Impact of Channel Doping Concentration on Random Telegraph Signal Noise

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1. Introduction
Random telegraph signal (RTS) has become one of the most troublesome issues with shrinkage of FET devices. Recently, RTS has had negative impacts on reliabilities of flash memory and SRAM, which are major drivers of device shrinkage [1, 2]. An image quality of CMOS imager is also degraded by RTS at pixel amplifier [3]. The recent research indicates that the amplitude of RTS will increase as gate length shortens [4]. In this work, we show that the relationship between the amplitude of RTS and the doping concentration based on statistical measured data, which is important to facilitate future device miniaturization.

2. Measurement Conditions and Sample Preparation
We have succeeded in measuring RTS for numerous FETs in a short time by a test structure which was reported in [5, 6]. In this structure, drain current noise of the measured device appeared as voltage fluctuation at the source terminal with the dc offset voltage corresponding to the threshold voltage (Vth). Thus, we can measure not only RTS noise but also Vth for each device at a time.

We prepared three samples with different channel doping concentrations (N_A) as shown in Table I. The doping concentrations were changed by Vth adjust implantation processes. These samples have almost same oxide thickness and flat band voltage extracted by high-frequency CV (HFCV) measurement. The test structures were fabricated with a conventional 0.22 μm CMOS logic process including thermal gate oxide, STI, and LDD.

3. Results and Discussion
Fig. 1 shows Vth distributions with 65,536 NMOS transistors for each sample measured by the test structure. Mean values of Vth separates clearly with about 0.2 V difference for each sample. Standard deviations of Vth (σ_Vth) are plotted as a function of 1/√LW in Fig. 2. The σ_Vth increases in proportion to 1/√LW and the slope increases with increase in N_A. Fig. 3 indicates the σ_Vth versus N_A for three gate sizes. It is expected that random dopant fluctuation which is a major component of Vth variations and characterized Poison distribution generates σ_Vth following N_A^-3/4 [7] and our experimental result confirms with this expectation for the devices with long gate length. However, devices with short gate length have additional components of Vth variations and differ from the model. This difference could be understood by variations of short channel effects [8].

Fig. 4 demonstrates the distributions of RTS amplitude (∆Vth) which is defined by peak-to-peak value in the sampling span. The measurement was performed with 393,216 NMOS transistors. This graph is represented by Gumbel plot which is used in extreme value statistics [2]. We interpret that the devices of tail parts in the distribution which corresponds to the part of small slope and extremely large ∆Vth show RTS. In Fig. 4, the tail parts expand drastically as N_A increases. This means noise intensity and the occurrence frequency of RTS increase as doping concentration becomes higher.

On the other hand, RTS is also affected by the quality of gate insulator film. To examine the quality of gate oxide in terms of interface state density and trap density, we implant 1/f noise, charge pumping (CP), and quasi-static CV (QSCV) measurement. Figs. 5 show 1/f noise characteristics for various drain currents conditions. There are little differences from sample to sample. Fig. 6 shows charge pumping currents (I_CP) as a function of pulse base voltage. I_CP is proportional to the density of trap (N_t) which locates on a region from the interface of insulator film to relatively deep. We also extract interface state density (D_I) by QSCV and D_t and N_t are summarized in Table II. Interface state density, trap density, and 1/f noise characteristic are almost the same in any samples and there is not much difference in the qualities of gate insulator film among the three samples. Thus the expansion of RTS amplitude in Fig. 3 is originated by high channel doping concentration.

We turn to a discussion of increase in RTS amplitude by high channel doping concentration. Generally, depletion layer width decreases and effective electric field at the Si-SiO₂ interface increases as channel doping concentration increases. As a result, average depth of quantized inversion layer move closer to the interface [9]. The charged trap inducing RTS should have more efficiency of scattering of carriers and generate larger amplitude as inversion layer depth become closer. Note that another explanation is suggested [4], which discrete random dopant fluctuation increases as channel doping concentration increases based on Poisson distribution and it causes narrowing of percolative channel path and increase the effect of trap on overall drain current.

4. Conclusion
We demonstrate the effects of channel doping concentration on RTS based on numerous measured data. Unless the quality of insulator film does not change, RTS amplitude drastically increases as channel doping concentration becomes higher. It is explained that effective electric field at the interface and random dopant fluctuation increase due to higher channel doping concentration.

References

Fig. 1. Distributions of threshold voltage ($V_{th}$) with 65536 transistors for each sample. Mean values of $V_{th}$ separate with about 0.2 V difference for each sample. Standard deviation of $V_{th}$ ($\sigma_{Vth}$) increases with increase in channel doping concentration.

Fig. 2. Standard deviation of $V_{th}$ versus $1/\sqrt{LW}$ (Pelgrom plot). The $\sigma_{Vth}$ increases in proportion to $1/\sqrt{LW}$.

Fig. 3. Standard deviation of $V_{th}$ as a function of channel doping concentration. $\sigma_{Vth}$ is proportional to $N_A^{-1/2}$.

Table I. Prepared samples and extracted parameters by high-frequency CV method.

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Oxide thickness ($T_{ox}$)</th>
<th>Channel doping concentration ($N_A$)</th>
<th>Flat band voltage ($V_{FB}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W#01</td>
<td>5.7</td>
<td>$2.3 \times 10^{11}$</td>
<td>-1.03</td>
</tr>
<tr>
<td>W#05</td>
<td>5.7</td>
<td>$3.6 \times 10^{11}$</td>
<td>-1.06</td>
</tr>
<tr>
<td>W#07</td>
<td>5.7</td>
<td>$5.2 \times 10^{11}$</td>
<td>-1.09</td>
</tr>
</tbody>
</table>

Table II. Interface state densities ($D_{it}$) and trap densities ($N_t$) extracted by quasi-static CV method and charge pumping method, respectively.

<table>
<thead>
<tr>
<th>Sample name</th>
<th>$D_{it}$ ($\text{cm}^{-2}\text{eV}^{-1}$)</th>
<th>$N_t$ ($\text{cm}^{-2}$)</th>
<th>Charge Pumping Current ($I_{CP}$) ($\mu\text{A}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W#01</td>
<td>$9.6 \times 10^{-4}$</td>
<td>-34.39</td>
<td>1.50</td>
</tr>
<tr>
<td>W#05</td>
<td>$9.7 \times 10^{-4}$</td>
<td>-33.93</td>
<td>1.57</td>
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<tr>
<td>W#07</td>
<td>$8.5 \times 10^{-4}$</td>
<td>-35.05</td>
<td>1.62</td>
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</table>

Fig. 4. Distributions of RTS amplitude ($\Delta V_{GS}$) by Gumbel plot [2]. The tail part expands drastically as $N_A$ increases.

Fig. 5. 1/f noise characteristics for four drain current conditions. (a) $I_D=2\text{mA}$, (b) $I_D=500\mu\text{A}$, (c) $I_D=100\mu\text{A}$, (d) $I_D=10\mu\text{A}$.

Fig. 6. Charge pumping current ($I_{CP}$) versus base voltage.