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Insights of V_G-dependent threshold voltage fluctuations from dual-point random telegraph noise characterization in nanoscale transistors

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Dear editor,

Random telegraph noise (RTN) has attracted rising attention with the diminishing device size. In each device, the number of dopant atoms and defects reduces to quantifiable levels, resulting in higher time-zero and -dependent variability. RTN is observed as the sudden and random discrete drain current fluctuation under constant voltage, whose parameters are broadly featured by time information and current fluctuations. Although the gate voltage (V_G)-dependent RTN time constants (τc, τe) are well known for revealing the trap locations and energy levels, the V_G-dependent RTN magnitudes are not thoroughly investigated in experiments, owing to the narrow measurement window inside specific voltages. RTN is becoming a more critical issue in influencing device performances and reliabilities for new devices. Understanding the RTN-induced fluctuations, particularly in a large V_G range, is essential to revealing the device's physics and performance. Lots of efforts have been devoted to investigating the V_G-dependent RTN magnitudes and their degrading impacts [1–3]. However, the majority of the existing studies are focused on numerical simulation with certain initial assumptions. The device selection in an experiment is typically restricted to a single dominated and slow-speed RTN trap which makes the measurements complex.

Using the suggested dual-point approach (Appendix B for detail), several relationships between the gate-overdrive (V_G-V_{th0}) and threshold voltage fluctuations are generated and illustrated in Figures 1(a) and (b). For p-field effect transistors (p-FETs), distributions of ΔV_{th0} and ΔV_{thH} are obtained, whereas they are slightly different for n-field effect transistors (n-FETs). The ΔV_{th0} and ΔV_{thH} of each device are extracted and illustrated in Figure 1(c) for n-FETs and p-FETs, respectively, for deep insight on the RTN-induced threshold voltage variations. Guided by the dash arrows, various trends are observed as the ΔV_{th0} increases, in which the ΔV_{thH} remains nearly constant for n-FETs and increases linearly for p-FETs. The significance of ΔV_{thH} and ΔV_{th0} is evaluated and demonstrated in Figure 1(d) employing the autocorrelation method. As the ΔV_{th0} increased from 1 to 4 mV, the autocorrelation coefficients decrease drastically, indicating that the relationships between ΔV_{th0} and ΔV_{thH} for n-FETs were weaker as the ΔV_{th0} increased. On the contrary, the autocorrelation coefficient roughly remains constant for p-FETs, indicating that ΔV_{th0} has a relatively stronger relevance to ΔV_{thH}. In other words, ΔV_{th0} is roughly proportional to ΔV_{thH}, which is consistent with the initial assumptions.

By examining the RTN time constants at different voltages, $\tau 0$ and the slope of the ($\tau c/\tau e$)-V_G curve are obtained from each device. The distributions of $\tau 0$ are shown in Figure C1, both of which roughly follow a normal distribution, indicated by the red dash line for n-FETs and p-FETs, respectively. Given that Type-II traps are prominent in p-FETs, it is speculated that the interactions between the oxide trap and gate electrode are likely to cause a strong influence of ΔV_{th0} on ΔV_{thH}. According to three-dimensional atomistic device simulations, the trap location and its relative distance to the percolation pathways in the conducting channel are the major determinants of threshold voltage variations at different voltages [3]. The V_G-dependent RTN magnitudes could be explained by the cooperating effects of percolation path revolutions, RTN types, and trap locations in the dielectric layer, which might explain the V_G-dependent RTN magnitudes; however, this requires a deeper understanding of the device physics.

With the flowchart in Appendix D, a simple technique for generating V_G-dependent ΔV_{ths} is provided based on the measured data. Similar log-normal distributions of the produced and measured ΔV_{ths} are obtained for n-FETs and p-FETs, respectively. Some examples of the generated ΔV_{th0} and ΔV_{thH} (100 samples) are indicated in Figure D2. For

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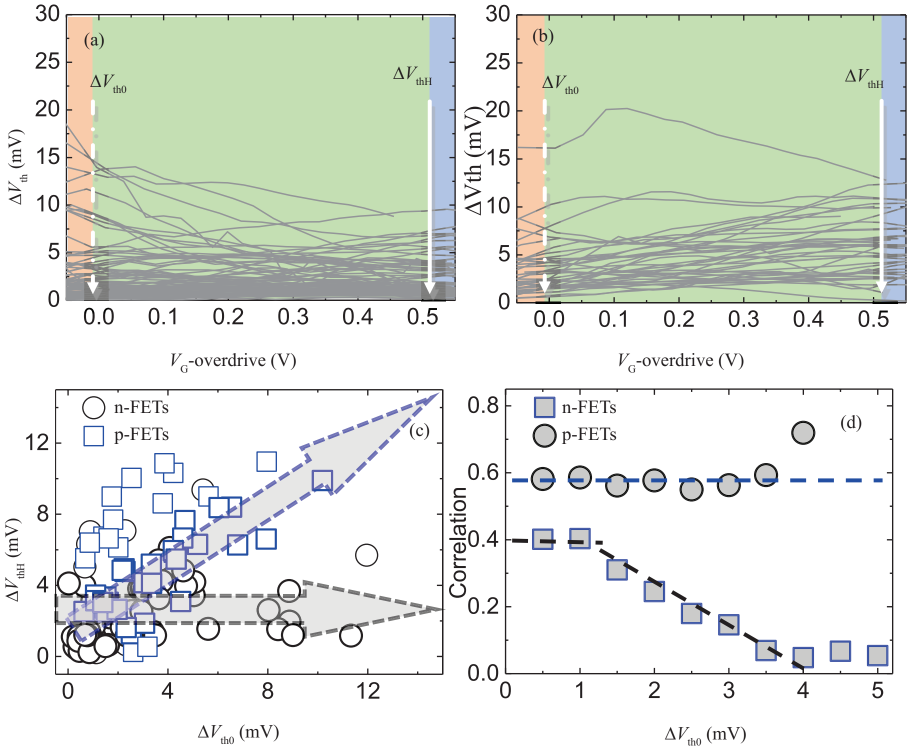

Figure 1 (Color online) The experimental relationship between V_G-overdrive (V_G-V_{th0}) and threshold voltages fluctuation in (a) n-FETs and (b) p-FETs, respectively. (c) The relationship between ΔV_{th0} and ΔV_{thH} and (d) the autocorrelation coefficient under various ΔV_{th0} for n-FETs and p-FETs, respectively.

the generated ΔV_{ths}, they are more dispersed in p-FETs than in n-FETs, which is consistent with the measured data in Figures 1(a) and (b). Since the suggested technique primarily focuses on the measured data and their statistical connection, the RTN-induced threshold voltage fluctuations at different voltages could be simulated validly.

In conclusion, the RTN-induced ΔV_{ths} is experimentally attained at various voltages in the range of the subthreshold to the linear region by employing the dual-point method. For n-FETs and p-FETs, the ΔV_{ths} has similar distributions but distinct trends under various V_G. The various relationships between the ΔV_{th0} and ΔV_{thH} are attributed to the cooperation effects of trap kinds and positions based on the statistical data. A simple and feasible method is proposed to generate the V_G-dependent ΔV_{ths} based on the measured data. Our findings provide potential possibilities to examine the RTN-induced intolerable fluctuations in circuit simulations and applications.

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Supporting information Appendixes A–D. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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