New Methods for the Direct Extraction of Mobility and Series Resistance from a Single Ultra-Scaled Device

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INTRODUCTION

The engineering of channel mobility (μ) and series resistance (R_{SD}) in advanced CMOS technologies are both extremely challenging and of paramount importance. Together, they determine the key metric of performance – ON current. The reported scaling trends suggest that these two quantities will remain a primary concern in advanced CMOS technology development. Reliable extraction methodology for both quantities directly from a single ultra-scaled device is therefore extremely important and urgently needed. In this work we demonstrate (1) a wafer level geometric magnetoresistance methodology for μ extraction that is free from the influence of series resistance and (2) an elegantly simple R_{SD} extraction methodology with verifiable accuracy. Both methodologies are applicable to ultra-scaled silicon nMOSFETs and **require only a single device**.

RESULTS AND DISCUSSION

Fig. 1a shows the Hall mobility μ_H of 1.6nm SiON nMOSFETs (with strained channel) as a function of gate overdrive for a variety of channel lengths extracted from our novel geometric magnetoresistance methodology. The observed gate length dependent mobility degradation (fig. 1b) is quite similar to that reported in [1]. The geometric magnetoresistance effect (fig. 2) is a magnetic field modified current transport (due to the Lorentz force) phenomenon similar to the Hall effect. In devices with large width by length ratios (W >> L), one can measure a magnetic field induced change in the channel resistance or drain current (eqn. 1). Note that Hall mobility (μ_H) is extracted from the geometric magnetoresistance measurement, not the magnetoresistance mobility (μ_{MR}). Extracted this way, μ_H is advantageously independent of trapped charges.

Due to the small size of the magnetoresistance effect in low mobility semiconductors such as silicon, all previous magnetoresistance efforts [1-4] require very high magnetic fields (> 10 T) and special device packaging. The large experimental obstacles relegate such measurements to special laboratories. Our approach introduce two basic innovations: (1) the use of AC measurements to enhance the signal to noise ratio and therefore greatly lower the required magnetic field strength; (2) measurement of the change in current rather than resistance to eliminate the influence of R_{SD}. The drastically lower field requirement enables the use of a small permanent magnet and therefore, the ability to perform the measurement directly at the wafer level with no packaging. Elimination of the influence of series resistance enables mobility extraction directly from a single device. AC modulation of the magnetic field is achieved through a voice coil driven magnet as shown in figs. 3 and 4.

We emphasize that we modulate the magnetic field at two non-zero values. This is the key to **extract μ_H values which are independent of R_{SD}** (eqn. 1). Likewise, separation of the small AC drain current variation from the large DC drain current (to achieve "background free" detection (fig. 4)) is the key to measurement of such a small current change. The magnetic field modulation (≈ 2000 G) is shown in fig. 5a. The measured drain currents, I_1 and I_2, as well as an unavoidable inductive current, $I_{inductive}$ are shown in fig. 5b. The difference between the current levels (ΔI) is extracted from an extended time series (inductive transient excluded) such that they are subject to less than < 0.1% error (fig. 5c). The extracted (ΔI) divided by the DC current level (I_{DC}) is directly proportional to the Hall mobility, μ_H (eqn. 1). As mentioned above, since drain current variation is the measured quantity, continuity ensures that the measured $\Delta I/I_{DC}$ is free from the influence of R_{SD} and therefore eliminated the need of a second device like in previous efforts [5,6].

A potential source of error can still arise from the magnetoresistance present in source-drain extension (SDE) regions. To understand the impact of the SDE, we first consider the fictitious case that the SDE has the same mobility as the channel. This results in an effectively longer channel length and leads to a **smaller** measured $\Delta I/I_{DC}$ (eqn. 1). However, since the SDE has a very high dopant concentration, and therefore low mobility, the effect will be quite small. For an aspect ratio of W/L > 10, correction to the measured mobility can be essentially ignored.

