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Extended Abstracts of the 2009 International Conference on Solid State Devices and Materials, Sendai, 2009, pp30-31

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 (V_{th}). Thus, we can measure not only RTS noise but also V_{th} 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 V_{th} 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 0.22μm CMOS logic process including thermal gate oxide, STI, and LDD.

3. Results and Discussion

Fig. 1 shows V_{th} distributions with 65,536 NMOS transistors for each sample measured by the test structure. Mean values of V_{th} separates clearly with about 0.2 V difference for each sample. Standard deviations of V_{th} (σ_{Vth}) are plotted as a function of $1/\sqrt{LW}$ in Fig. 2. The σ_{Vth} increases in proportion to $1/\sqrt{LW}$ 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 V_{th} variations and characterized Poison distribution generates σ_{Vth} following N_A^{-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 V_{th} 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 (ΔV_{GS}) 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 ΔV_{GS} 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 implement 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_{it}) by QSCV and D_{it} 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-SiO_2 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

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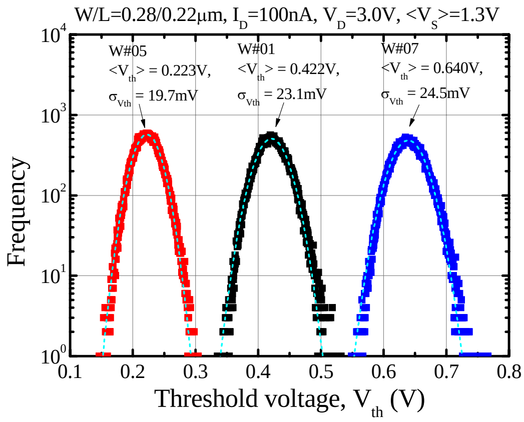

Fig. 1. Distributions of threshold voltage (V_{th}) with 65536 transistors for each sample. Mean values of V_{th} separates with about 0.2 V difference for each sample. Standard deviation of V_{th} (σ_{Vth}) increases with increase in channel doping concentration.

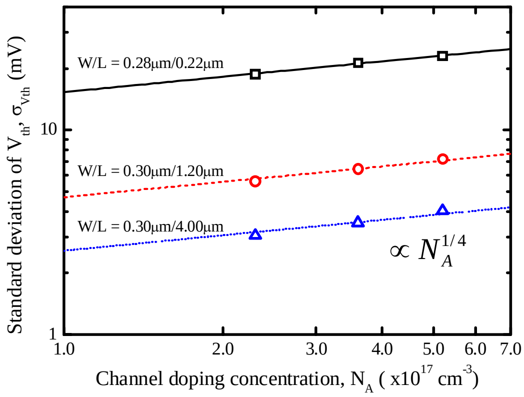

Fig. 3. Standard deviation of V_{th} as a function of channel doping concentration. σ_{Vth} is proportion to N_A^{-4}.

