$1/f$ Noise Reduction in PMOSFETs by an Additional Preoxidation Cleaning With an Ammonia Hydrogen Peroxide Mixture

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***Abstract*—$1/f$ noise magnitude in a 15 μm × 0.5 μm PMOSFET was remarkably reduced by simply adding a cleaning step using an ammonia hydrogen peroxide mixture (APM) prior to gate oxidation. Gate input-referred noise level for APM-finished PMOSFETs at $f = 10$ Hz was around -128 dBV^2/Hz whereas for standard, HF-finished devices, the level was around -114 dBV^2/Hz. Flat-band voltages (V_{FB}s) determined by a capacitance–voltage*(C–V)* measurement were -0.19 V for an APM-finished PMOS and -0.34 V for a HF-finished PMOS. Based on the V_{FB} values, interface state densities were determined to be $N_{it} = 3.02 \times 10^{11}$ cm^{-2} for APM-finished PMOS and $N_{it} = 6.47 \times 10^{11}$ cm^{-2} for HF-finished PMOS. Lower interface state density obtained by the APM preoxidation cleaning is consistent with the remarkable reduction in the $1/f$ noise magnitude.**

***Index Terms*—Ammonia hydrogen peroxide mixture, C–V plot, flat-band voltage, flicker noise, interface states, MOSFET, $1/f$ noise, PMOS, preoxidation cleaning.**

I. INTRODUCTION

FLICKER or $1/f$ noise appearing in MOSFETs can be a great obstacle to realizing precision analog and RF circuits using scaled MOSFETs [1]. Alternate trapping and detrapping of free carriers to a near-interface or border trap often observed as a random telegraph signal (RTS) is considered to be the origin of the low-frequency $1/f$ noise [2], [3]. Density of near-interface traps is therefore of critical importance and determines the $1/f$ noise characteristics of a MOSFET [4].

Despite wide-ranging discussions on modeling of the $1/f$ noise [5], [6], few reports on a straightforward procedure to improve the noise characteristics have been made. In this letter, we propose a simple process optimization to improve $1/f$ noise characteristics in PMOSFETs. An additional cleaning of the silicon surface prior to gate oxidation with an ammonia hydrogen peroxide mixture (APM) resulted in a remarkable improvement on $1/f$ noise magnitude. To investigate the origin of the improvement, we performed a current–voltage *(C–V)* measurement on PMOS capacitors. Interface state densities (N_{it}s) were determined form V_{FB} shifts and discussed in conjunction with $1/f$ noise characteristics.

II. EXPERIMENTAL

The 15 μm × 0.5 μm PMOSFETs were fabricated with a standard twin well CMOS process on n-type Si(100) substrates. After forming LOCOS field regions, sacrificial oxide was grown on active areas by thermal oxidation. Subsequently, ion implantation for $V_th$adjustment was performed using BF$_2^+$ ions. The sacrificial oxide was then removed by wet etching using a 5% HF solution. For a control device, gate oxide was grown immediately after the HF etching (HF-finished). While for our target device, an ammonia/hydrogen peroxide/water mixture (APM) at 80 °C with a mixing ratio of $1:5:50$ was employed for an additional preoxidation cleaning (APM-finished).

Gate oxide was grown by a wet oxidation at 850 °C to a thickness of 10 nm. N$^+$ polycrystalline silicon was used as gate electrodes for the buried channel PMOSFETs.

While $1/f$ noise level was measured, the PMOSFETs were biased in a saturation region where $V_d = -1.0$ V and $V_g = \mathrm{Vth} - 0.11$ V, and the drain dc current (I_ds) was kept constant at 20 μA by using a load resistor. Drain voltage power spectra in a frequency range between 2 Hz and 10 kHz were obtained using a HP89410A vector signal analyzer. To determine the gate-input-referred noise power, voltage gain of the system was measured and subtracted from the output noise level in the drain voltage.

A high-frequency (100 kHz) *C-V*measurement was performed for APM-finished and HF-finished PMOS capacitors with a size of 8400 μm^2. Flat-band voltages (V_{FB}s) and interface state densities (N_{it}s) were evaluated based on the*C-V* measurement results.

