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Methodology for Extracting Trap Depth using Statistical RTS Noise Data of Capture and Emission Time Constant

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Abstract—**In this paper, we propose a novel method for extracting an accurate depth of a trap that causes RTS(Random Telegraph Signal) noise. The error rates of the trap depth rely on the mean time constants and its ratio. Here, we determined how many data of the capture and emission time constant are necessary in order to reduce the trap depth error caused by an inaccurate mean time constant. We measured the capture and emission time constants up to 100,000 times in order to ensure that the samples had statistical meaning. As a result, we demonstrated that at least 1,000 samples are necessary to satisfy less than 10% error for trap depth. This result could be used to improve the accuracy of RTS noise analysis.**

Index Terms—**RTS noise, trap depth, capture time constant, emission time constant, mean time**

I. INTRODUCTION

It is widely known that low-frequency noise is a superposition of Lorentzian spectra [1]. From this point of view, it is high priority to do research on RTS noise to reduce the effects of low-frequency noise [2]. The source of RTS noise is not clear yet; however, it is thought to be due to a single active trap in the gate oxide bulk region. In the case of MOSFET(Metal-Oxide Semiconductor Field Effect Transistor), it is possible that electrons near the channel are captured and then emitted by this single active trap. As a result, it is easy to measure the two-level fluctuations in the drain current that degrades the device performance in MOSFETs, CIS(CMOS Image Sensors), and advanced memory devices [3-5]. There were many reports about the mechanism of RTS noise and the characteristics of a single trap, which include the horizontal and vertical locations, the energy level, the activation energy, the capture cross section, the geometric oxide lattice relaxation (inelastic tunneling), and the capture and emission time constant model by tunneling either from the conduction band to the trap or from an interface state to the trap [6-21].

Surprisingly, all of these characteristics can be extracted from the mean capture time constant (the average duration in the high state of a two-level fluctuation, $\overline{\tau_c}$) and mean emission time constant (the average duration in the low state of a two-level fluctuation, $\overline{\tau_e}$). The problem is that these time constants are random and follow a Poisson distribution [21]. Therefore, to utilize the mean time constant as a representative parameter, we have to determine the number of data(sample number) of the capture and emission time constants to have reliability.

In this paper, we measured the capture and emission time constants up to 100,000 times(sample number) to confirm the mean time constant error rate. Then, we derived the trap depth error rate due to an inaccurate mean time constant using a trap depth equation derived from previous works [10, 11]. Finally, we realized that

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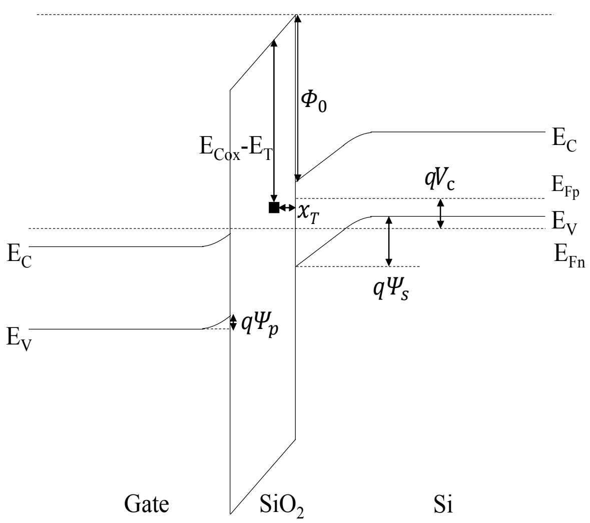

Fig. 1. Energy band diagram for a MOSFET.

an inaccurate mean time constant causes unreliable results and that it is very hazardous to extract the mean time constant from a few samples.

