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Anomalous RTS Extractions from a Very Large Number of n-MOSFETs using TEG with 0.47 Hz – 3.0 MHz Sampling Frequency

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1. Introduction

Random Telegraph Signal (RTS) noise occurring in various electronic devices has been studied for many years [1-2]. In recent year, RTS in MOSFET become a serious problem as progress of downscaling of CMOS devices [3-6]. In fact, threshold voltage (V_{th}) fluctuation induced by RTS triggers erroneous programs or reads in flash memories [3-4] and output voltage fluctuation from pixel source follower amplifiers in CMOS image sensors is visible to flickering noise [5].

V_{th} fluctuation induced by RTS at constant drain current condition varies widely because of the location variability of traps originating RTS and the channel nonuniformity from random dopant fluctuation. A simulated result has explained this phenomenon [6]. Meanwhile, we have been investigated it statistically based on measurement data obtained from the source follower array Test Element Group (TEG) including over 1 million n-MOSFET samples per 1 chip [8]. In this paper we present a method for extraction of RTS amplitude by very long sampling among many n-MOSFETs and experimental results. Also, we show some examples of anomalous RTS with complicated behaviors which can be detected only by long sampling.

2. Experimental

The schematic block diagram of TEG is shown in Fig. 1(a) [7, 8]. In this TEG, applied bias voltages to the measured MOSFETs (V_G, V_D) are forced simultaneously. The operating points of the MOSFETs are controlled widely by I_{DS} given by the current sources which are placed at every column. Electrical characteristics of the MOSFETs can be observed as the V_{GS} included in the output voltage V_{out} (Fig. 1(b)). When a particular cell shows RTS, we can specify and observe it as V_{GS} fluctuation (ΔV_{GS}) in time scale by the result of continuous sampling with an adequately sampling frequency. By using this TEG, we can easily measure the electrical characteristics of 1 million MOSFETs in a very short time (0.7s per 1 scan) [8]. After identifying the MOSFETs having RTS, the temperature and the I_{DS} dependence of RTS characteristics in these MOSFETs are evaluated by high speed measurement with the sampling frequency f_s = 3.0 MHz in detail. 131,072 Measured n-MOSFETs were contained in the array and were fabricated with L = 0.22 µm, W = 0.28 µm and T_{OX} = 5.8 nm, where L is the gate length, W is the gate width, T_{OX} is the gate insulator thickness.

3. Results and Discussions

Fig. 2 shows typical RTS waveforms of a particular transistor in TEG for various drain current conditions with f_s = 3.0 MHz. The upper state of V_{GS} indicates that the trap captures an electron and the lower state is corresponding to that the trap is empty. ΔV_{GS} and the mean time in lower state increase with decrease in I_{DS} because the channel carrier density decreases with decrease in I_{DS} under constant V_{DS}. Fig. 3 shows power spectral density (PSD) of RTS in Fig. 2 and a no RTS observed in the transistor neighboring the transistor in Fig. 2 at the distance with 5 µm. PSD with RTS follows a Lorentzian spectrum in theory [2]. On the other hand, PSD of neighboring transistor does not show a Lorentzian spectrum.

By extraction of ΔV_{GS} from the array statistically, we employed low sampling frequencies (f_s = 0.47 - 1.4 Hz) and long sampling observation period (N = 7000 points) measurement. The measurement enables to determine the transistors having RTS and to extract ΔV_{GS} in both high and low transition rate samples easily. Distributions of ΔV_{GS} represented as Gumbel plot [4] are shown in Fig. 4. The distribution tail with I_{DS} = 0.1 µA expands to 2 times than that with I_{DS} = 1.0 µA. Increase of ΔV_{GS} in subthreshold region will be problematic in analogue circuit applications. Fig. 5 shows the temperature dependence of ΔV_{GS} distributions. The tail of ΔV_{GS} distribution increases with decrease in temperature. This is explained that the channel carrier density increases as the temperature increases under constant I_{DS} conditions because of the degradation of the carrier mobility.

Fig. 6 shows some examples of anomalous RTS with f_s = 0.47 Hz and N = 7000 (about 4 hours). The RTS jumps just once or 3 times in 4 hours, but it won't be negligible in case of lager ΔV_{GS}. Fig. 7 shows anomalous multi-trap RTS with the same sampling condition of Fig. 6. In this multi-trap RTS one trap induces capture/emission of an electron very frequently, while another trap does almost nothing in contrast. As a result, the RTS will be misunderstanding as a single-trap type RTS and be underestimated as small ΔV_{GS} in case of a short observation period measurement.

