Extended Abstracts of the 1994 International Conference on Solid State Devices and Materials, Yokohama, 1994, pp. 883-885

Universality of Impact Ionization Rate in 0.1μm Si MOSFET

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We investigated impact ionization in Si MOSFET's with the gates as short as 0.1μm at room temperature. The impact ionization rate falls on a simple straight line regardless of the gate voltage V_{gs}-V_{th} and the gate length L_g when $\ln[I_{sub}/I_d(V_{ds}-V_{dsat})]$ is plotted versus $1/(V_{ds}-V_{dsat})$ where V_{dsat} is the drain saturation voltage. However, we found a deviation from the universal relation, which depends on gate voltage. We clarified the origin of the deviation and present a new method for obtaining the universal plot.

1. Introduction

Impact ionization in deep submicron MOSFET's has been studied in conjunction with non-stationary transport such as velocity overshoot[1),2)]. The method used to characterize impact ionization rate in these studies is based on pseudo-two-dimensional model that describes the maximum channel electric field E_m near the drain junction. The electric field E_m is roughly proportional to V_{ds}-V_{dsat}, where V_{dsat} is the voltage at the point where the carrier velocity saturates. Hence the impact ionization rates defined by the ratio of substrate current to drain current I_{sub}/I_d fall on a simple straight line regardless of the gate voltage V_{gs} and the gate length L_g, when $\ln(I_{sub}/I_d)$ is plotted versus $1/(V_{ds}-V_{dsat})$ [3)].

In this work, we investigated the impact ionization in deep submicron MOSFET's with the gate length L_g down to 0.1μm and found that such a universal straight line is not obtained for different V_{gs}. We clarified that the observed deviation dependent on V_{gs} is due to the difference in the saturation electric field E_{sat}, which is the channel electric field for the velocity saturation of electrons.

2. Experiments and Discussion

The two nMOSFET's used in this study (samples A and B) have LDD structures. Although the conditions of ion implantation for the channel and LDD are the same, the gate oxide thickness T_{ox} is different in these two samples (46Å for sample A and 32Å for sample B). Figure 1 shows the conventional plot $\ln[I_{sub}/I_d(V_{ds}-V_{dsat})]$ versus $1/(V_{ds}-V_{dsat})$ for an nMOSFET with L_g=0.15μm in sample A. We determined V_{dsat} using the method proposed by T.Chan et al., which is based on the idea that the loci of constant I_{sub}/I_d are parallel to the locus of V_{dsat} on the V_{ds}-I_d characteristics[3)]. One can find the deviation from the straight line for higher V_{gs}-V_{th} and/or lower V_{ds}-V_{dsat}. According to the analytical expression[4)]

$$I_{sub}=\frac{A_i}{B_i}lE_mI_d\exp[-\frac{B_i}{E_m}] \qquad (1)$$

I_{sub} is determined by the maximum electric field E_m at the drain edge. Hence the contribution of I_{sub} from other region leads to the increased impact ionization rate. However, the measured I_{sub} did not show any specific increase for the low E_m conditions where the deviation from the straight line occurs. In addition, similar deviations were observed for all the investigated nMOSFET's with L_g=0.1μm to 0.8μm in contrast to the result of T.Mizuno et al[2]. Thus we cannot attribute the deviations to the enhanced electron temperature in short channel MOSFET's with L_g near 0.1μm.

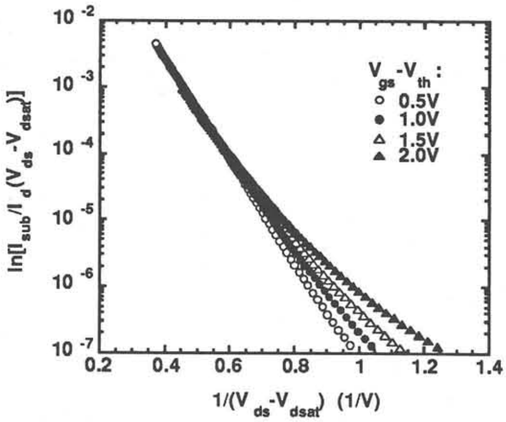

Fig.1 Plot of $\ln[I_{sub}/I_d(V_{ds}-V_{dsat})]$ versus $1/(V_{ds}-V_{dsat})$ for the sample A with L_g=0.15μm. Measured for $V_{gs}-V_{th}$ of 0.5V, 1.0V, 1.5V, and 2.0V.

