On The Magnitude of Random Telegraph Noise in Ultra-Scaled MOSFETs

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Abstract

Random telegraph noise (RTN) has been shown to be a more severe scaling issue than the Random Dopant Effect (RDE). However this observation relies heavily on studies which focus only on threshold voltage (V_{TH}) fluctuations. V_{TH} measurements make separation of these two scaling issues (RTN and RDE) difficult. Since future scaled devices may use channels with no or low doping, it is important to examine the impact of RTN without the influence of RDE. In this work, we experimentally verify the "hole in the inversion layer" model of RTN and then use it to examine the magnitude of RTN in ultra-scaled devices without the influence of RDE. This analysis strongly suggests that RTN is a serious issue even in the absence of RDE.

Introduction

The magnitude of RTN in MOSFET drain current is known to become larger as the size of the channel shrinks [1-3]. In recent years, RTN has become a serious concern for memory devices [4-12] due to their aggressively scaled geometries. It is these studies which have led to the conclusion that RTN is a more serious problem than RDE [8]. In these aggressively scaled devices, the measured RTN amplitudes are known to vary drastically [13, 14]. It is this long tail of the statistical distribution of RTN amplitudes which has become such an issue. In many studies, a V_{TH} fluctuation is measured instead of the RTN magnitude. This allows the direct comparison of the impact of RTN with RDE. However, at or below threshold, RDE and RTN are coupled, leading to an anomalously large RTN observation[15]. Since RDE and now RTN are well established scaling issues, it is quite possible future MOSFET's will combat RDE by using channels which are either intrinsic or have very low doping concentrations. Can the removal of RDE also solve the RTN issues? This is a very important question indeed.

RTN and Screening

A long held belief is that low frequency (1/f) drain current noise is the superposition of many RTN fluctuations. Thus, RTN is often attributed to mobility fluctuation, number fluctuation, or both. However, for very small device dimensions, a third mechanism may be more important [14, 16]. This third mechanism, first proposed by Reimbold [2], suggests that the trapped charge creates a "hole" (or cored-out section) in the inversion layer through Coulombic repulsion (fig. 1). A simple relationship between RTN amplitude and the size of the hole was also given [2].

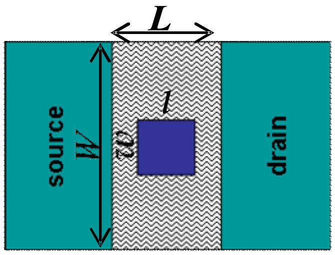

Fig. 1 Defect creates a hole (dark blue square) of the size w x l in the inversion layer.

A more refined equation (eqn. 1) was later introduced by Ohata *et al.* [17] relating the RTN amplitude to the hole size (approximated as a square). In this construct, the screening length determines the size of the hole.

$$\frac{\Delta I_d}{I_d} = \frac{wl(\sigma_0 - \sigma)}{WL(\sigma_0 - \sigma) - w(L-l)(\sigma_0 - \sigma)} \qquad (1)$$

where w and l are the width and length of the hole; W and L are width and length of the channel; and σ_0 and σ are the conductivity of the channel and in the cored out region respectively.

Even with the refined equation, Ohata *et al.* found that this "hole in the inversion layer" approach yields (at low gate overdrive) screening lengths which seem unreasonably large [17]. A

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decade later, anomalously large RTN amplitudes at low gate overdrives have been successfully explained using a channel percolation path concept [15]. A percolation path is the result of random dopant distribution leading to an uneven surface potential in the channel. At low gate overdrives, this percolation path (or uneven channel) has an effective channel width that can be drastically smaller than the drawn width. From equation 1 it is clear that Ohata *et al's* difficulty can be reconciled by using an effective channel width which is much smaller than the as-drawn dimension. In this work we revisit the "hole in the inversion layer" paradigm, and examine RTN in the absence of percolation.

Percolation Path & Screening Length

We utilize nMOSFET's with 1.4 nm SiON gate dielectrics in this study. RTN amplitudes from many highly-scaled devices were investigated. The observed RTN amplitude as a function of gate overdrive is typically non-monotonic (Fig. 2).

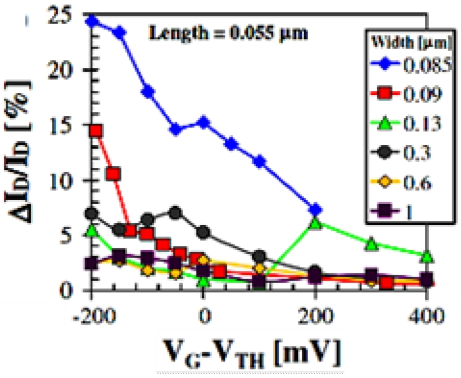

Fig. 2 RTN amplitudes as a function of gate overdrive for a number devices with different width. Typical trends are non-monotonic. Device sizes are as drawn.

