Uniaxial Strain Effect on Flicker Noise and Random Telegraph Noise of SiC Strained nMOSFETs in 40nm Technology

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Abstract
The uniaxial strain effect on flicker noise and random telegraph noise (RTN) was investigated in frequency and time domains, respectively. Both control and SiC strained nMOS reveal flicker noise dominated by number fluctuation model but the latter one with uniaxial strain suffers significantly higher noise. RTN measured from SiC strained nMOS features a complex spectrum with multi-level drain current fluctuation amplitudes. The capture time (τc), emission time (τe), and effective trap depth (Zeff) can be extracted to explore the impact from the uniaxial strain on trap properties, RTN, and flicker noise.

I. Introduction
Uniaxial strain engineering has been a vital technique for mobility enhancement in modern CMOS technology [1-3]. The uniaxial tensile strain created by silicon-carbon (SiC) solid phase epitaxy (SPE) in Source/Drain extension (SDE) region was demonstrated in 40nm technology as a feasible approach for mobility enhancement in nanoscale nMOS [2-3] and desired benefit in RF performance. However, the potential impact on trap density and flicker noise emerges as a concern for RF/analog circuits design but remains an open question in existing research literatures. In this paper, flicker noise measurement will be performed on both control and SiC strained nMOS to identify the impact from uniaxial tensile strain. To explore the properties of the gate oxide traps, RTN measurement will be implemented [4].

II. Experimental
In Fig.1, the strained nMOS with SiC SPE in SDE region (SiC-SDE) for uniaxial tensile strain were fabricated in 40nm technology with physical gate oxide thickness of 12Å. The SiC epi-layer was implanted with As75 ions and followed by a low temperature SPE anneal for dopant activation [2]. Ultra-small nMOS with L/W=0.04µm/0.06µm on layout, was employed for RTN analysis. The RTN in time domain was measured at room temperature, by using Agilent 4156B under fixed drain bias, VDS=50mV and varied gate biases, VGS=0.7~1.0V. By measuring the RTN in drain current (ID-RTN), the trap properties can be described by three critical parameters, capture time (τc), emission time (τe), and current noise amplitude (ΔID), as shown in Fig.2. τc and τe are the average of the high-state and low-state time constants, respectively. ΔID is the amplitude of the drain current fluctuation. Based on these three parameters extracted from RTN, the key physical parameter Zeff can be determined.

II. Results and Discussion
Fig. 3(a) and (b) present the measured ΔID and Gm versus VGS. The comparison between the SiC strained and control nMOS indicates more than 25% increase of both ΔID and Gm over the uniaxial tensile strain. Fig. 4 exhibits τc/τe extracted from linear I-V characteristics. SiC strain can contribute higher τc/τe and the enhancement increases with L scaling to more than 25% for L=50nm. Fig. 5(a) shows the measured flicker noise in terms of Snoise/ID2 over the frequencies 10~10kHz. Unfortunately, the SiC strained nMOS suffer around 3~5 times higher Snoise/ID2 than the control nMOS. As shown in Fig. 5(b), Snoise/ID2 just follows the curve proportional to 1/ID2 and it indicates that the flicker noise of nMOS is dominated by number fluctuation model given by (1) in which Snoise/ID2 will increase with increasing the traps density Nt [5].

The experimental suggests that the uniaxial tensile strain from SiC may introduce extra interface traps and lead to worse flicker noise in SiC strained nMOS. Fig. 6 illustrates the ID-RTN spectrum measured from SiC strained nMOS (W006L004). It is observed that τc, τe, and ΔID vary significantly under increasing VGS. The ID-RTN under lower VGS in 0.70~0.72V is a simple spectrum with a single level of ΔID, similar to the control nMOS (not shown). However, when the VGS is increased to 0.74~0.78V, the ID-RTN reveals a complex spectrum composed of multiple levels of ΔID. It is proposed that the measured ID-RTN (Fig.6) can be decomposed into two individual ID-RTN spectra, one with bigger ΔID and the other with smaller ΔID, as shown in Fig. 7.

Meanwhile, the time constants are also different for these two spectra. For the ID-RTN with big ΔID, the time constants associated with the high and low states, i.e. τc and τe are around hundreds of seconds. It explains why these RTN events cannot be observed at lower VGS in the limited time scale but appears at sufficiently high VGS. The VGS dependence suggests that ID-RTN with big ΔID is contributed from the traps with smaller capture cross section and higher VGS can reduce the capture time, maybe due to an increase of inversion carrier density and/or increase of the capture cross section. In Fig.8, it is found that τc and τe of the big ΔID RTN are much longer than those of the small ΔID RTN under the same VGS. It indicates that the trapping/detrapping process of the big ΔID RTN is much slower than that of small ΔID RTN. Moreover, it suggests that the location of traps responsible for big ΔID RTN may be deeper into the gate oxide and the traps causing small ΔID RTN is closer to the oxide-channel interface.