The pseudo-two-dimensional model describes E_m as

$$E_m=\sqrt{\frac{(V_{ds}-V_{dsat})^2}{l^2}+E_{sat}^2} \qquad (2)$$

where l is the effective length of the velocity-saturation region[3]. Usually the E_{sat} term in Eq.(2) is omitted and the universal relation between impact ionization rate and $1/(V_{ds}-V_{dsat})$ is derived by introducing Eq.(2) into Eq.(1). In this case, we must include the E_{sat} term, because the deviation occurs for lower $V_{ds}-V_{dsat}$. We deduced the effective length l from the slope of the curve for $V_{gs}-V_{th}$=0.5V in Fig.1 and an empirical parameter $B_i=1.7\times10^6$V/cm[3]. However, a similar deviation as that in Fig.1 remains, if we introduce the constant $E_{sat}=4\times10^4$V/cm proposed by T.Chan et al. into Eq.(2) for the plot of $\ln[I_{sub}/(I_d \cdot E_m)]$ versus $1/E_m$[3].

To obtain straight lines, we must consider E_{sat} as a fitting parameter and introduce a larger E_{sat} into Eq.(2) for the curve of higher $V_{gs}-V_{th}$. The conventional method to determine V_{dsat} becomes incorrect, because the loci of constant I_{sub}/I_d are not parallel to the locus of V_{dsat}. We deduced a new V_{dsat} for each $V_{gs}-V_{th}$ from the measured V_{ds}

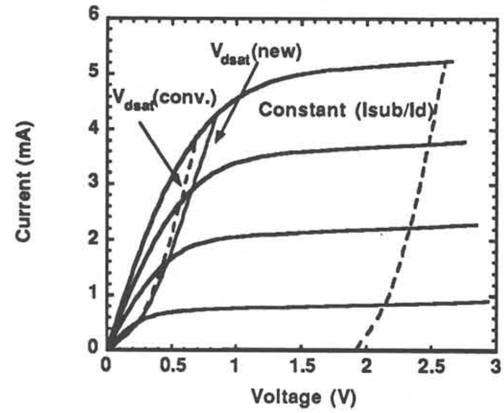

Fig.2 $V_{ds}-I_d$ characteristics of a 0.15μm nMOSFET for $V_{gs}-V_{th}$ of 0.5V, 1.0V, 1.5V, and 2.0V. The locus of V_{dsat}(conv.) is drawn parallel to that of constant I_{sub}/I_d according to the conventional method. The locus of V_{dsat}(new) shows the new V_{dsat} determined by the method we propose in this work.

on a constant I_{sub}/I_d locus according to

$$V_{dsat}=V_{ds}-l\sqrt{C-E_{sat}^2} \qquad (3)$$

where the constant C means E_m^2 for $V_{gs}-V_{th}$=0.5V. As shown in Fig.2, the difference between the new V_{dsat} and the former ones increases with $V_{gs}-V_{th}$. Figure 3 shows the plot of $\ln[I_{sub}/(I_d \cdot E_m)]$ versus $1/E_m$, where E_{sat} in Eq.(2) is considered to be a fitting parameter dependent on $V_{gs}-V_{th}$. One can find the recovery of universal relation. A similar procedure successfully recovered the universality in the plot for sample B which has a thinner gate oxide than sample A.

