Geometric Magnetoresistance Mobility Extraction in Highly Scaled Transistors

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***Abstract*—Geometric magnetoresistance (gMR) provides a promising solution to the difficult challenges associated with channel mobility extraction in nanoscale transistors. However, this technique requires significant experimental considerations which are uncommon in most laboratories. In addition, removing the influence of series resistance on the extracted mobility introduces further difficulty. In this letter, we present a new gMR measurement methodology that not only greatly simplifies the experimental requirements but also yields mobility values which are free from series resistance effects.**

***Index Terms*—Channel mobility, geometric magnetoresistance (gMR).**

I. Introduction

METAL–OXIDE–SEMICONDUCTOR field-effect-transistor (MOSFET) channel mobility has been observed to decrease severely as the effective channel length is deeply scaled [1]–[4]. Unraveling the physics behind this degradation requires accurate channel mobility measurements. However, channel mobility characterizations have become increasingly more difficult in small channel length transistors due to the breakdown of several fundamental electrostatic assumptions [5]. This has led several researchers to employ the geometric magnetoresistance (gMR) effect as an alternate means for channel mobility extraction [1]–[3].

The gMR effect is a special case of the Hall effect in which the chosen MOSFET geometry (minimum channel length) acts to short circuit the Hall voltage [6]. The Lorentz force alters the current path leading to a change in the measured resistance which is proportional to the square of Hall mobility (μ_H) [7]. Unfortunately, the size of the gMR effect is actually quite small when it is applied to relatively low-mobility silicon-based devices [7]. This measurement issue has been recently countered by using uncommonly high magnetic fields which require specialized experimental equipment and device preparations [1]–[3].

A unique complication which arises from gMR measurements in highly scaled MOSFETs is that the channel resistance is comparable or, in some cases, smaller than the source/drain series resistance $(R_{\rm SD})$ [8]. This results in a substantially smaller fractional change in the measured resistance, leading to erroneous channel mobility values. In a pioneering work, Chaisantikulwat *et al.* introduced a method to correct their gMR measurements for the $R_{\rm SD}$ component [1]. It involves the characterization of a second MOSFET with a similar channel length and some necessary assumptions [1]. Unfortunately, these assumptions are quite similar to those which rendered most of the existing mobility measurements unreliable [5].

In this letter, we demonstrate a low-field gMR measurement methodology which yields μ_H values that are free from the influence of $R_{\rm SD}$. This eliminates the need for measurement of a second device and the associated $R_{\rm SD}$ assumptions. A small low-cost permanent magnet placed very near the surface of the MOSFET provides the required magnetic field and greatly simplifies the experimental setup. This technique can be easily implemented in existing probe stations and allows the measurement to be carried out directly at the wafer level.

II. Experimental Procedures

For MOSFET geometries with a channel width/length that is greater than five, the gMR effect is often described as [7]

$$R_B/R_0 \cong 1 + \mu_H^2 B^2 \tag{1}$$

where B is the magnetic field, R_B is the measured resistance with $B \neq 0$, and R_0 is the measured resistance when $B = 0$. We note that μ_H extracted using this approach is remarkably similar but not precisely equal to the conventionally defined Hall mobility due to differences in energy-dependent scattering times [3]. Recent simulations have suggested that these differences can be quite small at room temperature [9]. Thus, in this letter, we stick to the more common μ_H designation. An examination of (1) reveals that the measured gMR effect is very small for typical silicon MOSFETs with mobility of 350 $\rm cm^2/V \cdot s$. A typical Hall magnet $(B = 0.4$ T) only produces a $(0.035\ \rm m^2/V \cdot s)^2 \times (0.4\ T)^2 \approx 0.02\%$ resistance change. It is for this reason that published works typically utilize heroically large magnetic fields ($>$ 10 T) [1]–[3], [7].

The need for a very high magnetic field is largely due to the experimental difficulty associated with measuring a small

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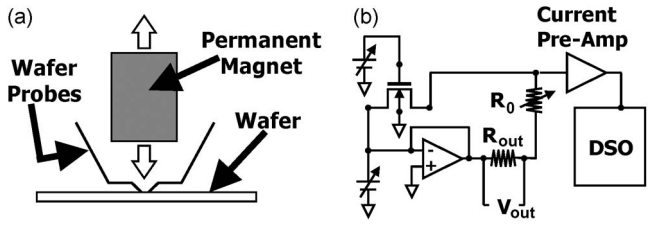

Fig. 1. (a) Schematic illustration of the measurement apparatus. (b) Detection circuit schematic illustrating how the source voltage is used to generate a current (through R_0 and $R_{\rm out}$) which exactly balances the dc drain current.

quasi-dc signal "buried" in a large background. The standard approach to overcome this difficulty is to turn to an ac detection scheme. This requires a large ac magnetic field modulation. Typical electromagnet ac modulations are well below 0.05 T and are too small to be useful in this application. We forgo the electromagnet approach and achieve ≈0.2-T ac magnetic field by using a voice coil to modulate the axial distance (≈0.45 cm) of a small permanent magnet from the surface of the wafer [see Fig. 1(a)]. We utilize a remarkably strong neodymium cylindrical magnet with a residual flux density of ≈1.45 T at the surface, a radius of 0.25 cm, and a length of 1 cm. The minimum axial distance between the magnet and the surface of the wafer is ≈0.15 cm.