II. THEORETICAL CONSIDERATIONS

1. Trap Depth

The trap depth can be extracted by measuring the mean capture and emission time constants. Using the principle of detailed balance, we can write the relationship between the mean time constant ratio and the trap energy level as [21]

$$\frac{\overline{\tau_c}}{\overline{\tau_e}} = \mathrm{g}\exp\left(\frac{E_T - E_F}{kT}\right) \quad (1)$$

where k is the Boltzmann constant, T is the temperature, $\overline{\tau_c}$ is the mean capture time constant, $\overline{\tau_e}$ is the mean emission time constant, g is the degeneracy factor, and E_T is the trap energy level related to the Fermi level E_F. We can derive an interpretation of the MOSFET energy diagram and the relationship between the mean time ratio and the trap depth in a differential form that depends on the gate voltage as in the following equations [10]:

$$\ln\left(\frac{\overline{\tau_c}}{\overline{\tau_e}}\right) = -\frac{1}{kT}\{(E_{Cox} - E_T) - (E_C - E_F) - \Phi_0 + q\Psi_s + q\frac{x_T}{T_{ox}}(V_{GS} - V_{FB} - \Psi_S - \Psi_P)\} \quad (2)$$

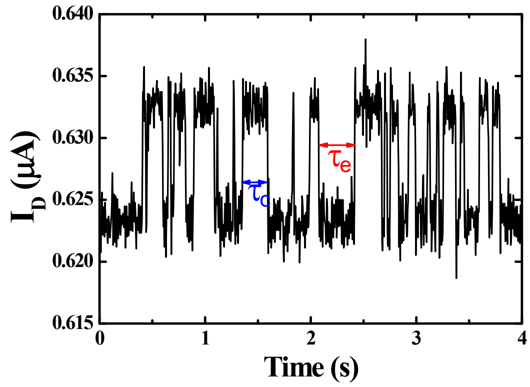

Fig. 2. Measured RTS noise in the time domain.

$$\frac{d\ln\left(\frac{\overline{\tau_c}}{\overline{\tau_e}}\right)}{dV_{GS}} = -\frac{q}{kT}\left\{\frac{d\Psi_s}{dV_{GS}} + \frac{x_T}{T_{ox}}\left(1 - \frac{d\Psi_P}{dV_{GS}} - \frac{d\Psi_s}{dV_{GS}}\right)\right\} \quad (3)$$

where E_{Cox} is the conduction band edge of the gate oxide, E_C is the conduction band edge in the silicon semiconductor, Φ_0 is the difference between the electron affinities of SiO_2 and Si, Ψ_s is the surface potential at the channel, x_T is the trap depth from the channel, V_{GS} is the gate voltage, V_{FB} is the flat-band voltage, Ψ_P is the band bending of the polysilicon gate caused by depletion, T_{ox} is the oxide thickness, and q is the electronic charge.

From Eqs. (2, 3), we can derive the trap depth by substituting for the mean capture and emission time constants. However, the calculated trap depth will be inaccurate if there is error in the mean time ratio, which indicates that errors in the mean time constant can directly affect the accuracy of the calculated depth of the trap.

2. Statistical Analysis of the Capture and Emission Time Constants

Fig. 2 shows the two-level fluctuations in the drain current(I_D) caused by the RTS noise. As the figure shows, the capture time(τ_c) is the time duration in the high state of a two-level fluctuation, whereas the emission time(τ_e) is the time duration in the low state of a two-level fluctuation.

The mean capture and emission time constants can be derived from the individual time constant data. However, these capture and emission time constants follow a Poisson distribution. Therefore, the mean time constant should be utilized after a sufficient number of time constant samples. There are references that suggest that 100–200 samples are sufficient for achieving an error rate less than 10%. However, we want to confirm that these number of samples are sufficient to extract the trap depth exactly [1, 13].

In this study, we decided to measure 100,000 samples of the capture and emission time constants to obtain a more reliable data set. Then, we assumed that the 100,000 samples are a population. Finally, we confirmed that the error rate decreases as the cumulative number of samples increases and determined how many samples were needed to achieve a 10% error rate in the trap depth.

III. Experiment and Algorithm

1. Measurement

The device used for this experiment had a width and length of 0.35 μm and 0.22 μm, and a physical gate oxide thickness of 7.2 nm. The RTS noise of the drain current was measured by varying the gate voltage. To avoid the pinch-off effect on the RTS noise, we applied 0.1 V to the drain electrode and connected both the source and the body electrodes to ground. Since the capture and emission time constants are temperature dependent, we performed all measurements at 25°C. Then, we measured the RTS noise while extracting 100,000 samples of the capture and emission time constants for all values of the gate voltage splits.

