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The Highly Reliable Evaluation of Mobility in an Ultra Thin High-k Gate Stack with an Advanced Pulse Measurement Method

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Introduction

The evaluation of mobility (μ_{eff}) of high-k MISFET is important in selecting the next-generation gate stack. Due to a charge trapping phenomenon of high-k dielectric (Fig.1a), there is a great difficulty in precise measurement of μ_{eff} by the split C-V method[1]. Pulse measurement techniques have been proposed by several researchers[2,3], which enable the measurement of μ_{eff} with suppressed charge trapping. On the other hand, with aggressive thinning of gate dielectric, two problems arise when these pulse methods are used. One is the increase of the leakage current from the inversion layer (I_g) in strong inversion (Fig.1b). The other is the overestimation of the inversion carrier density (N_{inv}) due to drain voltage (V_d) in moderate inversion (Fig.1c). Therefore, a new pulse measurement technique is needed for the purpose of the reliable evaluation of μ_{eff} in a whole range of inversion state in an ultra thin high-k gate stack.

An Advanced Pulse Mobility Measurement Method

Fig.2 shows I_g divided by the channel current (I_{ch}) as a function of EOT. I_g and I_{ch} are estimated assuming 20% degradation of μ_{eff} and 10^{-2} times reduction of I_g compared to SiO_2 N-MOSFET. When EOT is less than 1.7nm, I_g becomes more than 10% of I_{ch}. Due to such a large I_g, neither drain current nor source current is identical to I_{ch}, meaning that a proper correction of I_g is needed for the derivation of I_{ch}. The other problem is the influence of applying V_d on the total inversion charge (Q_{inv}). The reduction of Q_{inv} (ΔQ_{inv}) due to V_d is expressed as $\Delta Q_{inv} \approx \frac{Q_{dpl}}{4\varphi_s} V_d + \frac{C_{ox}}{2} V_d$. The first and second terms represent deepening of the depletion layer and weakening of the electric field on gate dielectric, respectively. With EOT scaling, the second term depending on gate capacitance (C_{ox}) brings about the increase of ΔQ_{inv}. Fig.3 shows ΔQ_{inv} / Q_{inv} as a function of EOT. When EOT is less than 1nm, ΔQ_{inv} is comparable to 10% of Q_{inv}. Since the disregard for ΔQ_{inv} causes the miscalculation of μ_{eff}, Q_{inv} needs to be measured under the V_d condition where I_{ch} is measured. These two requirements of the reliable evaluation of μ_{eff} in thin EOT MOSFET will never be satisfied by the pulse methods proposed previously, which are designed only to suppress charge trapping.

A key to solving these problems is to monitor the time dependence of both source current (I_s) and drain current (I_d) during a rapid change from depletion to inversion (Fig.4). A separation between a transient current charging the inversion layer (I_d+I_s) and a steady current flowing through the channel ((I_d–I_s)/2) enables the simultaneous measurement of Q_{inv} and I_{ch}, resulting in the direct determination of μ_{eff} by a single pulse input (Fig.5). Even if I_g is comparable to I_{ch}, the contribution of I_g is subtracted by the algebraic operation (Fig.6). Fig.7 shows I_{ch} and Q_{inv} of SiO_2 N-MOSFET in a wide range of V_d. The results of our pulse method are in good agreement with those of the conventional DC method[4], indicating that ΔQ_{inv} is properly taken care of by our pulse method, no matter how steep the potential gradient of the channel area due to V_d is. Fig.8 shows a comparison between the split C-V method and our pulse method. In the case of HfSiON, μ_{eff} for electron by our pulse method is larger than that by the split C-V method, whereas there is no difference between the results of the two methods in the case of SiO_2, indicating that our pulse method suppresses charge trapping sufficiently, resulting in the precise μ_{eff} measurement of high-k MISFET.

