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Advanced split-CV technique for accurate extraction of inversion layer mobility in short channel MOSFETs

H. Irie and A. Toriumi*
Department of Materials Engineering, School of Engineering, The University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
TEL and FAX: +81-3-5841-7161 *E-mail: toriumi@material.t.u-tokyo.ac.jp

1. Introduction

It has been reported[1,2] that the accuracy of the extracted mobility is harmed in ultrathin gate MOSFETs (T_{ox}<1.5nm) due to a significant leakage current. From the viewpoint of suppressing the influences of leakage current, using MOSFETs with a shorter channel length is favorable[1] because I_{ch}/I_g is proportional to L^{-2}. However, the uncertainty of effective channel length (L_{eff}) due to an ambiguity of its definition and the V_g dependence brings a significant error in short channel MOSFETs, where even a small error of L_{eff} introduces a severe artifact. Additionally, in short channel MOSFETs, parasitic capacitances (C_{ext}) and resistances (R_{ext}) deviate measured I_d and C_{gc} from ideal one and should be subtracted completely including those V_g dependences. These situations make it difficult to use short channel MOSFETs. As a result, previous authors have used relatively long channel length (L=10μm)[1,2]. In this study, we have developed a method to exclude both the uncertainty of L_{eff} and the V_g dependences of C_{ext} and R_{ext} in mobility extraction. This method allows accurate mobility extraction including short channel MOSFETs.

2. Measurement Samples

The samples were conventional n-MOSFETs with an n+ poly-Si gate. The channel length ranging from 1μm to 50μm and the channel width of 100μm were used. The substrate impurity concentration was undoped, N_A=2x10^{15} cm^{-3}. The gate oxide was SiO_2 formed by rapid thermal oxidation, and its thickness was 6nm.

3. The Double L_m Method

Mutual relationships among key parameters in mobility calculation can be described as follows:

$$\begin{aligned} L_m &= L_{eff}(V_g) + L_{ext}(V_g) \\ C_{gc} &= C_{ch}(V_g, L_{eff}) + C_{ext}(V_g) \\ R_{tot} &= R_{ch}(V_g, L_{eff}) + R_{ext}(V_g) = V_d / I_d \end{aligned} \qquad (1),$$

where L_m: mask length, L_{eff}: effective channel length, L_{ext}: mismatch between L_m and L_{eff} (generally called as ΔL but changed to prevent a confusion in this paper), C_{gc}: measured gate-channel capacitance, C_{ch}: intrinsic gate-channel capacitance, C_{ext}: parasitic capacitance, R_{tot}: total resistance (=V_d/I_d), R_{ch}: channel resistance, R_{ext}: parasitic resistance. Note that all the parasitic components (L_{ext}, C_{ext}, and R_{ext}) have V_g dependence and that only the intrinsic components (L_{eff}, C_{ch} and R_{ch}) change when L_m is changed.

In the proposed method, called as the double L_m method below, two MOSFETs with different L_m are used (L_{m1} and L_{m2}, L_{m1}>L_{m2}). And the characteristic parameters for mobility calculation are re-defined as the differences of each parameter between two devices as follows:

$$\begin{aligned} \Delta L &\equiv L_{m1} - L_{m2} = L_{eff1} - L_{eff2} \\ \Delta C_{ch}(V_g, \Delta L) &\equiv C_{gc1} - C_{gc2} = C_{ch1} - C_{ch2} \\ \Delta R_{ch}(V_g, \Delta L) &\equiv R_{tot1} - R_{tot2} = R_{ch1} - R_{ch2} \end{aligned} \qquad (2).$$

Note that these three parameters are determined experimentally without any assumptions and perfectly free from parasitic components. In equation (1), the parasitic components do not depend on L_m, so those are cancelled out when the subtraction is performed. Then, if we assume that the two MOSFETs have the same mobility and V_{th}, we can re-write the formula of effective mobility[1] by using the parameters in equation (2) as follows:

$$\begin{aligned} \mu_{eff} &= \Delta L^2 \cdot \frac{1}{\int \Delta C_{ch} \cdot dV_g} \cdot \frac{1}{\Delta R_{ch}} \\ &= (L_{m1} - L_{m2})^2 \frac{1}{\int (C_{gc1} - C_{gc2}) \cdot dV_g} \cdot \left(\frac{V_d}{I_{d1}} - \frac{V_d}{I_{d2}} \right)^{-1} \end{aligned} \qquad (3).$$

Comparing this method with the conventional split-CV technique, all parameters in equation (3) are free from parasitic components and determined experimentally. Therefore, we can extract accurate mobility independent of the presence of parasitic components.

