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# Statistical Performance-Instability Due to Three-Dimensional Nonuniformity of Dopant Atoms in a System of Many MOSFETs

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We have experimentally and analytically studied the influence of the statistical spatial-nonuniformity of dopant atoms on the threshold voltage $V_{th}$ in a system of many MOSFETs. According to experimental results and our analytical model, it is found that the nonuniformity of dopant atoms along the channel (the lateral nonuniformity) causes the unstable drain bias dependence of $V_{th}$. Moreover, the substrate bias dependence of $V_{th}$ fluctuates due to the vertical nonuniformity of dopant atoms which is perpendicular to the channel. Consequently, $V_{th}$ fluctuation is caused by the statistical spatial-nonuniformity of dopant atoms as well as their total-number variation in the channel depletion volume.

## 1 Introduction

With scaling the MOSFET dimensions down, we have experimentally and analytically demonstrated that the threshold voltage $V_{th}$ fluctuates due to the statistical total-number variation of dopant atoms in the channel depletion volume [1]. It is considered that this will become a serious problem in realizing future ULSIs [2]. In addition, the spatial distribution of the dopant atoms of the local region in the channel depletion volume is supposed to be statistically inhomogeneous, because the dopant atom number statistically and independently fluctuates

In this study, we have experimentally and analytically shown $V_{th}$ instability caused by the spatial nonuniformity of dopant atoms in a system of many MOSFETs.

## 2 Experimental

Using an 8192 MOSFET array in less than 0.7 $mm^{-2}$ [1], $V_{th}$ of an individual n-channel MOSFET can be measured. A MOSFET has a single drain structure in relatively uniform dopant distribution (p-well structure) whose peak concentration of $N_a=1\times10^{17}\ cm^{-3}$ is determined by the substrate bias sensitivity of $V_{th}$. The gate oxide thickness was 10 nm. The effective channel width was 1 $\mu$m and the effective channel length was varied from 0.5 $\mu$m to 0.3 $\mu$m. The measurement error of $V_{th}$ ($4\sigma$) was 0.5 mV in this study.

## 3 Model for Lateral and Vertical Nonuniformity of Dopant Atoms

In this section, we introduce the experimental method for evaluating the influence of spatial nonuniformity of dopant atoms on $V_{th}$. Here, we discuss the inhomogeneously distributed dopant atoms which are both parallel (the lateral nonuniformity shown in Fig. 1(a)) and perpendicular (the vertical nonuniformity shown in Fig. 1(b)) to the channel. Figures 1 (a) and (b) show the depletion layer edge by applying the drain and the substrate biases, respectively. The dopant numbers of regions [I] and [II] shown in Fig. 1 independently and statistically fluctuate in both the ion-implantation and the dopant-diffusion processes. As a result, in a system of many MOSFETs, the spatial distribution of dopant atoms becomes statistically inhomogeneous. At first, the influence of the lateral nonuniformity of dopant atoms on $V_{th}$ can be evaluated by applying the drain bias $V_d$, that is, by increasing the drain depletion width, as shown in Fig. 1(a). $V_{th}$ at very small $V_d$; $V_{th0}$ is given by the dopant atoms of both regions [I] and [II], that is $V_{th0} = q(n_1 + n_2)/[W_{eff}C_{ox}(L_{eff} - W_0)] + 2\phi_B + V_{FB}$ where $n_1$ and $n_2$ are the dopant numbers of regions [I] and [II], q the elementary charge, $W_{eff}$ the effective channel width, $L_{eff}$ the effective channel length, $W_0$ the drain depletion width, $C_{ox}$ the gate capacitance, $2\phi_B$ the surface potential, and $V_{FB}$ the flatband voltage [2]. On the other hand, $V_{th}$ at large $V_d$; $V_{thd}$ is determined by only $n_1$ of region [I], that is $V_{thd} = n_1/[W_{eff}C_{ox}L_{eff} - (W_0 + W_d)/2] +$

$2\phi_B + V_{FB}$, where $W_d$ is the drain depletion width. Since $n_1$ and $n_2$ indepently and statistically fluctuate, the correlation coefficient between $V_{th0}$ and $V_{thd}$ becomes smaller with increasing $V_d$. Here, we introduce $\Delta V_{thd} \equiv V_{th0} - V_{thd}$. As a result, the influence of the lateral nonuniformity of dopant atoms on $V_{th}$ can be evaluated by measuring $V_d$ dependence of $\Delta V_{th}$ fluctuation; $\delta(\Delta V_{thd})$, which can be simply obtained by the variation of $V_{th0}$ and $V_{thd}$, as follows,

$$\delta(\Delta V_{thd}) = \delta V_{th0} \sqrt{\frac{W_d - W_0}{2L_{eff} - (W_d + W_0)}} \qquad (1)$$

where $\delta V_{th0}$ is $V_{th0}$ fluctuation.