This behavior is expected since it is unlikely that a single defect is physically located precisely over the "pinch-off" point in the potential landscape. However, we were able to observe one device with a particularly large RTN amplitude as well as a monotonic dependence on gate overdrive (fig. 3). This device produced very clean 2-level RTN (fig. 4), implying a single defect. This behavior strongly suggests that the defect is positioned entirely within the active region of the channel, and is located right on top of the percolation path.

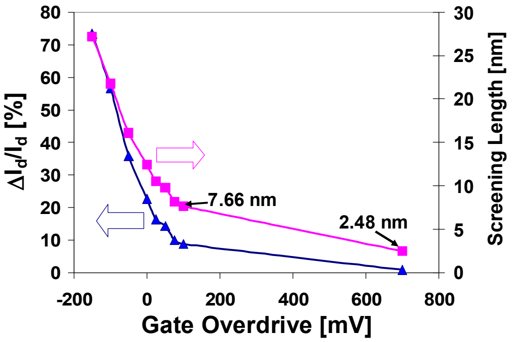

Fig. 3 RTN amplitude (triangles) for this particular device is a smooth monotonic function of gate overdrive. The calculated screening lengths drops rapidly as gate overdrive increase from below threshold to above threshold. The as drawn size of this device is 55 nm x 85 nm. The size used for the calculation is 35 nm x 85 nm.

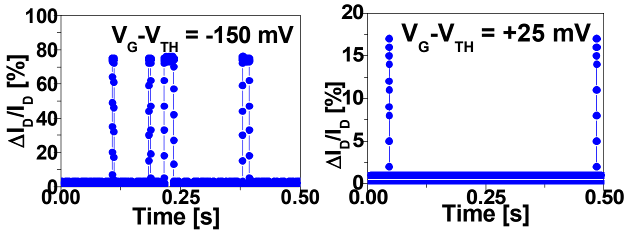

Fig. 4 The RTN signal from the device shown in fig. 3 are very large and very clean. Showing the characteristic of a single defect.

Also shown in fig. 3 are the calculated screening lengths (equation (1), assuming $w = l$, $\sigma = 0$) from the observed RTN amplitudes. At low gate overdrives, the screening length increases rapidly to unphysical lengths. Such large screening lengths led Ohata *et al.* [17] to doubt the "hole in the inversion layer" model. An examination of equation 1 reveals that an ultra-narrow channel width (or a percolation path-induced ultra-narrow effective channel width) can lead to large RTN amplitude, resulting in an artificially large screening length.

As the gate overdrive increases, the percolation path widens and eventually disappears [15]. This suggests that the screening length behavior depicted in fig. 3 is largely due to the widening of the percolation path under the hole (this includes the +150 mV gate overdrive point). To lend support to this assertion, we study the relationship between drain current and channel width (fig. 5). It is clear that a linear relationship is not established until at least +200 mV above threshold. It is also

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clear that the last point in fig. 3 (+700 mV) is completely free of the percolation effect. Thus the screening length for this point is purely due to the inversion charge density.

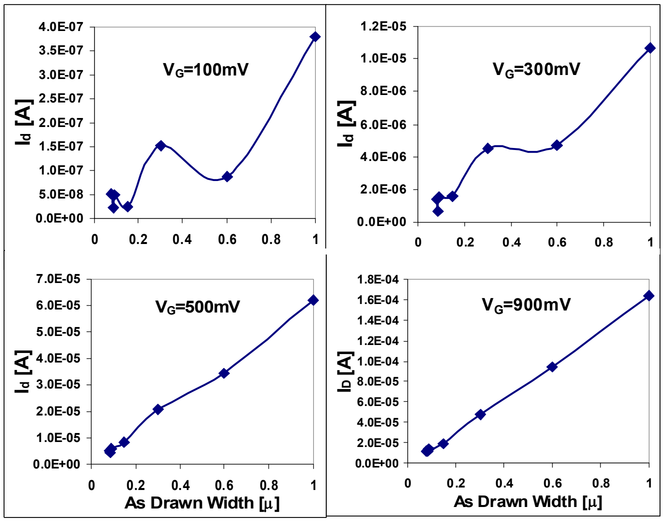

Fig. 5 Drain current as a function of device width for 55 nm (drawn) nMOSFET at various gate overdrives. Deviation from linear relationship is a sign of percolation path which makes the effective channel width smaller than the drawn width, sometimes by a larger factor. The percolation path is expected to disappear at some point above threshold. In this example, some hint of it is still there at V_G=500 mV, which is 200 mV above threshold.