Fig. 6a shows a comparison of the effective mobility (μ_{eff}) (eqn. 2) and the extracted μ_H as a function of gate overdrive for a 10 x 0.2 μm^2 nMOSFET. The striking discrepancy is a vivid demonstration of how R_{SD} affects the extracted μ_{eff}. In order to correct μ_{eff}, we must know R_{SD}. This leads to the second key innovation of this paper - a very simple and elegant series resistance extraction scheme. **At low drain biases**, both the square law model and the more accurate sheet charge model reduce to the simple drain current equation (eqn. 3) [7]. Taking the **ratio** of two I_D-V_G curves leads directly to R_{SD} as a function of gate overdrive (eqn. 4). The approximations behind this simple approach is that when the two drain biases are small, μ_{eff}, C_{OX}, L_{eff}, and R_{SD} can all be assumed identical.

The R_{SD} extracted from two drain biases (10 mV and 50 mV) as well as the total resistance ($R_T = V_{DS}/I_{DS}$) for the 10 x 0.2 μm^2 device is illustrated in fig. 7a. To verify the validity of this methodology, we corrected the original I_D-V_G curves for the extracted R_{SD} values (eqn. 5) to produce two new R_{SD}-free I_D-V_G curves. We then re-apply the methodology to extract a new R_{SD} (fig. 7b). The R_{SD} extracted from the corrected data is very nearly zero at higher gate overdrives and is subject to only small errors at lower gate overdrives. This serves as proof of the validity of our R_{SD} extraction technique as well as demonstrated its accuracy.

To understand why this simple R_{SD} extraction technique works, we examine the errors associated with our assumptions used to derive eqn. 4, namely a drain bias independence of L_{eff}, μ, and C_{ox}. Fig. 8a and 8b illustrate the simulated percentage change in L_{eff} (eqn. 6) and the percentage change in μ (eqn. 7) as a function of the change in V_{DS} in the linear regime, where V_{bi} is the built-in voltage drop between the SDE and the channel. Our R_{SD} extraction methodology using V_{DS} = 50 mV and 10 mV introduces a < 1% error in L_{eff} and ≈ 1% error in μ. The assumption of a constant C_{OX} is valid only when gate overdrive is at least 6 kT above threshold (fig. 8c), and is clearly seen in the extracted R_{SD}.

With confidence in our R_{SD} extraction, we use the corrected I_D-V_G curves for the 10 x 0.2 μm^2 device to extract a R_{SD}-free μ_{eff} (fig 9). We note that the R_{SD} corrected μ_{eff} is much closer to the μ_H. However, there is still some discrepancy due in part to the Hall factor that makes the μ_H 5 to 7% higher than the μ_{eff}, and in part due to the uncertainly in L_{eff} assumed in the μ_{eff} extraction.

CONCLUSION

In summary, we have presented a novel wafer-level Hall mobility (μ_H) measurement methodology which can be implemented in any conventional wafer prober (no specialized equipment needed). In addition, we demonstrated a simple R_{SD} extraction scheme with verifiable accuracy. Both techniques work directly on a single ultra-scaled MOSFET, providing an elegant solution to two very difficult but important measurements. The authors acknowledge the Office of Microelectronic Programs at NIST for financial support.

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$$\textbf{(1)}\quad \frac{\Delta I}{I_{DC}} = \mu_H^2\left(B_2^2 - B_1^2\right)\left[1 - 0.543\frac{L + \Delta L(\mu_{SD}/\mu_{CH})}{W}\right] \cong \mu_H^2\left(B_2^2 - B_1^2\right) \qquad \textbf{(2)}\ \mu_{eff} = \frac{I_{DS}L}{WC_{OX}(V_G - V_{TH})V_{DS}} \qquad \textbf{(3)}\ I_D = \mu C_{OX}\frac{W}{L_{eff}}\left(V_G - V_{th} - \frac{I_D R_{SD}}{2}\right)(V_D - I_D R_{SD})$$