Secondly, as shown in Fig. 1(b), the influence of the vertical nonuniformity of dopant atoms on $V_{th}$ can also be evaluated by increasing the substrate bias $V_{sub}$. $V_{sub}$ dependence of $V_{th}$ fluctuates with increasing the channel depletion width, because the vertical distribution of dopant atoms is statistically inhomogeneous. Namely, by measuring $V_{sub}$ dependence fluctuation of $V_{th}$ at $V_{sub}$; $V_{thb}$ minus $V_{th}$ at $V_{sub}$=0 V; $V_{th0}$ ($\equiv \Delta V_{thb}$), the vertical nonuniformity can be evaluated. This $\Delta V_{thb}$ fluctuation $\delta(\Delta V_{thb})$ can also be obtained by calculating the variation of both $V_{thb}$ and $V_{th0}$, as mentioned in Eq. (1). That is,

$$\delta(\Delta V_{thb}) = \frac{\delta n_1}{C_{ox} W_{eff}(L_{eff} - W_0)} \times \left[ \left( \frac{W_d - W_0}{L_{eff} - W_d} \right)^2 + \left( \frac{\delta n_2 (L_{eff} - W_0)}{\delta n_1 (L_{eff} - W_d)} \right)^2 \right]^{\frac{1}{2}} \qquad (2)$$

$\delta n_1$ and $\delta n_2$ are the dopant number fluctuations of regions I and II, respectively.

## 4 Results and Discussion

At first, we show the lateral nonuniformity of dopant atoms. Figure 2 shows the experimental data of the correlation of $V_{th}$ at various $V_d$ in an 8192 MOSFET array. Fig. 2(a) shows that $V_{th}$ has a good correlation in the case of small $V_d$ shift, but it was newly found that $V_{th}$ correlation decreases with increasing $V_d$, as shown in Fig. 2(b). In order to analyze this unstable $V_d$ dependence of $V_{th}$, the experimental data of $V_d$ dependence of $\Delta V_{thd}$ are shown in Fig. 3. $\Delta V_{thd}$ continues to increase by increasing $V_d$ and is enhanced with decreasing $L_{eff}$. The solid and the dashed lines in Fig. 3 show the calculated results of our analytical model mentioned in Sec. 3. and can explain all the experimental data well. Moreover, the influence of the lateral nonuniformity of dopant atoms on $V_{th}$ can be also evaluated by measuring the asymmetrical $V_{th}$ phenomena in exchanging the source and the drain terminals [3].

Statistical lateral-nonuniformity of dopant atoms can be directly verified by measuring the statistical fluctuation of $V_d$ dependence of $N_a$ obtained by $V_{sub}$ sensitivity of $V_{th}$. Figure 4 shows the correlation of $N_a$ at $V_d$=0.1 V and 1.5 V in an 8192 MOSFET array and that the correlation of $N_a$ decreases at large $V_d$ shift, whereas $N_a$ has a good correlation at small $V_d$ shift (not shown here). This is the direct experimental evidence for the lateral nonuniformity of dopant atoms.

Secondly, the influence of the vertical nonuniformity of dopant atoms on $V_{th}$ is shown in Fig. 5. The correlation of $V_{th}$ becomes smaller with increasing $V_{sub}$ shift. Figure 5 shows that $\Delta V_{thb}$ increases with increasing $V_{sub}$ and with decreasing $L_{eff}$. Our model shown by the solid lines can explain almost all experimental data. Therefore, the vertical inhomogeneous-distributed dopant atoms have been experimentally verified by this unstable $V_{sub}$ dependence of $V_{th}$, as well as the dopant number in the depletion layer volume has already been verified to be statistically fluctuated [1].

## 5 Conclusion

Using an 8192 MOSFET array, we have experimentally demonstrated that $V_{th}$ is affected by the statistical spatial-nonuniformity of dopant atoms in the channel depletion volume. The lateral and the vertical nonuniformity of dopant atoms induce unstable $V_d$ and $V_{sub}$ dependence of $V_{th}$ in a system of many MOSFETs, respectively. These results are enhanced with decreasing $L_{eff}$. Therefore, it is necessary to consider the spatially distributed dopant atoms as well as the statistical variation of dopant atom number, in designing MOSFETs in ULSIs.

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### References

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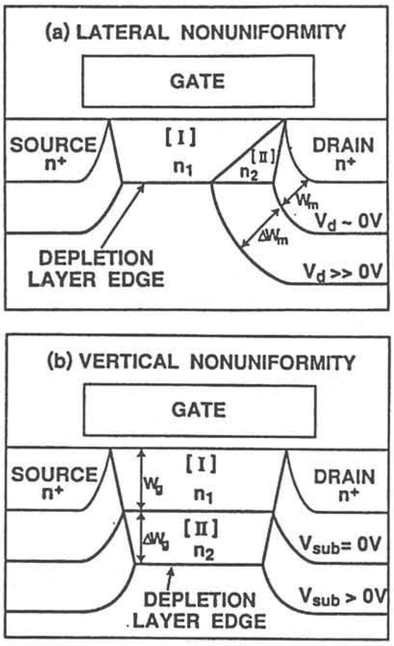


**Fig. 1** Schematic cross section of the depletion layer edge in the channel region, in order to study (a) the lateral and (b) the vertical nonuniformity of dopant atoms. $n_1$ and $n_2$ show the dopant numbers of regions [I] and [II], respectively. (a)$W_m$ and $\Delta W_m$ show the drain depletion width at small $V_d$ and its shift at applied large $V_d$, respectively. (b)$W_g$ is the channel depletion width and $\Delta W_g$ its shift at applied $V_{sub}$.