We note that nearly all the published gMR studies measure the effect as a change in resistance (1) [1]–[3], [7]. In our approach, we *instead* measure the magnetic-field-induced *change in drain current*. The small magnetic-field-induced drain current modulation is measured using a low-noise detection circuit [see Fig. 1(b)] which removes the dc background and achieves high sensitivity using a very high-gain current amplifier. The resultant ac response is recorded with a digital storage oscilloscope. The described detection scheme facilitates room-temperature gMR measurements in silicon-based devices at the wafer level.

In our method, the magnetic field oscillates between two nonzero values [a lower field (B_1) and a higher field (B_2)] associated with the maximum and minimum distances of the magnet from the wafer surface, respectively. The time-dependent magnetic field as seen by the MOSFET is illustrated in Fig. 2(a). The magnetic field is measured by a commercially available Hall sensor as well as a calibrated Van der Pauw structure. The Van der Pauw structure was used as an intermediary calibration structure to ensure that the measured magnetic field [see Fig. 2(a)] is indeed the same field seen by the MOSFET. The uncertainty in our magnetic field measurements is approximately ±0.51 mT. This is actually quite acceptable as it introduces less than 0.27% error in the extracted mobility. A square-wave modulated ac magnetic field is necessary to separate the drain current change due to the gMR effect from the inductive current arising from the time-varying magnetic field.

Since we are measuring the drain current at two nonzero magnetic fields, (1) must be modified to reflect our experimental conditions

$$\frac{I_{\rm B1}}{I_{\rm B2}} = \frac{\left(1+\mu_H^2 B_2^2\right)}{\left(1+\mu_H^2 B_1^2\right)} \tag{2}$$

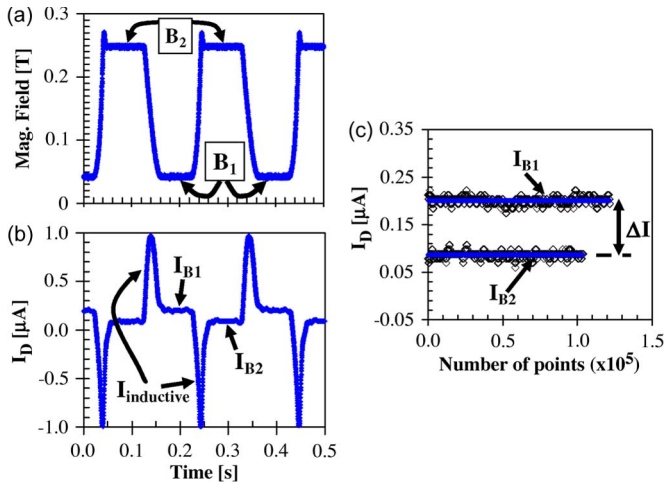

Fig. 2. (a) Typical magnetic field modulation between B_1 and B_2 as a function of time. (b) Drain current response ($I_{\rm B1}$, $I_{\rm B2}$, and $I_{\rm inductive}$) to the magnetic field modulation as a function of time. (c) $I_{\rm B1}$ and $I_{\rm B2}$ from an extended time series ($I_{\rm inductive}$ excluded).

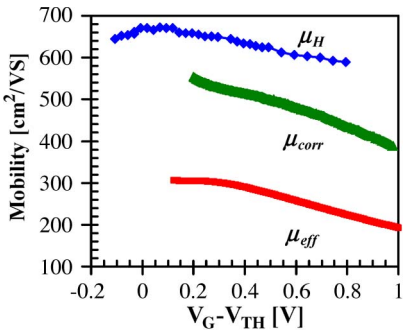

Fig. 3. gMR-derived μ_H, electrostatics-derived $\mu_{\rm eff}$, and a corrected mobility $(\mu_{\rm corr})$ corresponding to $\mu_{\rm eff}$ corrected for series resistance as a function of gate overdrive in a 10×0.2 μm^2 n-type MOSFET.

