mattausch
Graduate School of Advanced Sciences of Matter, Hiroshima University
1-3-1, Kagamiyama, Higashi-Hiroshima 739-8530, Japan

Introduction: Understanding of the carrier transport in metal oxide semiconductor field-effect transistors (MOSFETs) is one of the most important tasks for predicting their performance. In this work, we performed the time-of-flight (TOF) experiment to investigate the high-electric-field electron transport in inversion layer of a MOS device.

Experiments: For the experiment, a special MOS device, which can generates uniform tangential electric field $E_{//}$ at inversion layer is required.[1] The device structure using in our TOF experiment is depicted in Fig. 1(a). The electric field in normal and tangential direction to the silicon/silicon-dioxide interface of this device can exactly be estimated by simple formulae.[1] The specification of the device is also written in Fig. 1(a). The calculated tangential electric field along the interface with 2D device simulator is shown in Fig. 1(b). It can be confirmed that a uniform tangential electric field is impressed under all the resistive gate region. As can be seen in Fig. 1(a), there are two laser intake apertures (far from and near the drain) in the device. Electron packets are excited near the silicon/silicon-dioxide interface by pulsed-laser irradiation through both apertures and then drift into the drain. We can determine the electron drift velocity (v_d) of the excited electron packets by measuring the flight time of electron packets in the TOF device.

Results and Analyses: Figure 2 shows the measured v_d - $E_{//}$ characteristics for various effective normal electric field $E_{\perp,\mathrm{eff}}$. Inversion electron density n_{inv}, which depends on laser intensity and can be estimated from the measured signal level, is about 1.3×10^{11} cm^{-2}. The results of Cooper & Nelson[1] and Coen & Muller[2] are also depicted. We extrapolated the electron saturation velocity v_{sat} and the electron mobility μ_0 from the measured characteristics using the equation[3] in Fig. 2. The extrapolated v_{sat} in the [110] transport direction is 6.5 $\times$ 10^6 cm/s. This v_{sat} is close to the result of Coen & Muller ($v_{\mathrm{sat}} = 5.0 \times 10^6$ cm/s), which was measured with resistive gate MOSFETs fabricated on a (100) silicon substrate. On the other hand, Cooper & Nelson have

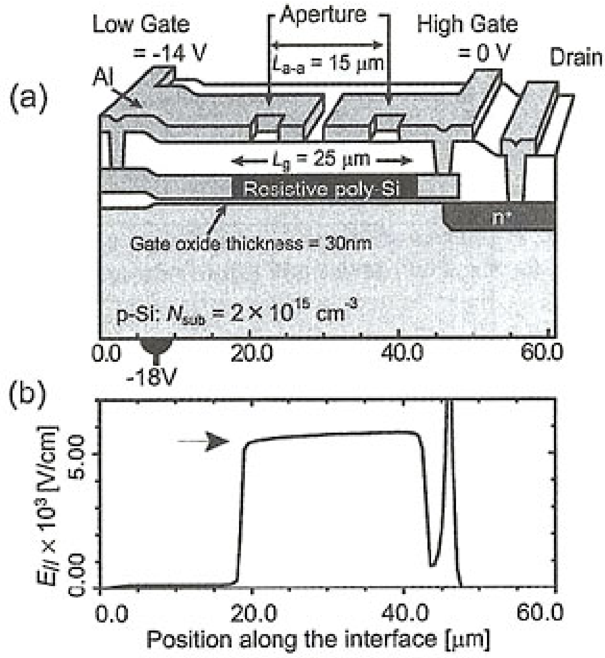


Figure 1: (a)Schematic diagram of a cross section of TOF device. (b)Simulation result of the tangential electric field at inversion layer.

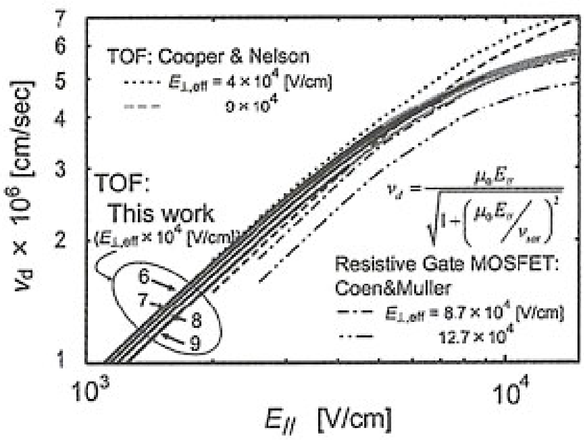


Figure 2: Measured electron drift velocity as a function of tangential electric field. The results of Cooper & Nelson and Coen & Muller are depicted together. The numerals in this figure represent the values of $E_{\perp,\mathrm{eff}}$.