2. Algorithm for Extracting the Capture and Emission Time Constants

We determined that it would be virtually impossible to manually extract 100,000 samples of the capture and emission time constants. In order to automate the sampling process, we used an algorithm that was implemented in MATLAB.

Fig. 3 shows a histogram of Fig. 2 and two Gaussian distributions. The first indicates the low state, while the second indicates the high state. To extract the capture and emission time constants, we need to locate a standard line at the midpoint between the two Gaussian distributions. In order to determine where this standard line should be located, we used an algorithm to fit the histogram data and then derived the midpoint between the two Gaussian distributions.

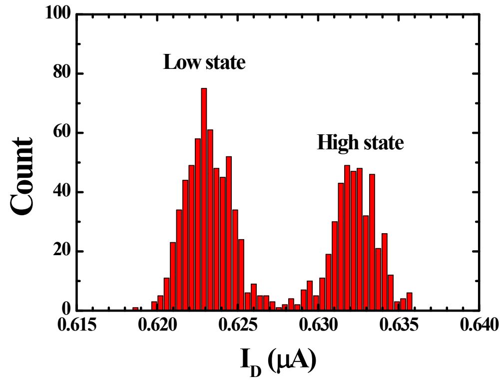

Fig. 3. Histogram plot of the RTS noise.

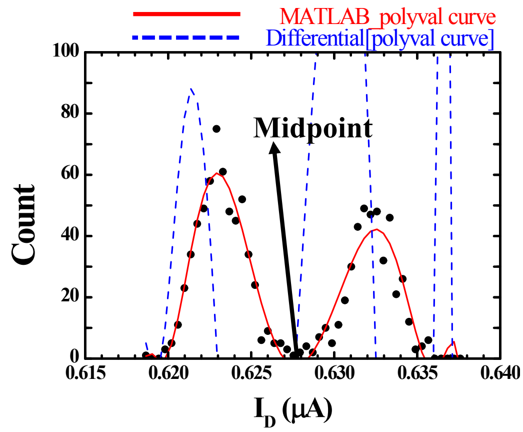

Fig. 4. Curve fitted using the algorithm.

Fig. 4 shows the procedure used to find the midpoint from the gradient. The solid line is the result of the curve fitting, and the dashed line is the result of the differential form of fitting the curve (solid line). From the dashed line, the algorithm can find where the gradient of the fitted curve is zero and then check to see if it is close to the middle of the two Gaussian distributions. If any point is determined to be satisfactory, the algorithm considers that point to act as the standard. Finally, the algorithm derived a midpoint, which is at I_D = 0.628 μA in Fig. 4. Fig. 5 shows the time-domain plot with the standard line (dashed line) that distinguishes the capture and emission time constants. The capture time is the time duration above the standard line, whereas the emission time is the time duration below it. We considered the rising and

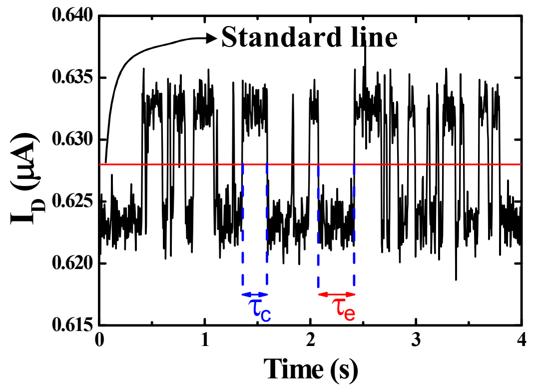

Fig. 5. Capture and emission time constants expressed by the standard line.

