Observation of Asymmetric Magnetoconductance in Strained 28-nm Si MOSFETs

E. A. Gutiérrez-D., E. Póndigo-de los A., V. H. Vega-G., and F. Guarin

***Abstract*—We have measured gate current components off the axis perpendicular to the surface. The measured gate oxide magnetoconductance exhibits a pronounced magnetic asymmetry, which indicates that the gate current is flowing into different crystallographic orientations with different effective masses and hole mobilities. By identifying and monitoring the different gate current axis components, we have enhanced the understanding of the physics for Si–oxide interface charge transfer and channel conductance in low-dimensional semiconductor devices.**

***Index Terms*—Nanoscaled MOSFETs, quantum magnetoconductance.**

I. Introduction

To IMPROVE hole mobility on 28-nm p-type Si MOSFET, a rotation of 45°, with respect to the $\langle 1\ 1\ 0 \rangle$ crystallographic wafer plane, is implemented in addition to the use of compressive elements [1] that induce strain and provide an extra hole mobility enhancement. Other technologies also make use of retrograde $\mathrm{Si}_x\mathrm{Ge}_{1-x}$ source and drain extensions to add uniaxial compressive strain [2]. These different technological and structural approaches have led up to 162% improvements for the hole mobility [3]. Even though these device structural changes improve the hole mobility, they give rise to multicrystallographic or anisotropic movement of charges that impact the transport properties along the channel as well as the tunneling of holes through the gate oxide. It is the purpose of this work to introduce an experimental framework that sheds light on the way that holes move through the channel-oxide and oxide-gate interfaces and contribute to the oxide leakage current. For this purpose, an external magnetic field Bz is applied with different strengths perpendicular to the surface of a 28-nm pMOSFET (see Fig. 1). By doing so, we have observed that, under the reversal of the Bz field, both the channel and gate currents Is and Ig do not preserve magnetosymmetry [4]. Numerical simulations indicate that this asymmetrical magnetomodulation mechanism is correlated to crystallographic anisotropy and to the morphology of the channel-oxide and gate-oxide interfaces [5].

Manuscript received October 18, 2011; accepted November 18, 2011. Date of publication January 6, 2012; date of current version January 27, 2012. This work was supported in part by CONACyT through Grant 100028. The review of this letter was arranged by Editor M. Östling.

E. A. Gutiérrez-D., E. Póndigo-de los A., and V. H. Vega-G. are with the National Institute of Astrophysics, Optics and Electronics (INAOE), Tonantzintla 72840, Mexico (e-mail: edmundo@inaoep.mx; poae830714@hotmail.com; vic_hvg@hotmail.com).

F. Guarin is with the Semiconductor Research and Development Center, IBM, Hopewell Junction, NY 12533 USA (e-mail: guarinf@us.ibm.com).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LED.2011.2177491

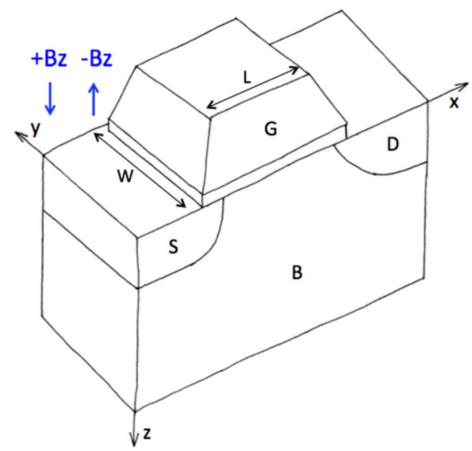

Fig. 1. Experimental setup. The magnetic field (Bz) is applied perpendicular to the MOSFET surface in the z-direction. Channel current Is flows in the x-direction, and gate current Ig does in the z-direction.