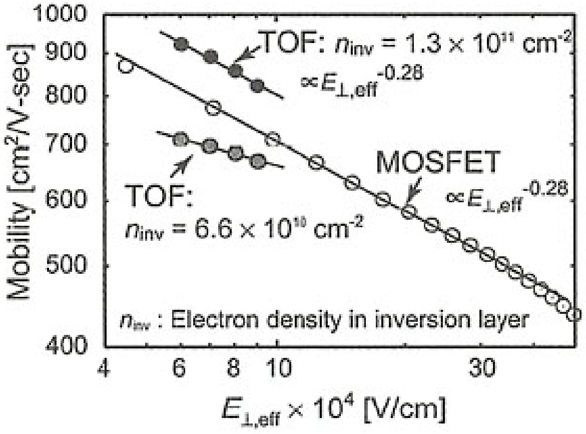


Figure 3: Measured electron mobility as a function of $E_{\perp,\mathrm{eff}}$ for the TOF device and a conventional MOSFET.

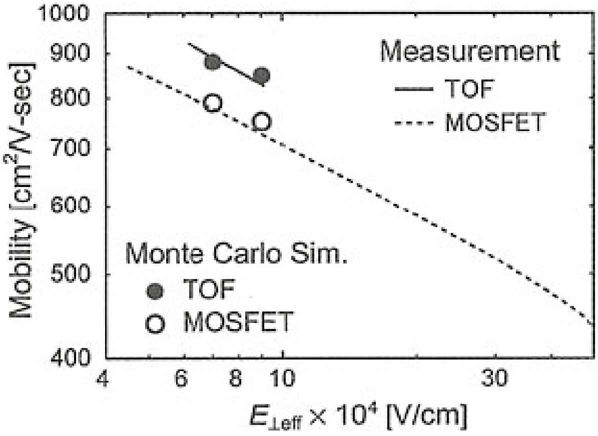


Figure 4: Comparison between the measured characteristics and the Monte Carlo simulation results of $\mu - E_{\perp,\mathrm{eff}}$.

reported v_{sat} of 9.2×10^6 cm/s in the [011] direction with their TOF experiment. Their v_{sat} is quite similar to that of the bulk Si measurement of 1×10^7 cm/s.[4,5]

The measured electron mobility μ as a function of effective normal electric field $E_{\perp,\mathrm{eff}}$ is shown in Fig. 3. The mobility of a MOSFET fabricated on the same chip is shown for comparison. Figure 3 shows the electron mobility of the TOF experiment is dependent on the inversion electron density n_{inv}. The electron mobility starts to fall off as n_{inv} becomes small and approaches to the substrate impurity concentration. The reduction of the mobility for low electron density is due to the Coulomb scattering. Figure 3 also shows that the mobility of the TOF device with n_{inv} of 1.3×10^{11} cm^{-2} and the conventional MOSFET exhibit the universal relationship of the phonon scattering ($\propto E_{\perp,\mathrm{eff}}^{-0.28}$). However, the mobility of the TOF device can be higher than that of the conventional MOSFET. We attribute the difference between the TOF device and the MOSFET to the different sub-band structures of electrons. Only the applied bias determines the sub-band structure in the inversion layer for the TOF-device case, whereas highly induced channel electrons modify the sub-band structure for the MOSFET case. The sub-band structure has a direct impact on the carrier transport in inversion layer.[6] To investigate the influence of the difference in the sub-band structure, the Monte Carlo device simulation is performed. Our Monte Carlo device simulator can theoretically deal with carrier scattering processes relating to the sub-band structure in inversion layer. Figure 4 shows the $\mu - E_{\perp,\mathrm{eff}}$ characteristics obtained from the measurement and the Monte Carlo simulation. The results of the Monte Carlo simulation reproduce the enhanced mobility measured with the TOF device as compared with the MOSFET. Thus, we can identify that the reason of the higher mobility observed with the TOF device is due to the properties of the sub-band structure such as the larger energy difference between each sub-band level and the broadish wave function of electron in inversion layer.

References

[1] J. A. Cooper, Jr. and D. F. Nelson: J. Appl. Phys. **54** (1983) 1445.

[2] R. W. Coen and R. S. Muller: Solid-State Electron. **23** (1980) 35.