According to the Shockley-Read-Hall statistics [6], τc is a function of carrier density n, average carrier velocity v, and the capture cross-section σ, given by (2). The mark-space ratio of τc fluctuation is the ratio of τc to τe, written as (3) [7], where g is the degeneracy factor and E0-Eg represents the trap energy level with respect to the Fermi energy level. Also, τc/τe can be described as (4), where β is a constant independent of VGS, Ψς is surface potential, and Zeff is the effective trap depth away from the oxide-channel interface [8]. Using (5) and τc/τe from Fig.8, Zeff can be extracted. Fig. 9 presents Zeff=6.8Å and 7.19Å extracted from small- and big- ΔID RTN for SiC strained nMOS, and Zeff=5.15Å for control nMOS. The result can be explained by McWorther’s model [9] that the deeper Zeff lead to longer trapping time constant and then higher flicker noise for SiC strained nMOS (Fig.5). The trade-off between μeff enhancement and flicker noise degradation becomes an important consideration in technology selection for RF and analog circuits design.
\[
\ln \left( \frac{\sigma}{\tau} \right) = \beta - \frac{q}{k_B T} \left( \ln \left( \frac{Z_{\text{eff}}}{T_{\text{eff}}} \right)^\Psi + \frac{Z_{\text{eff}}}{T_{\text{eff}}} \right)
\]

\[
\frac{d}{dV_{\text{GS}}} \ln \left( \frac{\sigma}{\tau} \right) = -\frac{q}{k_B T} \frac{Z_{\text{eff}}}{T_{\text{eff}}}
\]

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**References**


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**Fig. 1** The schematic representation of SiC strained nMOS with uniaxial tensile strain introduced by SiC SPE in the source/drain extension region

**Fig. 2** The drain current fluctuation spectrum over time defined as random telegraph noise of drain current ($I_D$-$\Delta T N$) described by capture time ($\tau_c$), emission time ($\tau_e$), and drain current fluctuation amplitude ($\Delta I_D$)

**Fig. 3** (a) $I_D$ vs $V_{\text{GS}}$ (b) $G_m$ vs $V_{\text{GS}}$ measured from control and SiC strained nMOS with W/L=10μm/0.05μm under fixed $V_{\text{DS}}$ at 50mV

**Fig. 4** The effective mobility $\mu_{\text{eff}}$ vs $L_{\text{min}}$ extracted from linear I-V ($V_{\text{DS}}=50mV$) of control and SiC strained nMOS with various lengths $L=0.05-1.0μm$ and fixed width, $W=10μm$.

**Fig. 5** The flicker noise measured from control and SiC strained nMOS (a) $S_{\text{INT}}/I_{\text{INT}}$ vs. frequency ($V_{\text{GS}}$ =0.6V) (b) $S_{\text{INT}}/I_{\text{INT}}$ vs. $I_{\text{DS}}$ ($V_{\text{GS}}$ =0.4-0.6V, $V_{\text{DS}}$ =0, 50,60V), $V_{\text{DS}}$ =50mV

**Fig. 6** The $I_D$-$\Delta T N$ spectra measured from ultra-small NMOS with W/L=0.06μm/0.04μm under varying $V_{\text{GS}}$ from 0.7V to 0.78V and fixed $V_{\text{DS}}$ at 50mV

**Fig. 7** The measured $I_D$-$\Delta T N$ can be decomposed into two individual $I_D$-$\Delta T N$ spectrum, one with bigger $\Delta I_D$ and the other with smaller $\Delta I_D$.

**Fig. 8** The capture time constant $\tau_c$ and emission time constant $\tau_e$ extracted from small $\Delta I_D$ RTN and big $\Delta I_D$ RTN under varying $V_{\text{GS}}$.

**Fig. 9** The ratio time constants $\tau_c/\tau_e$ under varying $V_{\text{GS}}$. The effective trap depth $Z_{\text{eff}}$ is extracted from $d[\ln(Z_{\text{eff}})]/dV_{\text{GS}}$, $Z_{\text{eff}}=6.8Å$ and $Z_{\text{eff}}=7.19Å$ extracted from small $\Delta I_D$ RTN and big $\Delta I_D$ RTN for SiC strained nMOS, and $Z_{\text{eff}}=5.15Å$ for control nMOS.