Fig. 8 shows an example of abruptly generated RTS. This phenomenon was observed under ordinary condition, which is room temperature and normally used bias voltages. It is shown that the trap inducing RTS will be generated under even normal use conditions. On the other hand, an example of annihilation of RTS is shown in Fig. 9. Thus it suggests the recovery phenomenon of RTS in room temperature.

4. Conclusions

The drain current and temperature dependences of ΔV_{GS} distributions are investigated using TEG and some anomalous RTS phenomena are indicated. Note that experimental data in Fig. 2 and Fig. 6-9 are included in the same TEG chip and are measured under the same condition, namely V_{th} or I_{DS} fluctuation by RTS occurs on the very wide time scale of several microseconds to a few hours. The newly developed TEG enables to measure a huge number of transistors' RTS phenomena in the wide time range (f_s: 0.47 Hz - 3 MHz, N: 7000).

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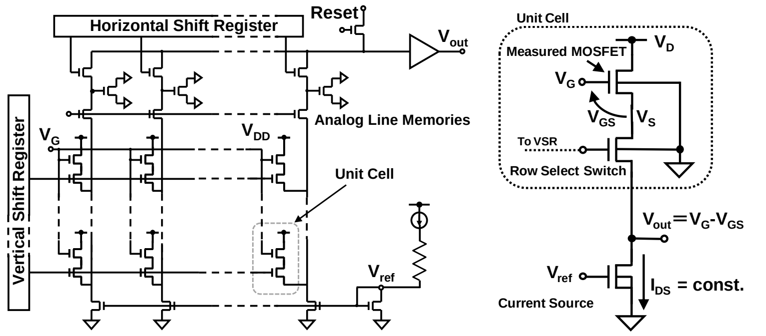


(a) (b)

Fig. 1(a) Schematic block diagram of n-MOSFET source follower array TEG, and (b) Measurement method.

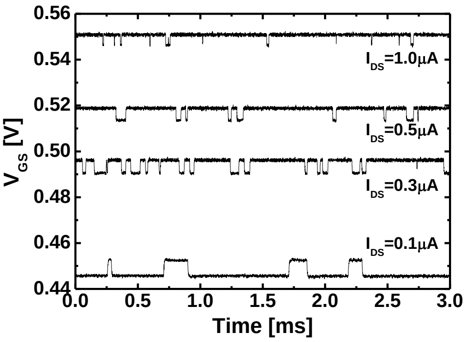


Fig. 2 Typical RTS waveforms for various drain current conditions with f_s = 3.0 MHz, V_D = 2.5 V, $<V_S>$ = 1.0 V.

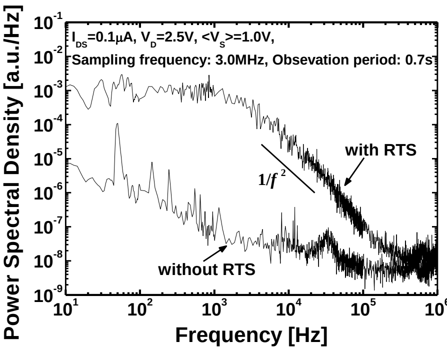


Fig. 3 Power spectral density of RTS and no RTS of neighboring transistor. PSD with a single-trap type RTS follows a Lorentzian spectrum in theory.

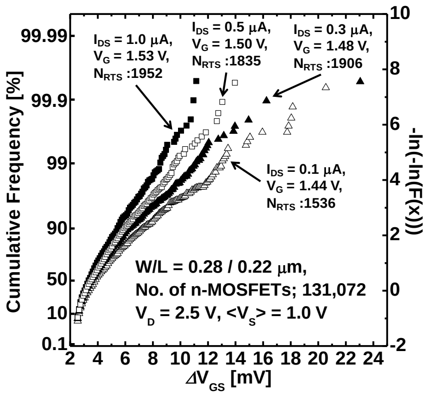


Fig. 4 Drain current dependence of V_{GS} fluctuation (ΔV_{GS}). As drain current decreases, a ratio of large ΔV_{GS} increases totally. N_{RTS} means the number of extracted RTS samples.