[3] R. S. Huang and P. H. Ladbrooke: J. Appl. Phys. **48** (1977) 4791.

[4] C. Canali, G. Ottaviani and A. A. Quaranta: J. Phys. & Chem. Solids **32** (1971) 1707.

[5] C. Jacoboni, C. Canali, G. Ottaviani and A. A. Quaranta: Solid-State Electron. **20** (1977) 77.

[6] T. Ando, A. B. Fowler and F. Stern: Rev. Mod. Phys. **54** (1982) 437.

Electron Transport in MOSFET's Inversion Layer under High Electric Field

M. Tanaka, H. Ueno, O. Matsushima and M. Miura-Mattausch
Graduate School of Advanced Sciences of Matter, Hiroshima University
1-4-1 Kagamiyama, Higashi-Hiroshima, 739-8527, Japan
Phone: +81-824-24-7637, Fax: +81-824-22-7195
E-mail: tanakama@hiroshima-u.ac.jp

Time-of-Flight (TOF) experiment is an accurate measurement method to measure the carrier velocity in silicon MOS device.

1. Achieving the accurate measurement of the carrier transport in MOSFET's inversion layer with TOF experiment.
   - Normal and tangential electric field dependency of electron drift velocity
   - Effective normal electric field dependency of electron mobility

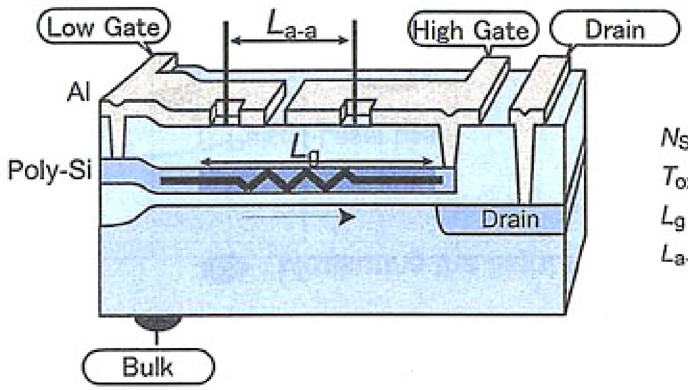
2. Understanding of the measured characteristic of the enhanced mobility in TOF device

[Methods]

The features required for TOF device

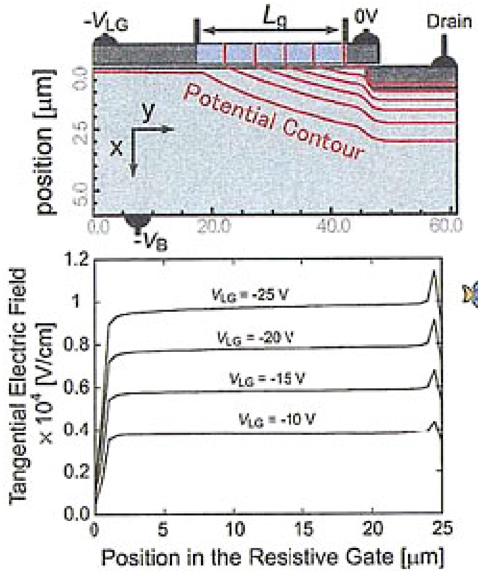
1. Constant tangential electric field in the channel
   --> Having a resistive gate

2. Electrons generated by the photoelectric effect
   --> There are two laser intake apertures



$N_{SUB} = 2\times10^{15}$ cm^{-3}
T_{ox} = 30 nm
L_g = 25 μm
$L_{a\text{-}a}$ = 15 μm

Simulation results of potential and electric field
(Device simulator, MEDICI)



Potential contour
Linear profile to the tangential (y) direction

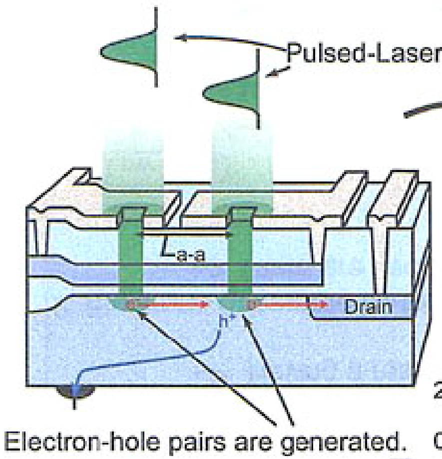
Tangential electric field

$$E_{//} = \frac{V_{LG}}{L_g}.$$

Uniform under the whole active region.

