Re-Examination on the Universality of Si-MOS Inversion Layer Mobility

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1. Introduction
The inversion layer mobility is one of the most important device parameters for Si MOSFETs. It has been known that the inversion layer mobility follows an universal characteristic when plotted as a function of effective normal fields, Eeff[1], where Eeff is defined by

$$E_{eff} = \frac{Q_{dep} + \eta \cdot Q_{inv}}{\varepsilon_{Si}}$$

Qdep and Qinv are the depletion and inversion layer charge densities, respectively. Since the universality is useful to describe the inversion layer mobility, it has been often referred as an index of device performances in various types of MOSFETs. However, the value of \(\eta\) in Eeff is not clearly defined. \(\eta=0.5\) is usually employed for n-MOSFET on (100) Si at room temperature, but it has been so far reported that \(\eta\) varies with surface orientation, inversion carrier type as well as temperature.

This paper re-examines the mobility universality of (100) MOSFET through a precise measurement with greatest cares, and demonstrates a new findings of \(\eta\), followed by the discussion of a relationship between \(\eta\) and dominant scattering mechanism.

2. Measurement Method and Samples
In quantitative analysis of \(\eta\), a precise measurement without any parasitic effects is indispensable. The split-CV method with a correction to Qinv under a finite drain bias gate-to-substrate capacitance, Cgb. After subtraction of pad-to-substrate capacitance related to a contact pad of the gate electrode must be subtracted before integral as shown in Fig.2(a). Using this method allows to obtain more accurate value and gate voltage dependence of Qdep than those obtained by using the well-known depletion approximation with \(\phi_{SB}=(\frac{Q_{dep}}{C_{gb}})^{\frac{1}{2}}\) (Fig.2(b)). Thus, all quantities except FET channel length are determined experimentally in the extraction of the mobility and Eeff. The source to substrate voltage, VSB, was used for changing Qdep and for investigating the universality. This method needs only a single device to study the universality, and we think it is better than using several samples with different doping concentrations, because the Si/SiO2 interface quality difference between doped samples would be concerned. To minimize the channel length uncertainty, a very long channel length n-MOSFET (L=500µm) was used. The oxide thickness (8.7nm) was thick enough to neglect any gate leakage current. The substrate impurity concentration was 2.2x10^{15}cm\(^{-3}\) and nearly uniform which was confirmed by SIMS and C-V analysis. It is worth while emphasizing again that the channel length is only needed in the mobility extraction as a parameter.

3. Results and Discussion
In Fig.3(a), the universal curves with \(\eta=0.5\) are shown in the linear scale. The three curves in the cases of different VSB apparently looks universal at a first glance. However, by enlarging a given part in Fig.3(a), a clear discrepancy between curves appears as shown in Fig.3(b), instead curves with \(\eta=0.35\) (Fig.3(c)) behave more universal. This indicates that \(\eta=0.35\) is more appropriate to describe the Eeff.
In order to define the most appropriate \( \eta \), the mobility difference, \( \delta \mu \), with different \( V_{SB} \) as a parameter of \( E_{eff} \) is plotted as a function of \( \eta \) as shown in Fig.4. One can easily find the minima around \( \eta = 0.35 \), and the position of minimum \( \delta \mu \) depends upon \( E_{eff} \). Since \( \eta \) should be determined to give a same mobility for different \( V_{SB} \), \( \eta \) at the minimum must be an appropriate value for the universality. In Fig.5, \( \eta \) is plotted versus \( E_{eff} \). Here, it should be noted that \( \eta \) clearly depends on \( E_{eff} \). This fact implies that the value of \( \eta \) should change depending upon the scattering mechanisms involved in a given \( E_{eff} \).

At the middle \( E_{eff} \) (0.2-0.4MV/cm), where it is considered that the phonon scattering dominates the mobility, \( \eta = 0.35 \) is appropriate from Fig.5. The phonon scattering model [3], using the variational wave function proposed by Stern and Howard [4] with the relaxation time approximation, can explain the value of \( \eta = 0.35 \) very well. On the other hand, at high \( E_{eff} \) (>0.4MV/cm) in Fig.4, \( \eta \) is about 0.4 or larger, and seems to increase with \( E_{eff} \). In this \( E_{eff} \) region, both phonon and surface roughness scattering determine the mobility. From the theoretical formulation given by Matsumoto and Uemura expects that \( \eta = 0.5 \) should be better for describing \( \mu_{SR} \) [5]. Assuming that \( \eta = 0.5 \) for high \( E_{eff} \) is correct, it is expected that \( \eta \) would increase with \( E_{eff} \) from 0.35 to 0.5, because the surface roughness scattering contributes to the total mobility more significantly at higher \( E_{eff} \). It is not easy to explain the \( E_{eff} \) dependence of \( \eta \) quantitatively because the correct value of \( \eta \) for describing \( \mu_{SR} \) is not known. However, Fig.5 indicates that \( \eta \) for describing \( \mu_{SR} \) is larger than \( \eta = 0.35 \) for \( \mu_{SR} \), and \( \eta \) varies with scattering mechanism.

In addition, Fig.5 shows that \( \eta \) slightly varies with applied \( V_{SB} \). And it means that the conventional universal relationship which always reproduces the mobility behavior irrespective of applied \( V_{SB} \) fails in the strict sense.

Finally, it should be mentioned about the conventional universality so far used for the standard analysis. This work does not intend to maintain the complete breakdown of the conventional universality. In fact, error is not so big at room temperature even if the conventional method is employed. Instead it would be emphasized that the universality strictly depends upon the definition of \( E_{eff} \) and \( \eta \) varies with scattering mechanism involved in the inversion layer. Thus, in the precise analysis and modeling of the scattering mechanism in the inversion layer, these facts should be taken into consideration.

### 4. Conclusions

The \( E_{eff} \) dependence of \( \eta \) has been demonstrated for the first time in the systematic experiments. Moreover, the direct evidence that the universality fails in the strict sense has been demonstrated experimentally. These facts should be taken into consideration for detailed analysis and modeling of scattering mechanism in the inversion layer.

### References