$$\textbf{(4)}\quad R_{SD}^2\left(\frac{I_{D2} - I_{D1}}{2}\right) + R_{SD}\left(V_{th2} - V_{th1} + \frac{V_{D1} - V_{D2}}{2}\right) = \frac{(V_G - V_{th1})V_{D1}I_{D2} - (V_G - V_{th2})V_{D2}I_{D1}}{I_{D2}I_{D1}} \qquad \textbf{(5)}\ I_{D\_corrected} = \left(\frac{V_D}{R_T - R_{SD}}\right)\left(\frac{V_G - V_{th}}{V_G - V_{th} - 0.5(R_{SD}I_D)}\right)$$

$$\textbf{(6)}\ L_{eff} \propto \frac{\sqrt{V_{bi} + V_{D1}} - \sqrt{V_{bi} + V_{D2}}}{\sqrt{V_{bi}} + \sqrt{V_{bi} + V_{DSAT}}} \qquad \textbf{(7)}\ \mu_{eff} \approx \left(\frac{V_{th} + 0.2}{3t_{ox}} + \frac{V_G - V_{th}}{6t_{ox}}\right)^{1/3}$$

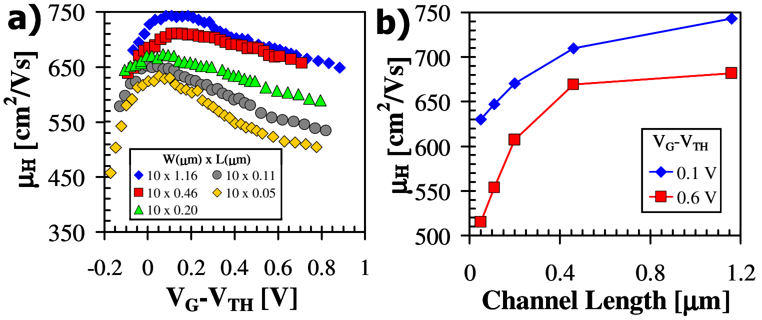


Fig 1: (a) Geometric magnetoresistance derived Hall mobility in 1.6nm SiON nMOSFETs as a function of gate overdrive for a variety of channel lengths. The extraction technique renders the observed mobility immune to R_{SD} effects. (b) μ_H as a function of channel length for 2 different gate overdrives. We observe a similar channel length dependence as reported in [1].

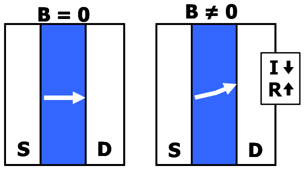


Fig 2: Schematic illustration of the geometric magnetoresistance effect. If the geometry of the device is such that W>L, the effect is measured as a current decrease or a resistance increase.

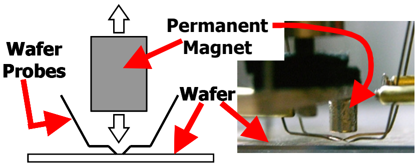


Fig 3: Schematic illustration (a) and photograph (b) of the our wafer level geometric magnetoresistance measurement.

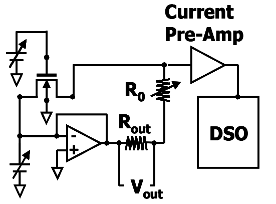
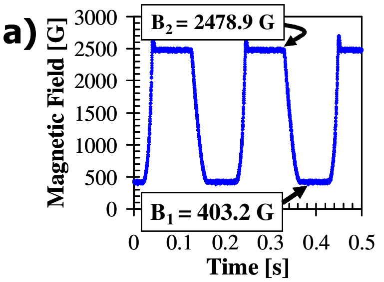


Fig 4: Detection circuit used to measure the magnetoresistance modified drain current. The source voltage is used to "balance" the DC drain current using a variable resistor (R_0). The resultant AC magnetoresistance modified drain current is measured using a current pre-amplifier and digital storage oscilloscope (DSO).