How to measure the electron drift velocity

Measuring the flight time of photo-exited electron packets running along the interface in TOF device.



Measured signals of Electron packets at drain electord.

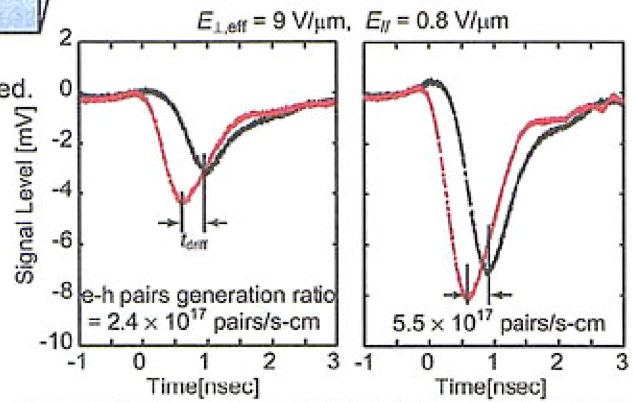
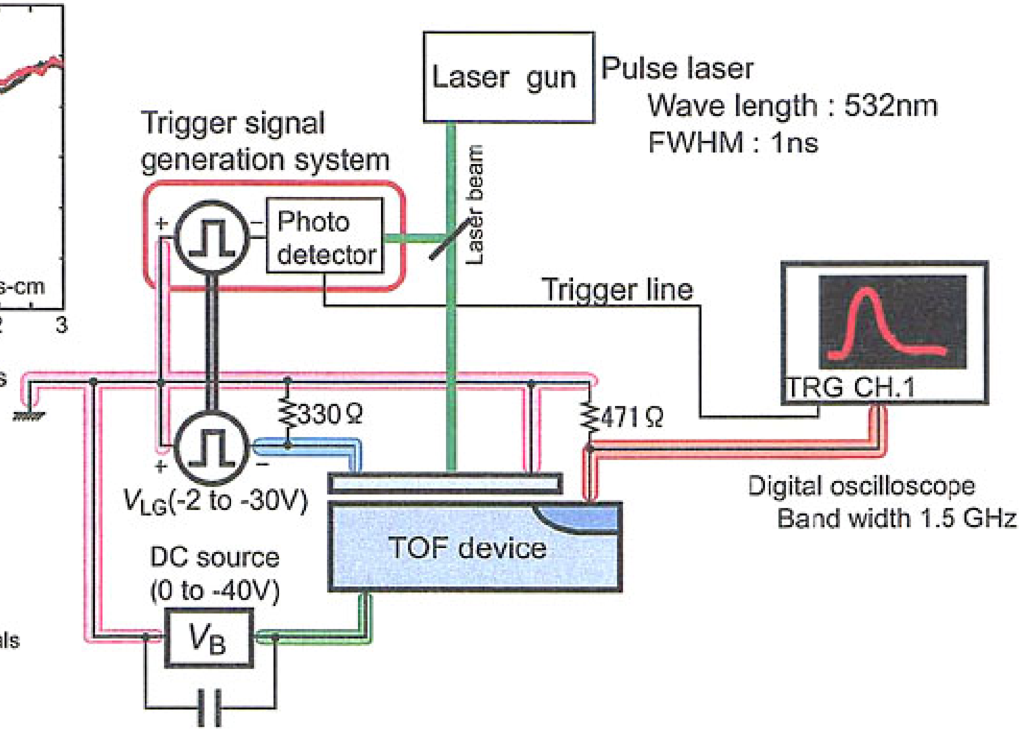


Figure: Measured photo-excited electron packets signals arriving at the drain electrode.

Experimental Setup



Electron drift velocity can be determine by measured flight-time of electron packets in TOF device.