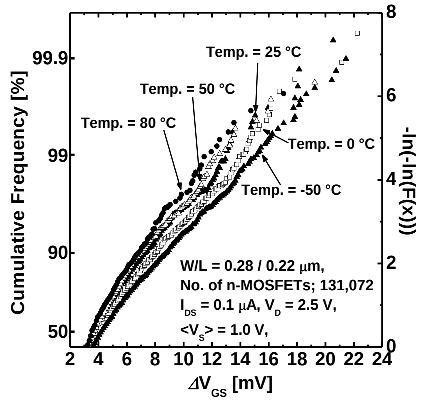


Fig. 5 Temperature dependence of ΔV_{GS}. The tail of ΔV_{GS} decreases with increase in temperature.

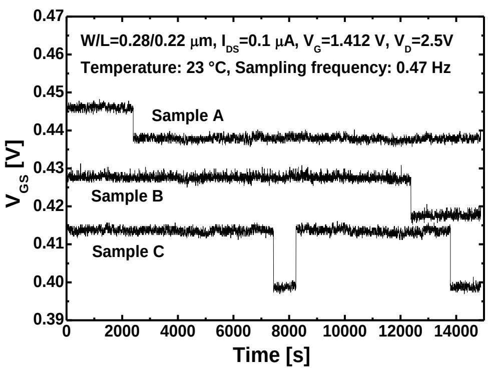
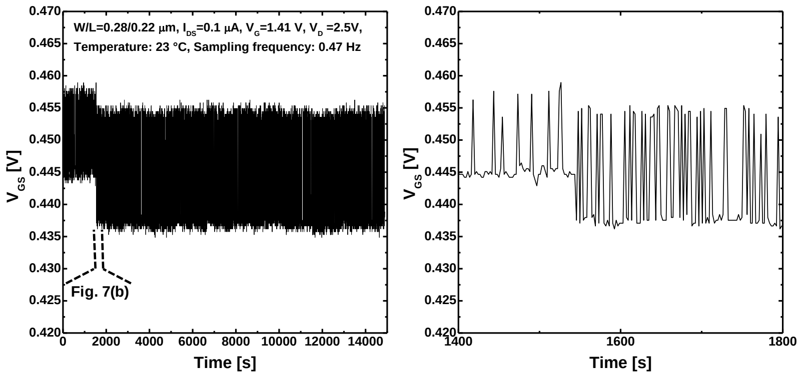
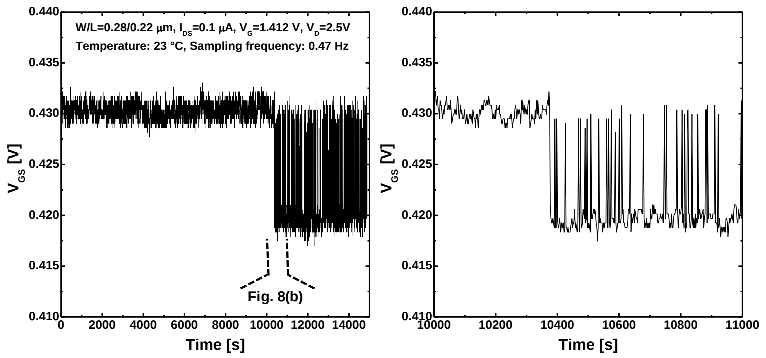


Fig. 6 Examples of anomalous RTS extracted from 131,072 transistors with very long time sampling. Just 1 or 3 transitions were observed within about 4 hours.



(a) (b)

Fig. 7(a) Multi-trap type RTS observed with very long sampling. A very low capture/emission rate trap and high rate trap are contained within the same transistor. (b) The expansion of part of the (a) trace.



(a) (b)

Fig. 8(a) An example of abrupt generated RTS. In this case, large RTS was begun to be observed after 10,300s. (b) The expansion of part of (a) trace.

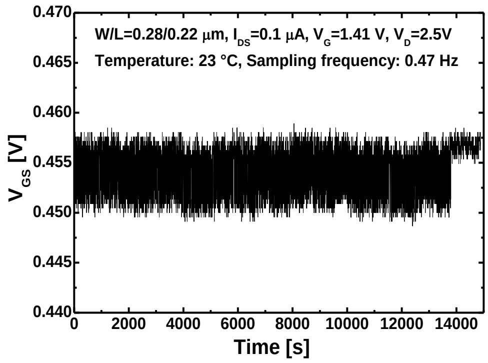


Fig. 9 An example of disappeared RTS. In this case, RTS disappeared at 13,800s suddenly.