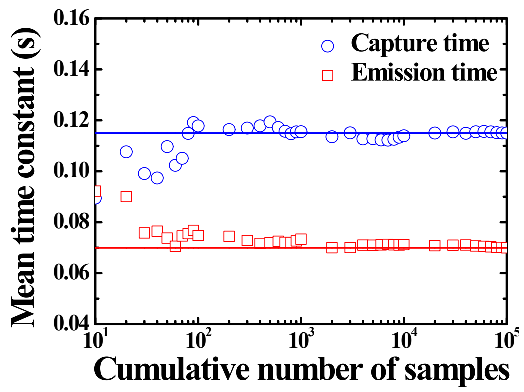

Fig. 6. Mean capture and emission time constants as the cumulative number of time constant samples increases.

falling edge times as dead times because they could not be used to determine the state. Therefore, we disregarded these data. This algorithm enabled us to automatically and quickly extract the 100,000 samples used in our analysis.

IV. Results and Discussion

1. Qualification for the Representativeness of the Mean Time Constant

Because both the capture and emission times are Poisson processes, the mean time becomes more accurate as the cumulative number of samples increases. Therefore, we demonstrated two qualifications for the representativeness of the mean time constant.

Fig. 6 shows the mean capture and emission time constants that are calculated as the cumulative number of time constant samples increased. The two straight lines are the mean time constants calculated using all 100,000

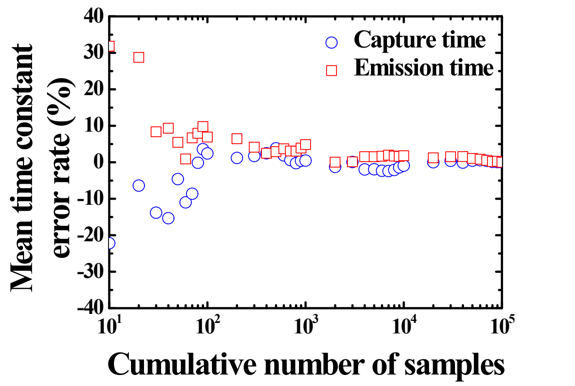

Fig. 7. Mean time constant error rate as the cumulative number of time constant samples increases.

samples, and each dot represents the mean time constant calculated using the corresponding number of time constant samples.

The mean time constants of both the capture and emission time constants converged to a constant point respectively, as shown in Fig. 6. This result supports our assumption that the 100,000 samples could be replaced by a population. The mean time constant error rate can be expressed as

$$\text{mean time constant error rate (\%)} = \left(\frac{\text{mean time constant from cumulative samples}}{\text{mean time constant from 100, 000 samples}} \times 100\right) - 100 \quad (4)$$

From this simple formula, we can derive an objective comparison of the mean time calculated using 100,000 samples with the mean times calculated using an increasing cumulative number of samples. In Fig. 7, the error rate of approximately 100 samples is 10%, and this shows similar results to those exhibited in previous research [1, 13].

In addition, we also compared the standard deviations (STDs) of the mean time constants. If the capture and emission time constants each perfectly follow a Poisson distribution, then the mean time constant and STD must be identical [6]. The difference between mean time constant and STD is derived using the follow equation:

$$\text{Difference between mean time constant and STD (\%)} = \left(\frac{\text{mean time constant from cumulative samples}}{\text{STD from 100, 000 samples}} \times 100\right) - 100 \quad (5)$$

From this equation, we can compare the difference as the cumulative number of time constant samples

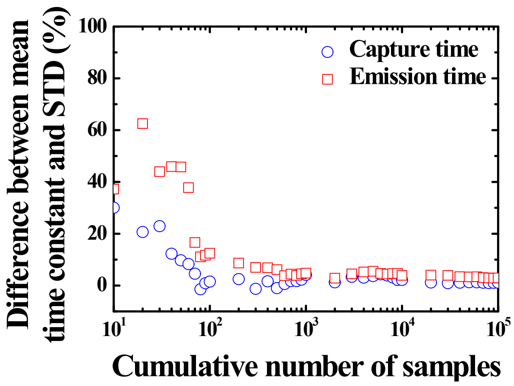

Fig. 8. Difference between mean time constant and STD as the cumulative number of time constant samples increases.