To confirm the validity of E_{sat} deduced by the fitting of curves in Fig.3, we performed a simple estimation of E_{sat} from the effective surface mobility μ_{eff}. We deduced μ_{eff} from the measured channel conductance for a MOSFET with L_g=5μm fabricated on the same chip as the deep submicron MOSFET's we investigated, because the conductance of a long channel device is not affected by the parasitic resistance. We estimated E_{sat} by the empirical relation $E_{sat}=2\upsilon_{sat}/\mu_{eff}$, where υ_{sat} is the saturation velocity of electrons. Although the reported values of υ_{sat} scatter between 4×10^6cm/sec and 1×10^7cm/sec so far, we assumed υ_{sat} to be 7.0×10^6cm/sec. In Table1, we compared the results with E_{sat} obtained for a MOSFET with L_g=0.15μm in samples A and B by the fitting of impact ionization rate. The fairly good agreement of E_{sat} data supports that the deviation of the curves in Fig.1 is due to the gate voltage dependence of E_{sat}, which results from the degradation of mobility μ_{eff} by the normal electric field.

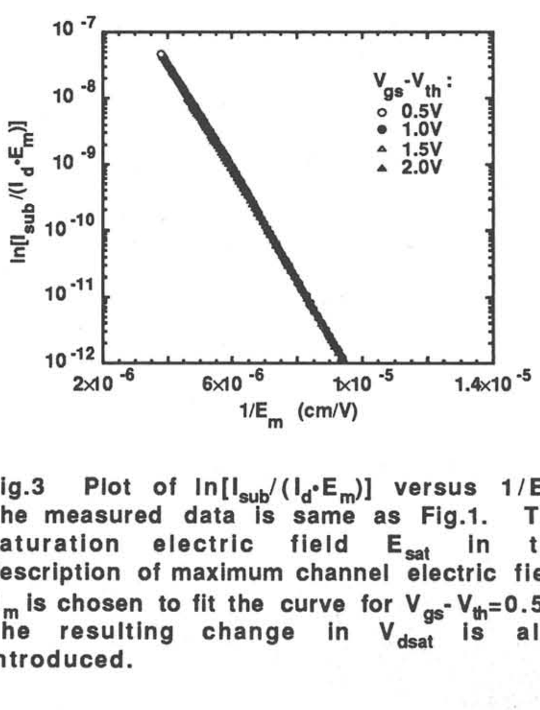

Fig.3 Plot of $\ln[I_{sub}/(I_d \cdot E_m)]$ versus $1/E_m$. The measured data is same as Fig.1. The saturation electric field E_{sat} in the description of maximum channel electric field E_m is chosen to fit the curve for V_{gs}-V_{th}=0.5V. The resulting change in V_{dsat} is also introduced.

3. Conclusion

For nMOSFET's with thin gate oxides, the universal relation is not obtained using the simple plot $\ln[I_{sub}/I_d(V_{ds}-V_{dsat})]$ versus $1/(V_{ds}-V_{dsat})$ and the conventional method to determine V_{dsat}. Universality can be restored by considering E_{sat} as a parameter dependent on the gate voltage, and modifying V_{dsat} for the description of maximum channel electric field E_m. The fitted E_{sat} for the recovery of universality agrees quite well with the estimated E_{sat} from the empirical relation for the υ-E curve and the measured effective mobility μ_{eff}. These results show that the pseudo-two-dimensional model is still useful for describing the maximum channel electric field E_m in deep submicron MOSFET's with gates as short as 0.1μm.

V_{gs}-V_{th}	1.0V	1.5V	2.0V
E_{sat}(f)[A]	6×10^4	7×10^4	8.5×10^4
E_{sat}(μ)[A]	5.8×10^4	6.6×10^4	7.7×10^4
E_{sat}(f)[B]	6×10^4	7.5×10^4	9×10^4
E_{sat}(μ)[B]	6.1×10^4	7.6×10^4	9.6×10^4

Table 1 The saturation electric field E_{sat} data obtained by the fitting are denoted by E_{sat}(f). Those estimated with the effective mobility μ_{eff} are denoted by E_{sat}(μ). These E_{sat} data are compared for each V_{gs}-V_{th} in samples A and B with L_g=0.15μm.

Acknowledgement

We thank T.Yamazaki and T.Fukano of the ULSI device technology laboratory, and the Wafer Process Division of Fujitsu for the fabrication of devices. We also thank K.Suzuki for stimulating discussions and Dr.S.Hijiya for his constant encouragement.

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