III. RESULTS AND DISCUSSIONS

Gate oxide capacitance was electrically measured as $C_{OX} = 3.13 \times 10^{-7}$ F/cm^2, either for HF-finished or APM-finished capacitors. The addition of APM preoxidation cleaning was shown to have no influence over the gate oxide capacitance. Electrical characteristics of HF-finished and APM-finished PMOSFETs are listed in Table I. No significant difference in the characteristics is observed between differently finished devices.

Gate-input-referred voltage $1/f$ noise spectra for each preoxidation procedure are compared in Fig. 1. An APM-finished PMOSFET showed a remarkably lower noise level than that with a standard, HF etching only. The noise levels at $f = 10$ Hz for seven nominally identical samples for each preoxidation procedure are summarized in Fig. 2. The averaged noise level for APM-finished PMOSFETs was around -128 dBV^2/Hz

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TABLE I
ELECTRICAL CHARACTERISTICS OF HF-FINISHED AND APM-FINISHED PMOSFETs

	HF-finished	APM-finished
Vth (V)	-0.86	-0.94
Saturated Drain Current (mA)	-2.18	-2.15
Max. Transconductance (μS)	121	120
Gate Oxide Capacitance (F/cm^2)	3.13 x 10^{-7}	3.12 x 10^{-7}
Zero-field Mobility (cm^2/Vs)	145	145

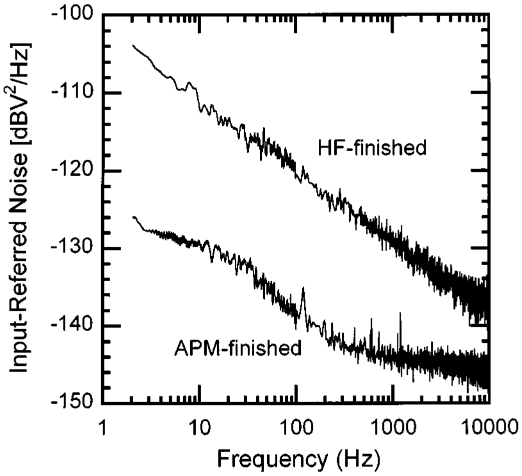

Fig. 1. Typical drain voltage noise spectra for PMOSFETs with $L = 0.5\ \mu$m and $W = 15\ \mu$m under $Vd = -1.0$ V and $Vg = Vth-0.11$ V. Significantly lower noise power was observed for an APM-finished device than for a HF-finished device.

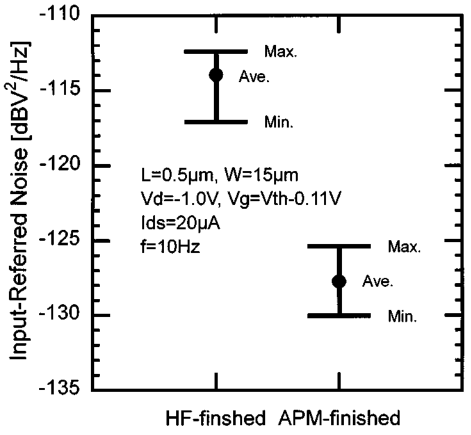

Fig. 2. Gate input referred noise compared at $f = 10$ Hz for HF-finished and APM-finished PMOSFETs. Seven nominally identical samples for each preoxidation cleaning procedure were evaluated.

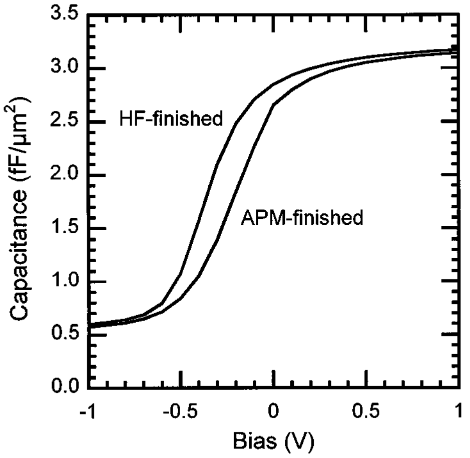

Fig. 3. High-frequency*C-V* plots for PMOS capacitors with APM and HF preoxidation procedures. V_FB determined from these *C-V* curves were -0.34 V for a HF-finished PMOS and -0.19 V for an APM-finished PMOS.