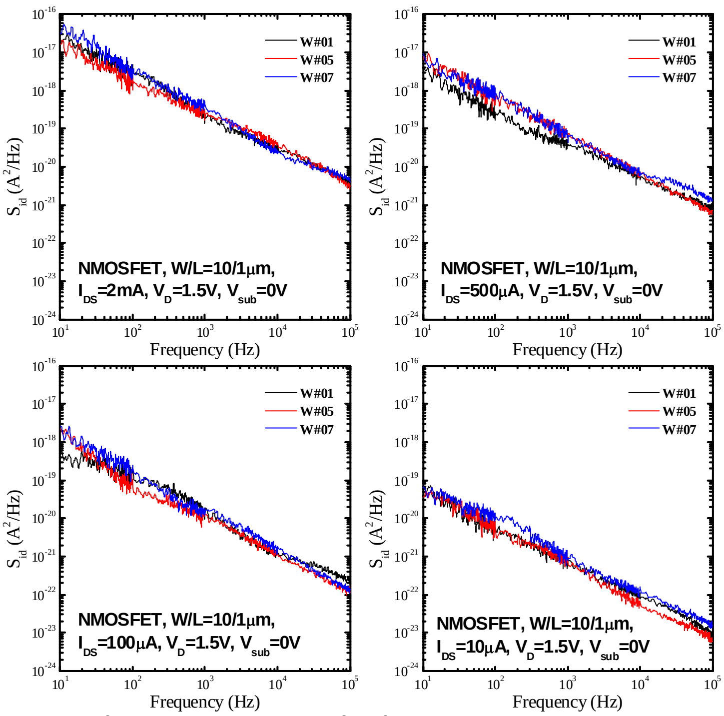

Fig. 5. 1/f noise characteristics for four drain current conditions. (a) I_D=2mA, (b) I_D=500μA, (c) I_D=100μA, (d) I_D=10μA.

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

Sample name	Oxide thickness T_{ox} (nm)	Channel doping concentration N_A (cm^{-3})	Flat band voltage V_{FB} (V)
W#01	5.7	2.3×10^{17}	-1.03
W#05	5.7	3.6×10^{17}	-1.06
W#07	5.7	5.2×10^{17}	-1.09

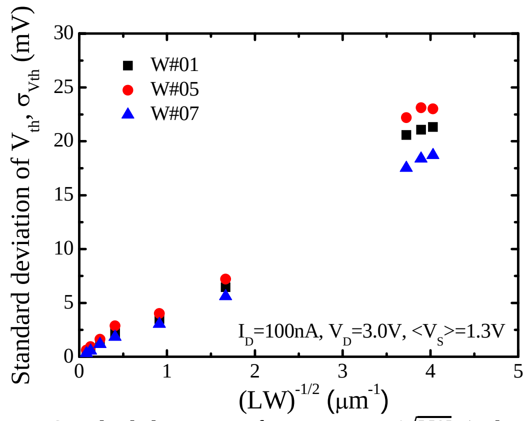

Fig. 2. Standard deviation of V_{th} versus $1/\sqrt{LW}$ (Pelgrom plot). The σ_{Vth} increases in proportion to $1/\sqrt{LW}$.

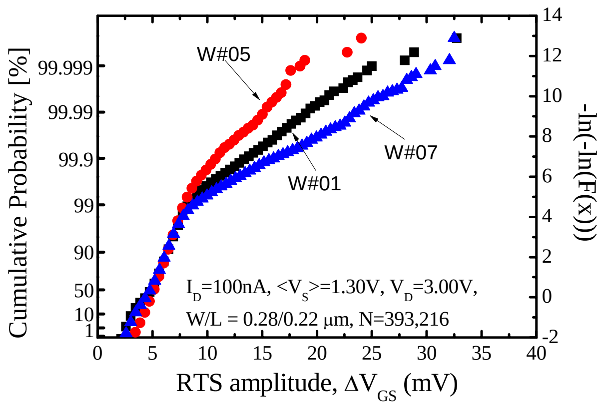

Fig. 4. Distributions of RTS amplitude (ΔV_{GS}) by Gumbel plot [2]. The tail part expands drastically as N_A increases.

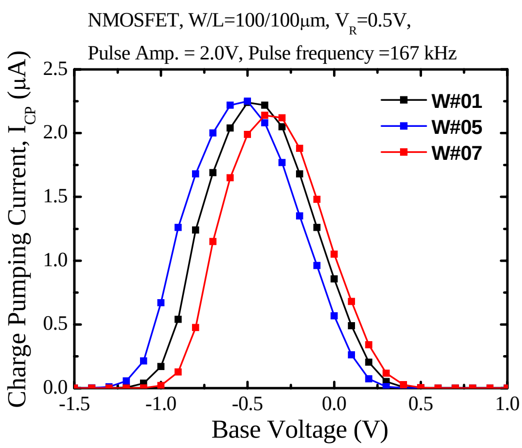

Fig. 6. Charge pumping current (I_{CP}) versus base voltage.

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

Sample name	QSCV D_{it} @ Midgap($cm^{-2}eV^{-1}$)	Charge Pumping N_t (cm^{-2})
W#01	9.6×10^{10}	8.4×10^{11}
W#05	9.7×10^{10}	8.5×10^{11}
W#07	8.5×10^{10}	8.0×10^{11}