Random Telegraph Noise of a 28-nm Cryogenic MOSFET in the Coulomb Blockade Regime

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Abstract

We observe rich phenomena of two-level random telegraph noise (RTN) from a commercial bulk 28-nm p-MOSFET (PMOS) near threshold at 14 K, where a Coulomb blockade (CB) hump arises from a quantum dot (QD) formed in the channel. Minimum RTN is observed at the CB hump where the high-current RTN level dramatically switches to the low-current level. The gate-voltage dependence of the RTN amplitude and power spectral density match well with the transconductance from the DC transfer curve in the CB hump region. Our work unequivocally captures these QD transport signatures in both current and noise, revealing quantum confinement effects in commercial short-channel PMOS even at 14 K, over 100 times higher than the typical dilution refrigerator temperatures of QD experiments (<100 mK). We envision that our reported RTN characteristics rooted from the QD and a defect trap would be more prominent for smaller technology nodes, where the quantum effect should be carefully examined in cryogenic CMOS circuit designs.

1 Introduction

Random telegraph noise (RTN) refers to two-level single-charge signal fluctuations and has been intensively studied for many decades in metal-oxide-semiconductor field-effect transistors (MOSFETs) \[1\] \[2\] \[3\] \[4\] \[5\] \[6\]. The root cause of RTN in most MOSFETs is the capture and emission of a charged particle (i.e. an electron or a hole) by a defect (e.g. a charge trap) at the oxide layer interface or within the oxide layer. State-of-the-art commercial technology has further reduced the MOSFET size into deep sub-\SI{100}{\nano\meter} regime. This transistor scaling exacerbates the charge trap phenomenon which significantly affects the device operation and performance. Recently, there are growing demands to develop large-scale fault-tolerant quantum computers based on short-channel complementary metal-oxide-semiconductor (CMOS) devices operating at cryogenic temperatures \[7\]. Two physical parameters of CMOS, sub-micron size and low operation temperatures, trigger the observation of quantum transport phenomena such as the Coulomb blockade (CB) and resonant tunneling appearing in small-size (<100 nm) quantum dots (QDs) \[8\] \[9\]. Furthermore, it is crucial to investigate the electrical transport noise properties of commercial MOSFETs in RTN, along with the CB oscillation, which was already reported in a silicon QD \[10\], CMOS \[11\] \[12\], and individual carbon nanotubes \[13\] below 4 K. Recently, 22-nm and 40-nm CMOS devices are characterized at low temperatures, 2 K and 50 mK to exhibit QD transport signatures in Refs. \[14\] and \[15\], respectively. However, noise measurements were not done in these sub-micron commercial CMOS at low temperatures yet. Here we report the RTN responses in the CB regime with commercial 28-nm MOSFETs at 14 K. This work deepens the understanding of commercial CMOS noise and their uses for cryogenic applications.

2 Energy Band Diagram and Coulomb Blockade

Among several foundry 28-nm PMOS and NMOS devices, we present our experimental data with a PMOS transistor with gate width \(W = 1.2\ \mu\text{m}\) and gate length \(L = 28\ \text{nm}\) as the device under test (DUT). The device sits at 14 K in a dry cryostat (Advanced Research Sys-
series of capacitance (C) to three terminals of the PMOS: gate-capacitance $C_G = 2.28 \text{ aF}$ from the gate voltage separation between adjacent CB humps of 70 mV, source-capacitance $C_S = 2.75 \text{ aF}$, and drain-capacitance $C_D = 1.37 \text{ aF}$ from two slopes of the DC curves in Fig. 1(a). The location of the QD in the 28 nm channel is about 9 nm from S, which is estimated by the ratio between $C_S$ and $C_D$. We assume that the QD is a disk shaped, and with the oxide thickness of 1.3 nm and $\text{SiO}_2$ relative permittivity, the size of the QD is also theoretically calculated to be a radius as about 5.96 nm which is sketched in Fig. 1(b).

Temporal current $|I_D(t)|$ traces are recorded at the sampling interval of 4.96 ms (the minimum time interval in HP4156 for the current value range (0.5-14 nA) without any artificial digitization) in the CB hump region (0.54 V $> |V_{GS}| > 0.60$ V), and typical $|I_D(t)|$ data are presented at the left and right sides of the maximum hump at $|V_{GS}| = 0.566$ V in Figs. 2(a) and 2(b), respectively. Random jumps between two unique current levels ($|I_{D, \text{high}}|$ and $|I_{D, \text{low}}|$) on top of background white-noise fluctuations occur distinctly and persis-
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![Figure 3](image-url) | ![Figure 3](image-url) |
---|---|
(a) | (b) |
(c) | (d) |
(e) | (f) |