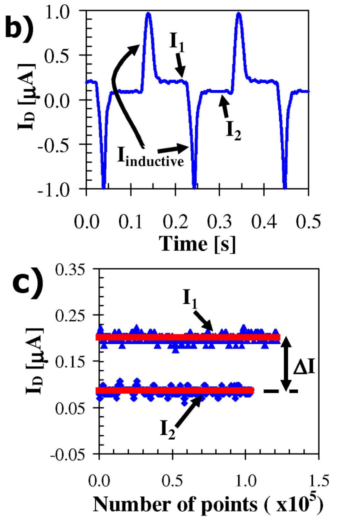


Fig 5: (a) Modulated magnetic field at the surface of the wafer. (b) Representative current trace showing the two different current levels (I_1 and I_2) as well as the inductive current generated due to the time varying magnetic field. (c) The difference (ΔI) is ∝ to μ_H.

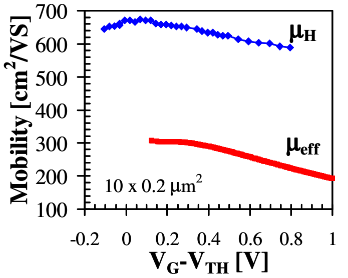


Fig 6: Comparison of the extracted Hall mobility and the effective mobility (eqn. 2) in the 10 x 0.2 μm². The effective mobility is drastically underestimated due to series resistance (not an issue for the Hall mobility).

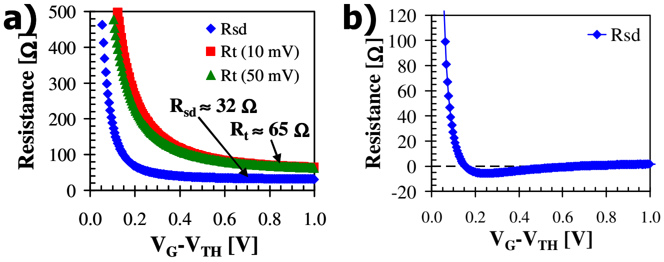


Fig 7: (a) Extracted R_{SD} as a function of gate overdrive for the 10 x 0.2 μm² device. The extracted R_{SD} in (a) is used to correct the original I_D-V_G data and re-extract a second series resistance (b) using eqns. 4-5. The second R_{SD} extraction is ≈0 Ω (for larger gate overdrives) which serves as proof of the validity of this approach.

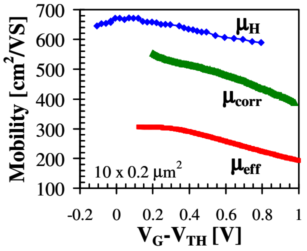
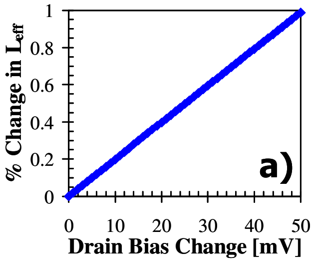


Fig 9: Magnetoresistance extracted Hall mobility, effective mobility, and the effective mobility corrected for the series resistance.



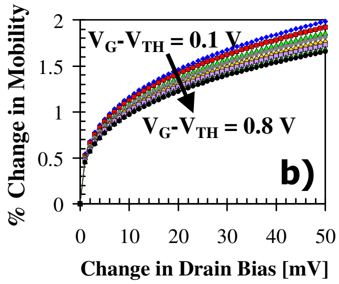
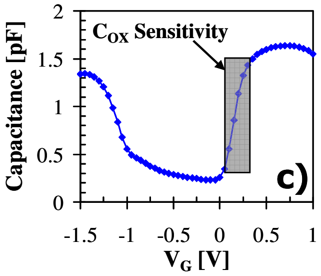


Fig 8: (a) Simulated (eqn. 6) %change in L_{eff} and (b) simulated (eqn. 7) %change in μ as a function of the change in V_D in the linear regime. The R_{SD} extraction methodology using V_{DS} = 50 mV and 10 mV only introduces a < 1% error in L_{eff} and ≈ 1% error in μ. However, there is some uncertainty in C_{OX} near threshold as the drain bias will induce a change in vertical field and consequent change in C_{OX} (c).



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