Electron Drift Velocity

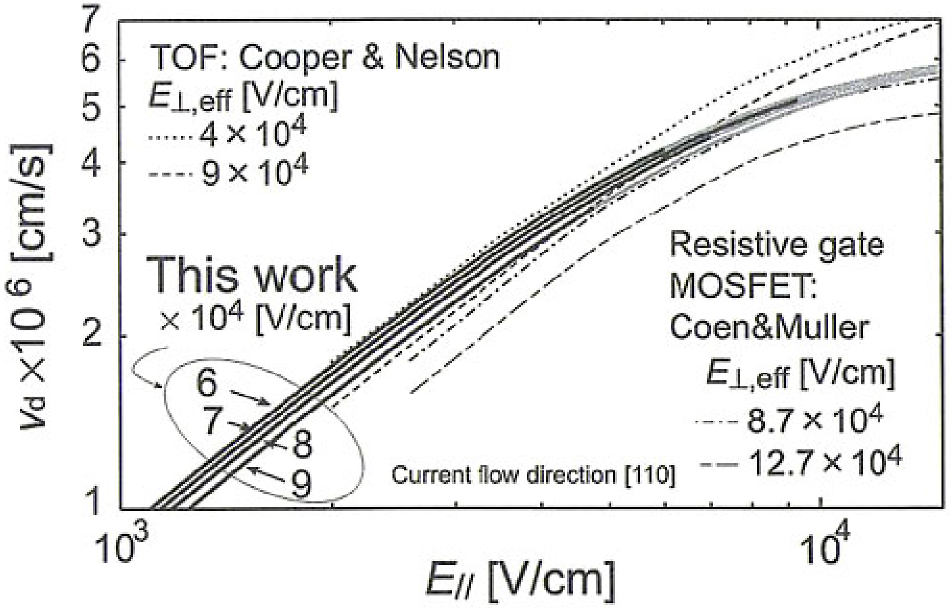
$$v_d = \left.\frac{L_{a\text{-}a}}{t_{drift}}\right|_{E_{//}=\mathrm{const}}$$

1. Measuring the time difference t_{drift} of two electron packet signals arriving at the drain electrode.
2. t_{drift} is time for electrons to run the distance $L_{a\text{-}a}$.

[Measurements]

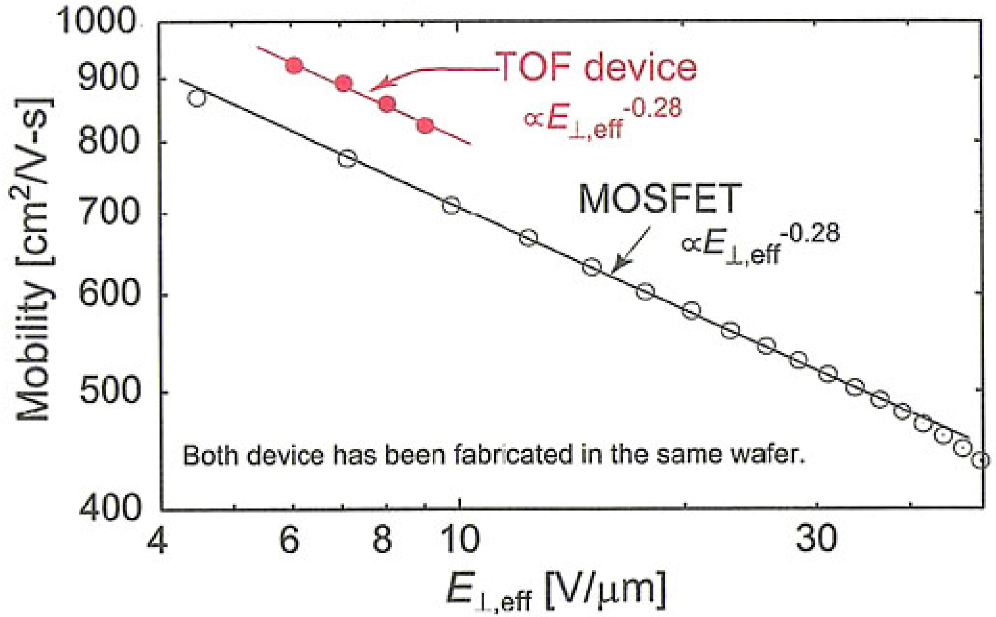
Time-of-Flight experiment

Electron velocity versus tangential electric field



Time-of-Flight experiment

Electron mobility versus effective normal electric field



- Our measured v_d - $E_{//}$ characteristics are well reproduced by the following theoretical expression.

$$v_d = \frac{\mu_0 E_{//}}{\sqrt{1+\left(\mu_0 E_{//} / v_{sat}\right)^2}}$$

- Extracted electron saturation velocity is

v_{sat} = [6.0 - 6.5] × 10^6 cm/s.

- Electron velocity (same as for mobility) depends on $E_{\perp,eff}$.

The dependence is arranged in next figure.

- Comparison of channel mobility between TOF device and MOSFET
- Mobility of both device has same dependence $\propto E_{\perp,eff}^{-0.28}$.
- Measured mobility with TOF experiment becomes higher than that of MOSFET.