What we have observed and discussed so far is entirely consistent with the simulation done by Asenov *et al.* [15]. They have shown that as gate overdrive increases, the RDE signature of RTN amplitude disappears.

A 2.48 nm screening length at such strong inversion seems large because the Debye length is expected to be ~ 1nm. On the other hand, Debye *et al.*'s Screened Coulomb Potential is a 3-D model [18]. The inversion layer is a 2-D system, and screening length is expected to be larger than the 3-D value [19]. In addition, equation 1 is only an approximation. The actual value may be some what different. The key point is that the calculated screening length from RTN amplitude is no longer outside the reasonable range. Given the crude nature of the equation, this is a strong indication that the "hole in the inversion layer" model is correct and we can now use this data point to anchor an extrapolation to see what lies ahead as we scale the MOSFET further.

Implication to scaling

Here we consider only the conditions in which percolation is absent (its presence will make matters worse). Let $w = l = p/\sqrt{n}$ where n is inversion charge density, and p is proportionality constant, we get

$$\frac{\Delta I_d}{I_d} = \frac{p^2}{n\left(WL - \frac{L}{p\sqrt{n}} + p^2 n\right)} \qquad (2)$$

Recall that $n \cong C_{OX,eff}\left(V_G - V_{TH}\right)$ [20], where $C_{OX,eff}$ is the effective inversion capacitance. If we assume n remains more or less constant with scaling (oxide capacitance increase is offset by gate overdrive decrease), we can use equation 2 to extrapolate to smaller device sizes. Since we can anchor the equation with a known experimental data point (RTN amplitude and device size), the extrapolation should be on solid ground.

In fig. 6, we show the projected RTN amplitude for various technology nodes. Three different channel widths are simulated (W=L, W=3L, and W=5L). If we set the acceptable RTN amplitude to 10%, then the minimum width of $W = L$ can only be used in the 22 nm node. At 16 nm node, it is marginal. Wider channel widths do help. At $W = 5L$, the RTN amplitude is within 10% down to the 8 nm node.

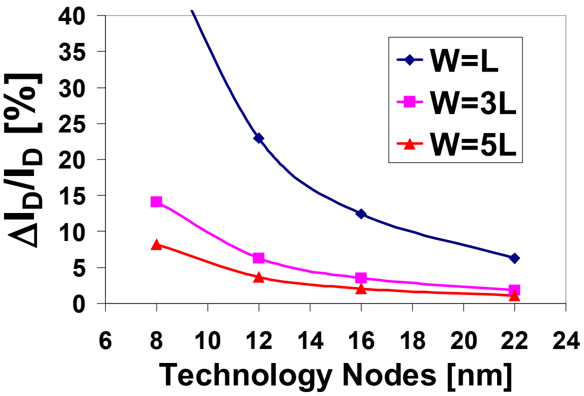

Fig. 6 RTN amplitude at different technology nodes for minimum width ($W = L$) devices as well as wider devices ($W = 3L$, and $W = 5L$).

Note that the extrapolation result in fig. 6 represents the worst case scenario – the defect is right at the center of the active area. This is very likely the tail of the RTN amplitude distribution. To experimentally observe this, the sample size must be large, or one gets lucky as in our case. Since we cannot ignore the tail of the distribution, the results presented in figure 6 are instructional.

Fig. 6 reinforces the conclusion that RTN is a new limiting factor for scaling [10]. Because the RDE has been removed in the data, our conclusion is stronger. It suggests that while going to an undoped channel may alleviate RDE, RTN will remain a huge factor that can cause large V_{TH} or equivalently drain current fluctuations.

Equations (1) and (2), as they are written, are not suitable to assess V_{TH} fluctuation. However, if the “hole in the inversion layer” model is indeed correct, it is not hard to see that the effect is huge at threshold. If we consider that the inversion charge density is two orders of magnitude lower at threshold, the screening length becomes comparable to the minimum device size at 22 nm.

Conclusions

In this work, we show that the “hole in the inversion layer model” together with a percolation path reduced channel width works reasonably well to explain RTN in ultra-small MOSFETs. This establishes the relationship between RTN amplitude and inversion charge density. Using this relation, we show that the RTN amplitude will grow to unacceptable levels in future technology nodes. We also show that V_{TH} fluctuation will continue to grow even when using undoped channels.

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