The analysis of μ_{eff} in a whole range of inversion state

Another advantage of our pulse method is that it facilitates the μ_{eff} measurement under substrate bias conditions. When combined with control of substrate voltage (V_{sub}), the reliable evaluation of μ_{eff} provides a quantitative analysis of mobility determining factors in a whole range of inversion state. So, we focus on two issues for an ultra thin high-k gate stack. One is the influence of remote Coulomb scattering (RCS) due to fixed charges in bulk high-k, which is important in moderate inversion. The other is the effective field (E_{eff}) dependence of μ_{eff} in strong inversion, in which μ_{eff} is expected to be dominated by non-Coulombic scattering. Fig.9 shows μ_{eff} of HfO_2 N-MISFET as a function of N_{inv}. Owing to our pulse method, the reliable μ_{eff} values in moderate inversion ($N_{inv} \leq 10^{12}cm^{-2}$) were obtained without the miscalculation of Q_{inv} caused by thin EOT of HfO_2 film (0.8nm). The N_{inv} dependence of μ_{eff} ($\propto N_{inv}^{+0.3 \sim +0.5}$) is much weaker than that of mobility limited by substrate impurity scattering ($\propto N_{inv}^{+1}$) [5]. In addition, μ_{eff} decreases significantly with the increase of $|V_{sub}|$. These results indicate that it is true in the ultra thin HfO_2 MISFET that shortening the distance of inversion carriers from fixed charges enhances the impact of RCS. Moreover, Fig.10 shows the E_{eff} dependence of μ_{eff} of HfSiON N-MISFET in strong inversion, where the correction of I_g by our pulse method is indispensable to the precise μ_{eff} measurement. E_{eff}, irrespective of V_{sub}, uniquely determines μ_{eff} in the high E_{eff} region (>0.8MV/cm). This universal μ_{eff}-E_{eff} relation similar to the behavior in the SiO_2 system[5,6] verifies that μ_{eff} is dominated by non-Coulombic scattering (e.g. phonon scattering, roughness scattering). However, the E_{eff} dependence of μ_{eff} ($\propto E_{eff}^{-1}$) is different from that in the SiO_2 system, suggesting that the presence of Hafnium has an impact on the scattering mechanism dominant in this E_{eff} region.

Conclusions

We proposed an advanced pulse mobility measurement method, which enables the proper correction of I_g and takes into consideration the decrease of N_{inv} caused by the potential gradient of the channel area due to V_d. This method is the most reliable way to evaluate μ_{eff} applicable to the ultra thin (EOT~0.8nm) high-k MISFET. Owing to this pulse method, we strictly confirmed that mobility determining factors in the ultra thin Hf-based high-k MISFETs can be comprehensively understood in a whole range of inversion state, on the basis of accumulated knowledge concerning the SiO_2 system.

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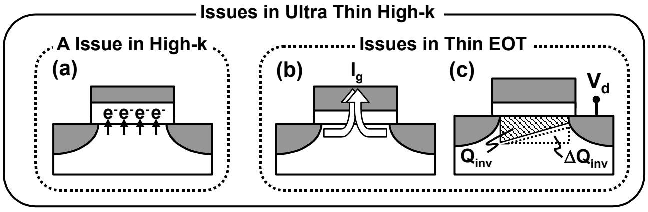

Fig.1 Schematic images of issues concerning the evaluation of μ_{eff} in an ultra thin high-k gate stack. **(a)** The charge trapping phenomenon. **(b)** The leakage current from the inversion layer (I_g). **(c)** The reduction of the total inversion charge (Q_{inv}) due to drain voltage. The inversion carrier density (N_{inv}) is defined as $N_{inv} \equiv Q_{inv}/(eLW)$.

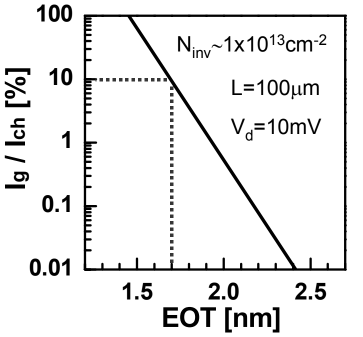

Fig.2 The EOT dependence of I_g divided by I_{ch} in strong inversion (N_{inv}~10^{13}cm^{-2}), assuming 80% mobility and 1/100 leakage current to SiO_2 N-MOSFET.

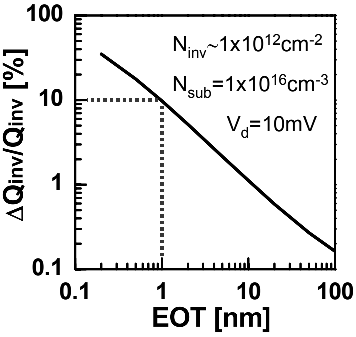

Fig.3 The EOT dependence of ΔQ_{inv} divided by Q_{inv} in moderate inversion (N_{inv}~10^{12}cm^{-2}).

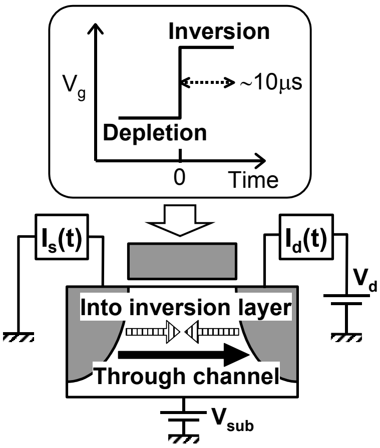

Fig.4 A schematic diagram of an advanced pulse mobility measurement method. Both I_s and I_d are monitored by current measurement systems with fast response. When the silicon surface changes rapidly from depletion to inversion, I_s and I_d consist of two components. One is charging the inversion layer. The other is flowing through the channel.