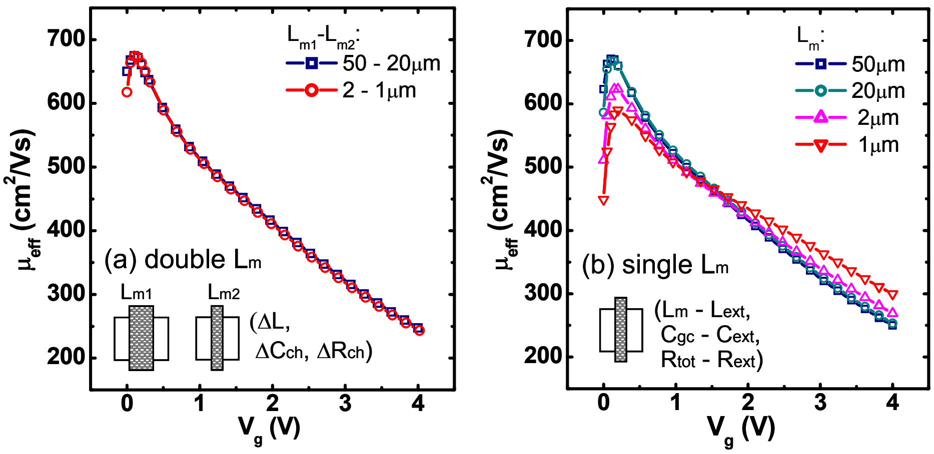

Fig.1. (a) Effective mobility extracted by newly developed double L_m method for two L_m sets, (L_{m1}-L_{m2}: 50-20μm) and (L_{m1}-L_{m2}: 2-1μm). The double L_m method uses two MOSFETs with different L_m and calculates the mobility by using the differences of parameters. One can see that the two curves agree with each other perfectly independent of L_m value. (b) Effective mobility extraced by the conventional single L_m method, where L_{ext} and R_{ext} were assumed to be constant and obtained by the channel resistance method[3], and C_{ext} was defined as C_{gc} at strong accumulation. A clear deviation is observed among different L_ms.

4. Results and Discussions

Figure 1(a) shows effective mobility extracted by newly developed double L_m method for two L_m sets, (L_{m1}-L_{m2}: 50-20μm) and (L_{m1}-L_{m2}: 2-1μm). One can see that the two curves agree with each other perfectly independent of L_m value. This indicates that the double L_m method allows accurate mobility extraction in short channel MOSFETs down to L_m=1μm. On the other hand, **Fig.1(b)** shows effective mobility extracted by the single L_m method (conventional split-CV technique with some considerations to parasitic components), where L_{ext} and R_{ext} were assumed to be constants and obtained by channel resistance method[3], and C_{ext} was defined as C_{gc} at strong accumulation. A clear deviation is observed among different L_ms.

Then, what causes the error in the single L_m method? We suspect that the error is necessarily introduced because the single L_m method ignores the V_g dependences of L_{ext}, C_{ext}, and R_{ext}. To verify this hypothesis, C_{ext} and R_{ext} were estimated on the assumption that L_{eff} is a constant. **Fig.2** and **Fig.3** show the V_g dependences of C_{ext} and R_{ext}, which were decomposed from C_{gc} and R_{ext} by using the constant L_{eff} obtained by the shift-and-ratio method[3]. Those figures clearly show that C_{ext} and R_{ext} are not constants but depend on the V_g. The single L_m method does not consider this V_g dependence, so that causes significant error when L_m is small, where C_{ext} and R_{ext} cannot be negligible.