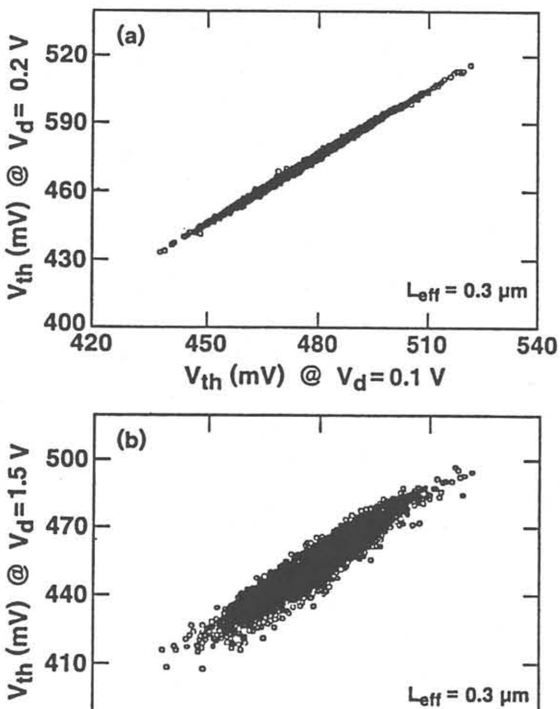


**Fig. 2** Correlation of $V_{th}$ at various $V_d$, where $L_{eff}$=0.3 $\mu m$. (a)$V_{th}$ at $V_d = 0.1V$ versus $V_{th}$ at $V_d = 0.2V$. (b)$V_{th}$ at $V_d = 0.1V$ versus $V_{th}$ at $V_d = 1.5V$.

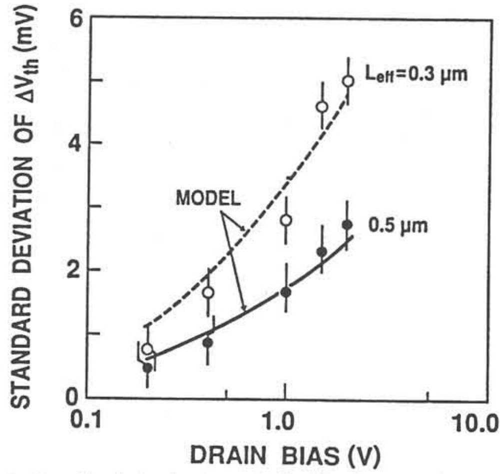


**Fig. 3** Standard deviation of $\delta(\Delta V_{thd})$ as a function of $V_d$. The open and the closed circles show the experimental data at $L_{eff}$=0.5 $\mu m$ and 0.3 $\mu m$, respectively. The solid and the dashed lines are the calculated results of Eq. (1) at $L_{eff}$=0.5 $\mu m$ and 0.3 $\mu m$, respectively.

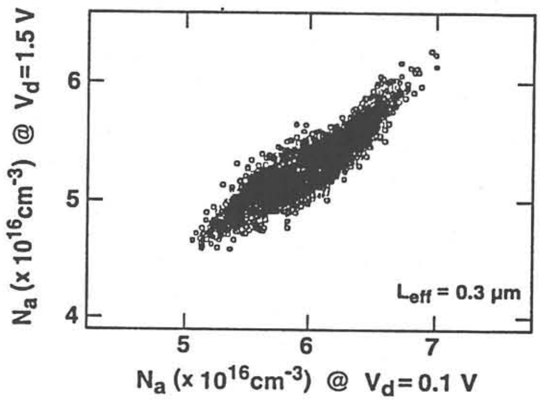


**Fig. 4** Correlation of $N_a$ at $V_d$=0.1 V and 1.5 V, where $L_{eff}$=0.3 $\mu m$. $N_a$ is obtained by $V_{th}$ shift at applied $V_{sub}$=-1 V.

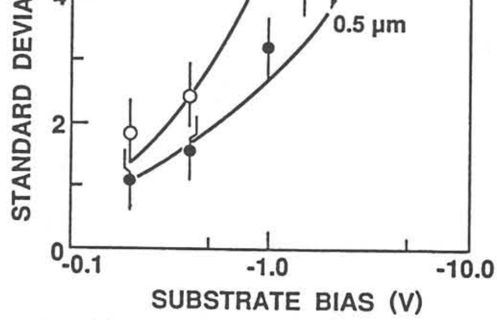


**Fig. 5** Standard deviation of $\delta(\Delta V_{thb})$ as a function of $V_{sub}$. The open and the closed circles show the experimental data at $L_{eff}$=0.5 $\mu m$ and 0.3 $\mu m$, respectively. The solid and the dashed lines are the calculated results of Eq. (1) at $L_{eff}$=0.5 $\mu m$ and 0.3 $\mu m$, respectively.