1. Introduction
Low field mobility is still one of the most important device parameters for scaled MOSFETs. It has recently been reported that MOSFETs with ultrathin gate oxides allowing significant direct tunneling current can exhibit lower inversion-layer mobility, because of several plausible scattering mechanisms inherent to ultrathin gate oxides, such as remote impurity scattering [1-3], poly Si/SiO2 interface roughness scattering [4] and MOS interface plasma scattering [5]. Actually, the decrease in Gm with a decrease in gate oxide thickness, Tox, has been observed in Tox region down to 1.5 nm [6]. However, the direct experimental evidence of mobility lowering with ultrathin gate oxides less than 3 nm has not been sufficient yet. This lack in the experimental result is attributable to the fact that high gate current prevents us from simply using the conventional split C-V method for mobility extraction.

This paper shows that, by modifying split C-V method under optimized device size and measurement parameters, inversion-layer mobility of MOSFETs with ultrathin gate oxides can be accurately determined, at least down to Tox of 1.5 nm. It is experimentally shown, as a consequence, that mobility decreases in lower Eeff or Ns (surface carrier concentration) region with a decrease in Tox, while little lowering of mobility is observed in higher Eeff or Ns region.

2. Measurement Method and Samples
There are mainly two difficulties in the mobility measurement for MOSFETs with high gate current. One is that the channel conductance cannot be determined simply by the derivative of ID with respect to VD, as shown in Fig. 1 and Fig. 2. However, if source and drain regions are symmetry for gate electrode and VD is sufficiently small, the current from the source to the gate and the current from the drain to the gate must be identical. Therefore, the drain conductance, GD, is determined by the derivative of (ID-IL)/2VD with respect to VD. No VG dependence of GD, shown in Fig. 2, validates the accuracy of GD.

The other difficulty in mobility measurement is that CG-VG measurement becomes inaccurate for Tox with higher leakage current, because of the significant influence of the channel resistance [7]. However, this problem is avoidable by using MOSFETs with relatively short gate length, which reduce the channel resistance. On the other hand, the gate length should be long enough to define the channel length. Fig. 3 shows CG-VG curves for L/W of 10 μm/10 μm as a parameter of measurement frequency. Almost no frequency dependence and the good agreement with CG determined by the two-frequency method [7] validate the accuracy of CG measurement. As a result, inversion-layer mobility can be determined by combining the above measurements of GD and CG(Ns) under the framework of the split C-V method.

N-channel MOSFETs used in the measurement have gate oxides of pure SiO2 with Tox of 3.5, 2.8, 2.2 and 1.5 nm for comparison with the universal mobility [8]. The substrate impurity concentration has been chosen to be as low as 2.3 x10^{16} cm^{-2} in order to reduce the influence of substrate impurity scattering. It has been confirmed from C-V characteristics that there is no significant penetration of As atoms in the poly-Si gate into substrates.

3. Experimental Results
Fig. 4 shows the experimental mobility with Tox of 3.5-1.5 nm and the universal mobility, as a function of Eeff. It is found that the mobility with Tox less than 2.8 nm decreases in low Eeff region with a decrease in Tox, while the mobility in higher Eeff region is in agreement with the universal mobility, down to 1.5 nm. Since the influence of gate current on C-V characteristics is larger in higher VD or Eeff region, this mobility lowering in low Eeff region is not attributed to any spurious effect due to gate current, but to some additional scattering mechanism inherent to thin gate oxides.

Fig. 5 shows the mobility component due to this additional scattering mechanism as function of Ns. Here, according to Matthiessen’s rule, the universal mobility and mobility limited by substrate impurity scattering [8] have been subtracted from the total mobility shown in Fig. 4. The mobility component due to the additional scattering is found to be almost constant, irrespective of Ns, which is not necessarily in agreement with the results of the theoretical calculations for several scattering mechanisms inherent to thin oxides [1-5]. Fig. 6 shows the Tox dependence of this mobility component and the theoretical mobility values limited by remote impurity scattering [1, 2] at Ns of 2.8 x10^{12} cm^{-2}. Although the experimental Tox dependence is similar with those in the theoretical calculations of remote impurity scattering [1, 2], these calculated mobility values have large variation in the amount. Thus, it is difficult, at present, to judge whether remote impurity scattering is responsible or not for the observed mobility lowering. As a result, the scattering mechanisms inherent to thin gate oxides, reported so far [1-5], seem not to be able to sufficiently explain the present experimental results in terms of the Ns dependence and the amount of mobility. Further theoretical studies on scattering mechanisms are needed to identify the physical origin of the mobility lowering.

4. Conclusion
It was experimentally found that inversion-layer electron mobility in the $T_{ox}$ region less than 3 nm decreases in lower $N_{s}$ or $E_{eff}$ region with a decrease in $T_{ox}$. This fact means the existence of some additional scattering mechanism associated with thinning gate oxides.

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References

Fig.1 Schematic diagram of current flow of MOSFETs with high gate tunneling current. Here, $I_{S} < 0$ and $I_{D} > 0$.

Fig.2 Drain, source and gate current (left axis) and drain conductance (right axis) as a function of $V_{G}$.

Fig.3 $C_{GS}$ – $V_{G}$ characteristics of MOSFETs with L/W of 10 $\mu$m/10 $\mu$m and $T_{ox}$ of 1.5 nm.

Fig.4 Inversion-layer electron mobility as a function of $E_{eff}$ with $T_{ox}$ of 3.5 – 1.5 nm. A solid line means the universal mobility.

Fig.5 Mobility component of additional scattering term at $N_{s}$ of 2.8 $\times$ $10^{12}$ $cm^{-2}$ as a function of $T_{ox}$. Solid lines show the calculated mobility by remote impurity scattering [1,2].