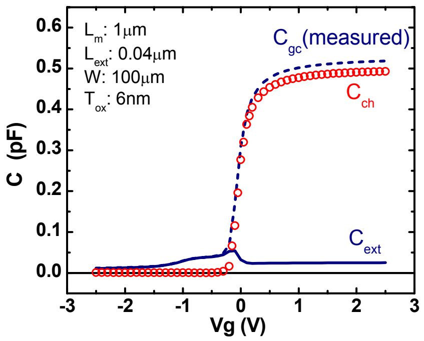

Fig.2. V_g dependences of C_{gc} (broken line), C_{ch}, and C_{ext} on the assumption that L_{eff} is a constant. The used L_{eff} was 0.96μm, estimated by the shift-and-ratio method[3].

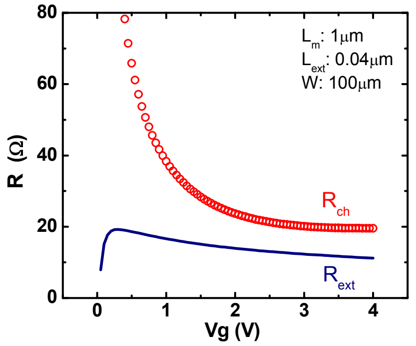

Fig.3. V_g dependences of R_{ch} and R_{ext} on the assumption that L_{eff} is a constant. The used L_{eff} was 0.96μm, estimated by the shift-and-ratio method[3].

Next, V_g dependence of L_{eff} is discussed. We can describe I_d characteristics as follows:

$$I_d = \frac{W}{L_{eff}} \cdot \mu \cdot qN_s \cdot (V_d - R_{ext} I_d) \qquad (4).$$

Therefore, once the accurate value of mobility and carrier concentration are obtained by the double L_m method, uncertain parameters are only L_{eff} and R_{ext}. Though the two parameters cannot be determined automatically, we can estimate those by fitting the calculated I_d to the measured one as considering both L_{eff} and R_{ext} are two fitting parameters. In addition, if we consider L_{eff} and R_{ext} are constant in a certain range of V_g and change the V_g range by a certain step, the V_g dependence of L_{eff} and R_{ext} can be obtained. Actually, we define correct values of L_{eff} and R_{ext} as those minimize the value of σ described as follows:

$$\sigma(L_{eff}, R_{ext}) \equiv \sum_{V_g} \left(\frac{I_{d\_calc}(L_{eff}, R_{ext}) - I_{d\_meas}}{I_{d\_meas}} \right)^2 \qquad (5).$$

Figure 4 shows the V_g dependences of L_{eff} and R_{ext}. One can see that L_{eff} shows a strong dependence on the V_g.

Through those investigations, it is clarified experimentally that all the parasitic components in mobility calculation, L_{eff}, R_{ext}, and C_{ext}, depend on the V_g and that the proposed double L_m method is valid to correct this effect completely.

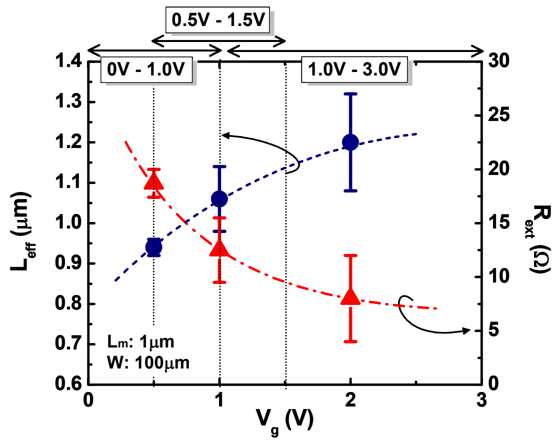

Fig.4. L_{eff} and R_{ext} which gives best fit between calculated I_d and measured I_d in three regions of V_g; V_g:0V-1.0V, V_g:0.5V-1.5V, and V_g:1.0V-3.0V. The two parameters show strong dependences on the V_g.

5. Conclusions

We have developed a simple but rigorous correction method for accurate mobility extraction. The method uses two MOSFETs with different channel lengths and re-defines differences of channel length, capacitance, and resistance as the parameters for mobility calculation. We also demonstrate the superiority of this method in short channel MOSFETs where parasitic components play a significant role. This method is a promising method to extract mobility in MOSFETs with ultrathin gate dielectrics because it gives accurate mobility even in short channel MOSFETs.

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