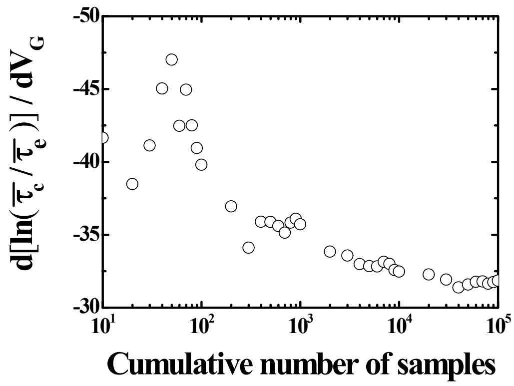

Fig. 9. Converged slope as the cumulative number of time constant samples increases.

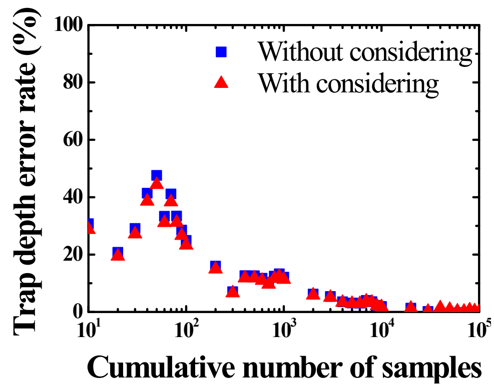

Fig. 10. Trap location error rate as the cumulative number of time constant samples.

increases. Fig. 8 shows the results of the comparison. These results indicate that the mean time constants cannot have representativeness and be applied to extract the trap depth if the cumulative number of time constant samples is less than 100.

Finally, we demonstrated that there are some important requirements in order for the mean capture and emission time constants to have representativeness. First, the value of the mean time constant must converge as the cumulative number of time constant samples increases. Second, the mean time constant and STD must be identical since the original distributions are Poisson distributions.

2. Error Rate of the Trap Depth

We confirmed the error rate of the trap depth caused by an inaccurate mean time constant. We can estimate where a single active trap is located from the gate oxide and channel interface by applying the mean capture and emission time constant to Eq. (2), assuming that there is no depletion effect of poly-silicon gate and surface potential variation. Because we confirmed that the error rate of trap depth is not significantly changed, even though we consider these two effects. The results are shown in Fig. 10.

$$x_T = -\frac{kT}{q}T_{ox}\frac{d\ln\left(\frac{\overline{\tau_c}}{\overline{\tau_e}}\right)}{dV_{GS}} \quad (6)$$

The right-hand side of Eq. (6) is important for extracting the trap depth, which is the gradient of the mean capture and emission time constant ratio with respect to the gate voltage. This means that we also should confirm the error rate of the slope ($\frac{d\ln\left(\frac{\overline{\tau_c}}{\overline{\tau_e}}\right)}{dV_{GS}}$) as the cumulative number of capture and emission time constant samples increases.

Fig. 9 shows the converged slope as the cumulative number of time constant samples increases. As mentioned earlier, in cases of less than 100 samples, the slope is random and unreliable. On the other hand, in cases of over 100 samples, the slope becomes stable and converges as expected. The error rate of the trap depth can be derived from the error in the slope. Fig. 10 shows the trap depth error rate as the cumulative number of samples increases and shows that we need 1,000 time constant samples to reduce the error rate to less than 10% and approximately 10,000 time constant samples for a 5% error rate.

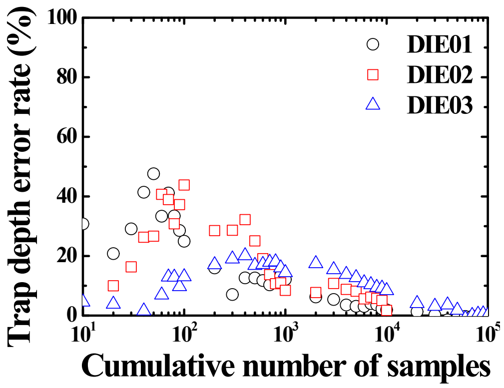

Fig. 11. Extracted trap depth error rate for three MOSFETs.