whereas for standard, HF-finished devices the reading was around -114 dBV^2/Hz. Similar investigation was also performed on NMOS FETs. Gate-input-referred noise at $f = 10$ Hz for 15 μm $\times$ 0.5 μm NMOS FETs was around -114 dBV^2/Hz and no significant difference in the noise levels was observed between HF-finished and APM-finished NMOS FETs.

It is meaningful to compare the observed $1/f$ noise levels with that shown in literature. We took Hooge's α as a common indicator to make an objective comparison. $1/f$ noise appearing in a MOSFET biased in saturation region is empirically expressed by [7],

$$\frac{S_{vg}}{(V_g - V_{th})^2} = \frac{\alpha}{2Nf} \tag{1}$$

where

S_{vg}	gate-input-referred noise;
f	frequency;
N	the total number of free carriers in the channel.

Considering charge balance between gate voltage and charged carriers in the channel, one can calculate N by

$$N = \frac{WLC_{OX}(V_g - V_{th})}{q} \tag{2}$$

where q is the unit charge.

According to these equations, α values were found to be $\alpha = 1.1\times\ 10^{-4}$ for our HF-finished PMOSFETs and $\alpha = 4.2 \times 10^{-6}$ for our APM-finished PMOSFETs. The α value found in literature is, for example, $\alpha = 2.0 \times 10^{-7} \sim 7.0 \times 10^{-7}$ for buried channel PMOSFETs [8]. Therefore, our devices with APM cleaning still have rather high α compared to the reference value, which means we may have even more room for improvement on the $1/f$ noise magnitude.

High-frequency*C-V* plots for PMOS capacitors with APM and HF preoxidation procedures are shown in Fig. 3. As can be seen from this figure, the*C-V* characteristics were strongly affected by the preoxidation cleaning. $\mathrm{V_{FB}}$s determined from the *C-V* curves were -0.34 V for HF-finished and -0.19 V for APM-finished capacitors, respectively. Based on the $\mathrm{V_{FB}}$ values, interface state densities were determined to be $N_{\mathrm{it}} = 3.02 \times 10^{11}$ cm^{-2} for APM-finished PMOS and $N_{\mathrm{it}} = 6.47 \times 10^{11}$ cm^{-2} for HF-finished PMOS. There are discussions regarding relationship between interface state densities and $1/f$ noise magnitude [1]. In some cases, a strong correlation between an interface trap density and a $1/f$ noise magnitude in PMOSFETs is observed [9]. Therefore, lower interface state density obtained by an additional APM preoxidation cleaning is consistent with the lower $1/f$ noise magnitude observed for APM-finished PMOSFETs.

However, the causal relationship between preoxidation cleaning procedures and the interface state density is yet to be explained. It is known that APM, particularly in rather low ammonia concentration, effectively removes organic and metallic contamination without affecting micro-roughness of a silicon surface [10]. In a SiO_2 film grown on a Si surface, a structural transition layer exists at the border region of the SiO_2/Si interface. The transition layer contains a certain amount of imperfections such as Si–Si bonds, which could evolve into hole traps [11]. The interface structure strongly depends on the chemical treatment that has been performed on the silicon surface prior to the thermal oxidation [12]. In order to fully understand the effect of APM preoxidation cleaning, further investigation is currently being conducted.

IV. CONCLUSION

A simple process optimization was proposed to successfully reduce $1/f$ noise magnitude in PMOSFETs. PMOSFETs with gate oxide thermally grown after an additional preoxidation cleaning by an APM showed a remarkable improvement on $1/f$ noise magnitude.

V_{FB}s evaluated from a *C-V* measurement showed a smaller density of interface states in the APM-finished devices compared with the HF-finished devices. The difference in the interface state density is consistent with the fact that a lower $1/f$ noise magnitude was observed for APM-finished PMOSFETs than for conventional, HF-finished PMOSFETs.

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