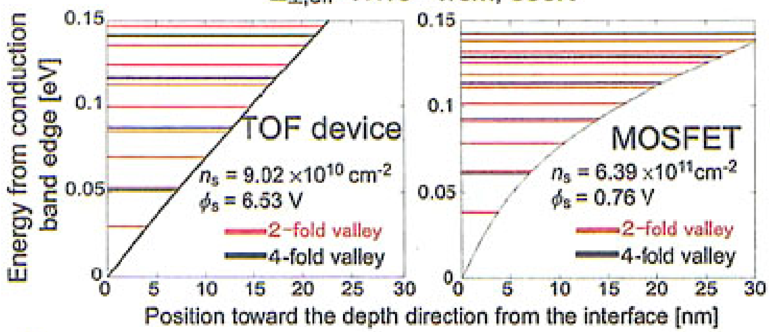
==> The reason is attributable to the device structure.

[Analysis]

Calculated sub-band structure in inversion layer of TOF device and MOSFET

(Solving Schrodinger equation and Poisson equation)

$E_{\perp,\mathrm{eff}}=7\times10^4$ V/cm, 300K



- Wider wave function at the ground state for TOF device.
- Larger energy difference between each energy level for TOF device.

Above two properties diminished the scattering ratio of electron in inversion layer

Scattering rate of electrons in inversion layer due to acoustic phonons

$$\frac{1}{\tau_{\mathrm{ac}}}=\frac{k_B T D_{ac}^2 m^{*}}{\rho \hbar^3 s_l^2}\cdot\frac{1}{2b_{mn}}$$

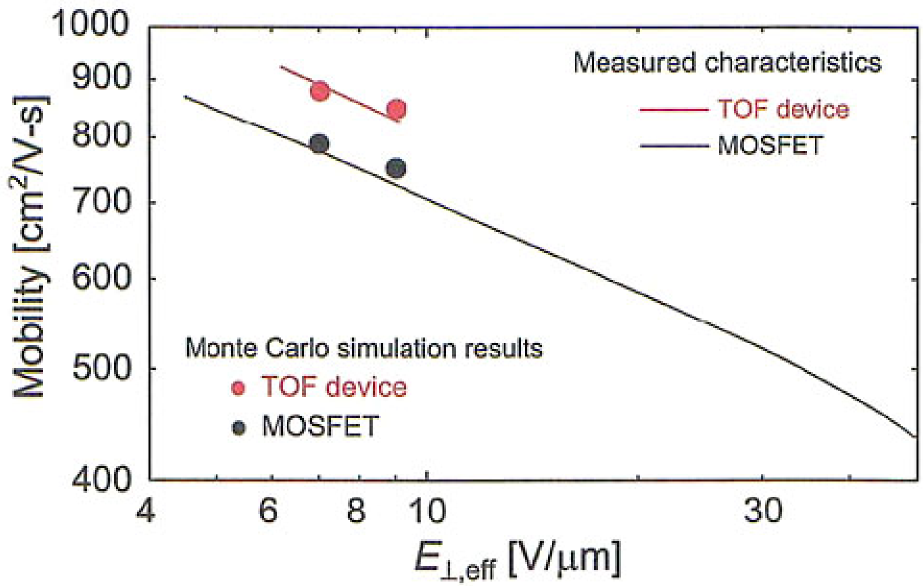
b_{mn} : Width of a wave function of electron

Scattering rate of electrons in inversion layer due to optical phonons.

$$\frac{1}{\tau_{\mathrm{int}}}=\frac{n_v D_{ij}^2 m_j^{*}}{\rho \hbar^2 \omega_{ij}}\cdot\frac{1}{2b_{mn}}u(D)\left(N_q+\frac{1}{2}\mp\frac{1}{2}\right)$$

b_{mn} : Width of a wave function of electron
$u(D)$: Energy difference between each sub-band levels

Monte Carlo device simulation results and measured characteristics
Electron mobility versus effective normal electric field



- The Monte Carlo simulation results reproduce the measured characteristics of the enhanced mobility of TOF device.

[Conclusion]

Accurate measurement results of electron velocity versus tangential electric field can be obtained implementing the time-of-flight method.

Electron saturation velocity in inversion layer is about 6.5×10^6 cm/sec.

Mobility of the TOF device becomes higher than that of the MOSFET.

TOF device has characteristics of an enhanced mobility as compared with the MOSFET on its sub-band structure of electrons in inversion layer.