where $I_{\rm B1}$ is the current measured at the lower magnetic field B_1 and $I_{\rm B2}$ is the current measured at the higher magnetic field B_2. Since the gMR-induced perturbation on the drain current is at least four orders of magnitude smaller than the absolute dc value $(I_{\rm dc})$, (2) can be further simplified to

$$\mu_H^2 \cong \frac{\Delta I}{I_{\rm dc}\left(B_2^2 - B_1^2\right)} \tag{3}$$

where ΔI is $I_{\rm B1} - I_{\rm B2}$. Fig. 2(b) illustrates typical measured drain currents $I_{\rm B1}$ and $I_{\rm B2}$ as well as the unavoidable inductive currents $I_{\rm inductive}$ arising from the time-varying magnetic field. The difference between the noninductive current levels (ΔI) is extracted from an extended time series (inductive transient excluded) such that they are subject to less than 0.1% error [see Fig. 2(c)]. The extracted $\Delta I/I_{\rm dc}$ as well as knowledge of the two magnetic field levels (B_1 and B_2) allows for a direct extraction of Hall mobility μ_H (3).

III. Results and Discussion

Fig. 3 illustrates a typical gMR μ_H for a 10×0.2 μm^2 1.6-nm SiON n-type MOSFET as a function of gate voltage

(V_G) minus the threshold voltage $(V_{\rm th})$ or gate overdrive. In addition, Fig. 3 shows the extracted effective mobility $(\mu_{\rm eff})$ from standard I_D–V_G measurements using [10]

$$\mu_{\rm eff} = \frac{I_D L_{\rm eff}}{W C_{\rm OX} (V_G - V_{\rm th}) V_D} \tag{4}$$

where I_D is the drain current, V_D is the applied drain voltage, W is the channel width, $L_{\rm eff}$ is the effective channel length, and $C_{\rm OX}$ is the oxide capacitance. In this form, $C_{\rm OX}(V_G - V_{\rm th})$ serves as a crude estimation of inversion charge [10]. $\mu_{\rm eff}$ is obviously much smaller than μ_H. This is due to several reasons, one of the most important of which is $R_{\rm SD}$.

We mentioned before that, when using our approach, the gMR-derived μ_H is free from the influence of $R_{\rm SD}$. This is because we measure $\Delta I/I_{\rm dc}$ (3) instead of measuring the magnetic-field-induced *resistance* change (1). This is a direct measure of the fractional change in the channel current due to the magnetic field. Since the current which flows through the channel is the same current which flows through the source and drain (continuity), the measured $\Delta I/I_{\rm dc}$ and subsequent μ_H are void of an $R_{\rm SD}$ contribution.

On the other hand, $\mu_{\rm eff}$ is subject to a significant $R_{\rm SD}$ influence. This $R_{\rm SD}$ influence can be accounted for by altering (4) such that [11]

$$\mu_{\rm eff} = \frac{I_D L_{\rm eff}}{W C_{\rm OX} \left(V_G - V_{\rm th} - \frac{I_D R_{\rm SD}}{2}\right) (V_D - I_D R_{\rm SD})}. \tag{5}$$

The $R_{\rm SD}$ values are extracted using a simple technique which is accurate to within 10% [12]. This $R_{\rm SD}$ extraction technique has the benefit of direct $R_{\rm SD}$ extraction on a single highly scaled transistor with limited assumptions [12]. The $R_{\rm SD}$-corrected $\mu_{\rm eff}$ values $(\mu_{\rm corr})$ in Fig. 3 account for a large part of the discrepancy between μ_H and $\mu_{\rm eff}$. However, we do note that, even after the $R_{\rm SD}$ correction, there is still a discrepancy between μ_H and $\mu_{\rm eff}$. This discrepancy has a number of contributors. The accuracy of the extracted $R_{\rm SD}$ is only within 10% (previously mentioned). The values used for both $L_{\rm eff}$ and $C_{\rm OX}$ also have similar levels of uncertainty. Uncertainties also arise from nonunity Hall factors at room temperature for all gate overdrives [3], [13], [14]. We note that $\mu_{\rm eff}$ is subject to an additional inaccuracy due to the trapped charge in the channel. Since standard I_D–V_G measurements on these devices did not reveal any sort of hysteretic charge trapping characteristics (not shown), we believe this charge trapping effect to be quite small for these devices. However, all these uncertainties can account for the discrepancy between μ_H and the corrected $\mu_{\rm eff}$. These reconcilable differences, combined with an inherent $R_{\rm SD}$ independence, further validate this alternative μ_H extraction technique as an attractive measurement solution.

IV. Conclusion

In summary, we have presented a low-field μ_H measurement methodology based on the gMR effect. The approach provides a viable solution to mobility extraction in highly scaled transistor geometries where purely electrical characterizations fail. This technique drastically relaxes the experimental requirements (large magnetic fields and special device preparation) typical in most gMR measurements and yields μ_H values which are immune to $R_{\rm SD}$.

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