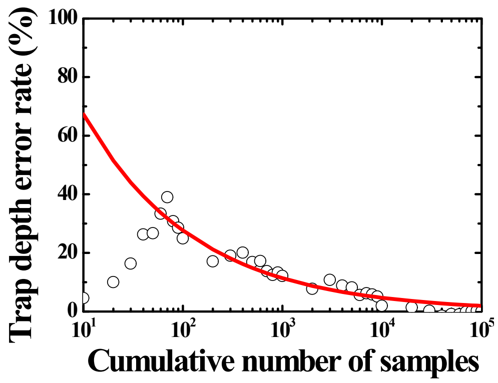

Fig. 12. Fitting Trap depth error rate derived by three MOSFETs.

3. Fitting and Applying the Results

Although we experimentally derived the trap depth error rate, we also needed to confirm its reproducibility. We repeated the same measurement and extraction procedures to confirm the reproducibility of our results for three MOSFETs. Fig. 11 shows the trap depth error rates extracted from three MOSFETs. All show the same tendencies, even though there are minor differences. We applied an arithmetic mean function and fitted the curves to derive the trap depth error rate. Fig. 12 shows the results.

We extended these results to high-k devices to verify its compatibility, regardless of the oxide material. Fig. 13 shows the trap depth error rate of high-k devices and the fitted curve that was derived from SiO_2 devices. Fig. 13 shows the same tendency.

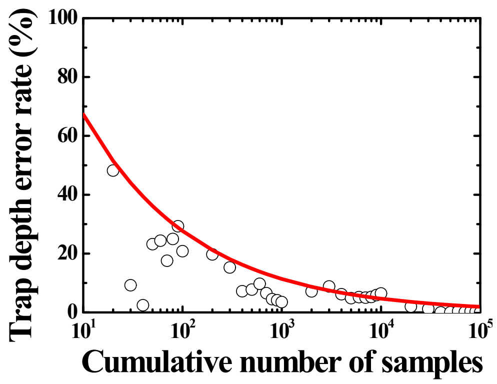

Fig. 13. Applying the fitting results to a high-k MOSFET for confirming its reliability.

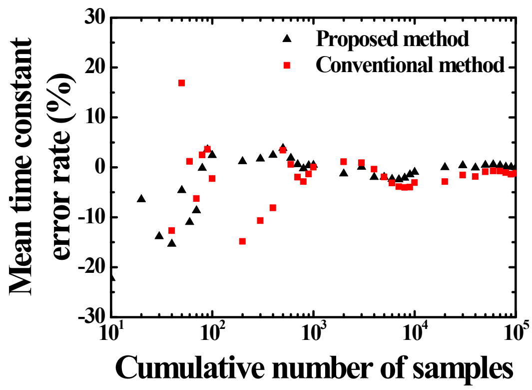

Fig. 14. Comparison of error rate between proposed method and conventional method.

V. Comparison between Proposed Method and Conventional Method

We confirmed that proposed method is more accurate than the conventional method from our analysis. Mean time can also be extracted by the exponential fitting method(conventional method) [10, 17]. Therefore, we compared the conventional method and our method through checking the mean time constant error rate as the cumulative number of samples increases in Fig. 14. The conventional method shows higher error rate than that of our method. Therefore, we can suggest the best way is applying the arithmetic mean formula and measuring a lot of data needed to extract an accurate mean time constant.

VI. Conclusions

In this paper, we proposed a novel method for extracting the accurate trap depth of a trap that causes RTS noise. We demonstrated that at least 1,000 samples of both the capture and emission time constants are necessary to achieve an error rate of less than 10% in the trap depth. We also compared the proposed method to conventional method and we were convinced that the proposed method is more accurate. This is the first report to our knowledge that indicates the importance of the mean time constant for accurately extracting characteristics of trap (especially for the trap depth). Therefore, these results could be used to improve the accuracy of RTS noise analysis.

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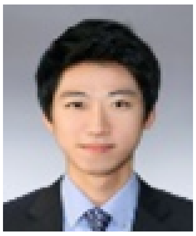

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