3 RTN Behavior around CB hump

The average \( \tau_{\text{high}} \) and \( \tau_{\text{low}} \) from discretized signals exhibit dramatic switching from \( |I_{\text{D, high}}| \)-dominance to \( |I_{\text{D, low}}| \)-dominance around \( |V_{\text{GS}}| = 0.566 \) V. This voltage corresponds to the humps of the DC \( I_{\text{D}} - V_{\text{GS}} \) variations (gray solid line) in Figs. 2(a) and (b), where the QD energy levels align with \( E_{F,S} \) or \( E_{F,D} \). Below \( |V_{\text{GS}}| = 0.566 \) V (light orange region), the device prefers the \( |I_{\text{D, high}}| \) level with longer \( \tau_{\text{high}} \). For \( |V_{\text{GS}}| > 0.566 \) V, a drastic switching of the time constants occurs in \( |V_{\text{DS}}| = 10 \) mV and 25 mV (Figs. 2(a) and (b)).

\( \Delta I_{\text{RTN}} \) is displayed against \( |V_{\text{GS}}| \) in Figs. 3(c) and (d). \( \Delta I_{\text{RTN}} \) oscillates at half period of the CB hump broadening in \( |V_{\text{GS}}| \), where the sharp minimum coincides with \( |V_{\text{GS}}| \approx 0.566 \) V. The unclear second hump of \( \Delta I_{\text{RTN}} \) in Fig. 3(d) may be due to the larger bias voltages with more charges in the channel to screen the quantum behavior. This \( \Delta I_{\text{RTN}} - |V_{\text{GS}}| \)-oscillation is exactly the same as the RTN amplitude behavior in a silicon QD reported in [10], where the QD surface potential \( \phi \) is controlled by \( |V_{\text{GS}}| \) but disturbed by a trap nearby. In addition, for the DUT biased near threshold region, \( \phi \) is linearly modulated by \( |V_{\text{GS}}| \). We could express \( \Delta I_{\text{RTN}} \) as the uniform potential fluctuation model,

\[
\Delta I_{\text{RTN}} = \frac{\partial I_{\text{RTN}}}{\partial \phi} \Delta \phi = \frac{\partial I_{\text{D}}}{\partial V_{\text{GS}}} \Delta V_{\text{GS}} = g_{\text{m}} \Delta V_{\text{GS}},
\]  

(1)

where \( g_{\text{m}} \) is the transconductance and \( \Delta V_{\text{GS}} \) is the equivalent fluctuation with respect to \( V_{\text{GS}} \) caused by the capture and emission behavior of the trap. Under this picture, the capture and emission behavior causes a constant shift to the DC transfer curve (Fig. 2(c)). We examine the current noise power spectral density (PSD) that exhibits the \( 1/f^2 \)-Lorentzian signature from a single RTN trap in Fig. 2(d).

One prominent observation is the high \( \Delta I_{\text{RTN}}/|I_{\text{D}}| \), over 50% of \( |I_{\text{D}}| \), which implies the significant RTN impact the charge transport, in particular when the number of charges \( N \) in the channel is small. \( N \) is estimated theoretically by the inverse of \( \Delta I_{\text{RTN}}/|I_{\text{D}}| \) described in [13]. \( N \) is around 1-5 at \( |V_{\text{GS}}| = 0.56 \) V, but it grows quickly to 20-40 at \( |V_{\text{GS}}| = 0.57 \) V, consistent with \( N \sim 10-20 \) estimated from the thermal energy hopping picture. The charged trap may gen-
erate an additional electric-field to push the transfer curve, which demonstrates that the device acts like a quantum single-electron transistor to sensitively detect environmental conditions. Hence, quantum transport properties should be taken into account when designing cryogenic CMOS circuits, especially for devices that are biased at low voltage.

Figs. 3(e) and (f) give the PSD values at 10 Hz as a function of $|V_{GS}|$. The half-period PSD oscillations in both $|V_{DS}|$ nicely match with the $g_m|V_{GS}|$ trend, which further supports the previous uniform potential fluctuation model. The interesting observation of the minimum noise at the maximum of $I_D$ in the hump region offers an optimal bias condition with minimum RTN to operate cryogenic devices.

4 Conclusion

We observe quantum footprints in the RTN behavior of foundry 28-nm bulk PMOS devices even at 14 K arising from CB and resonant tunneling through systematic analysis of fluctuating currents in both time and frequency domains to quantify the RTN parameters. A uniform potential fluctuation model is proposed to explain the dramatic RTN switching behavior around the CB hump. Our complete DC and noise studies of commercial MOSFETs support potential cryo-applications including CMOS quantum computers.

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