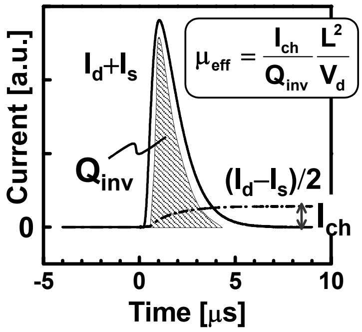

Fig.5 The time dependence of I_d+I_s and (I_d–I_s)/2. These currents correspond to the components charging the inversion layer and flowing through the channel, which determine Q_{inv} and I_{ch} simultaneously.

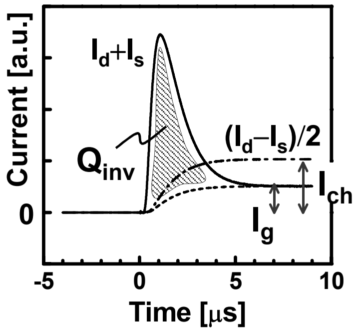

Fig.6 The time dependence of I_d+I_s and (I_d–I_s)/2 with large leakage current. Although the leakage component is superimposed on I_d+I_s, it can be estimated and subtracted by the algebraic operation.

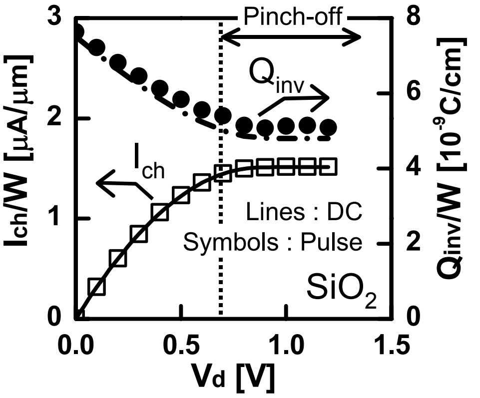

Fig.7 The V_d dependence of I_{ch} and Q_{inv} of SiO_2 N-MOSFET with L=100μm. V_d changes from a linear region to a saturation region.

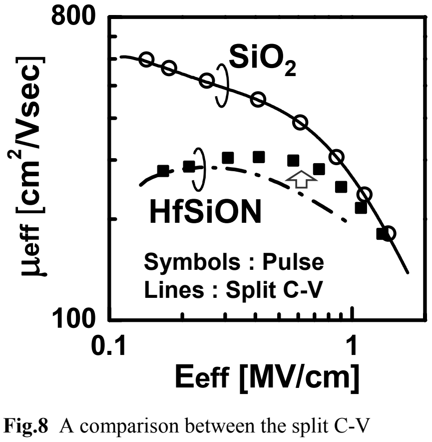

Fig.8 A comparison between the split C-V method and our pulse method. μ_{eff} for electron of SiO_2 and HfSiON MISFETs were measured by the two methods.

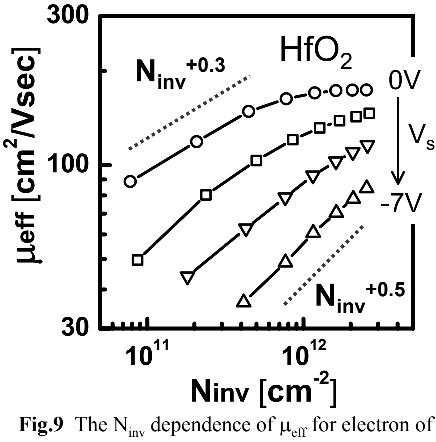

Fig.9 The N_{inv} dependence of μ_{eff} for electron of HfO_2 MISFET under various substrate bias conditions. EOT of HfO_2 film is 0.8nm.

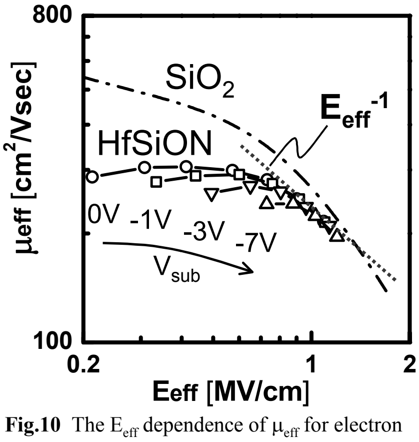

Fig.10 The E_{eff} dependence of μ_{eff} for electron of HfSiON MISFET under various substrate bias conditions.