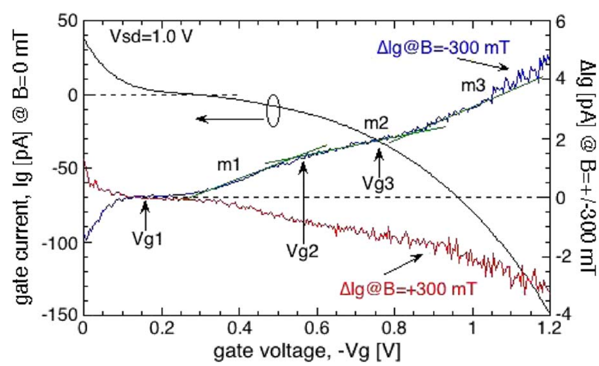

Fig. 2. Measured gate current Ig and magnetomodulated gate current ΔIg for $Vsd = 1.0$ V and $Bz = \pm 300$ mT.

II. Experimental Observation and Hypothesis

Static electromagnetic measurements were performed on five samples of a 28-nm pMOSFET with a gate oxide thickness of 1.7 nm and a (W/L) aspect ratio of (1 μm/28 nm). Following the technique reported in [6], the electrical characteristics were statistically measured, five times in each sample, while the device was assembled in between the poles of an electromagnet that generated a B field from -300 to $+300$ mT in steps of 25 mT. Changing the sign of the electromagnet current source changes the B field direction. The average experimental value of five different samples is used for the analysis. In all the experiments, the magnetic field B was applied perpendicular to the MOSFET surface.

Fig. 2 shows the measured $Ig{-}Vg$ and $\Delta Ig{-}Vg$ characteristics at $Vsd = 1.0$ V and $B = +300$ mT and -300 mT,

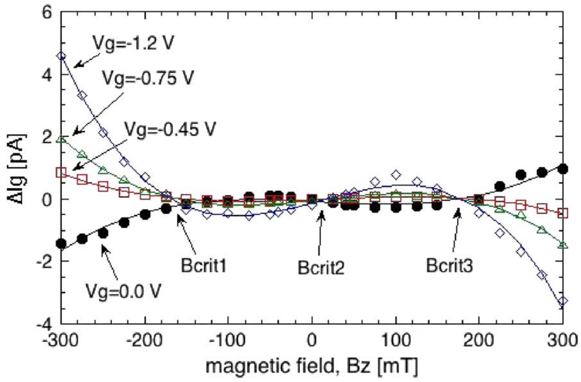

Fig. 3. Measured magnetomodulated gate current ΔIg as a function of the Bz field for $Vg = 0.0$, -0.45, -0.75, and -1.2 V, for $Vsd = 1.0$ V.

where the magnetomodulated gate current is defined as $\Delta Ig = (Ig_{B\neq 0} - Ig_{B=0})$. There are three distinctive Vg points, i.e., $Vg1$, $Vg2$, and $Vg3$, where the slope $d\Delta Ig/dVg$ changes. For $Vg < Vg1$, the $+B$ field increases the gate leakage current flow from drain to gate, while for $Vg > Vg1$, the gate-to-channel gate current flows in the reverse direction from gate to channel. Changing the sign of B reverses the situation, which confirms the magnetoconductance reversibility [4]. The $Vg1$ region correlates to subthreshold channel conduction, while $Vg2$ corresponds with the subthreshold-to-inversion channel conduction transition. The third transition at $Vg3$ is located at the onset of strong inversion. As the Bz field is parallel to the surface-to-gate axis (z-axis), the $(v_{\mathrm{hg}} \times B)$ cross product, where v_{hg} is the gate hole leakage velocity, should be zero. However, the different $m1$, $m2$, and $m3$ slopes indicate the presence of an Ig current component off the z-axis. We have two relevant observations: 1) The off-z-axis Ig components increase from low to high Vg voltages, and 2) the magnetodeflection of the Ig x and y components is slightly different in magnitude and shape under the reversal of the Bz field. The second observation reveals that the morphologic structures of the lower channel-oxide and upper gate-oxide interfaces are different, which forces Ig to have off-z-axis components. By changing the strength of the Bz field, the magnetodeflection ΔIg should change [4]; the experimental results are shown in Fig. 3, where ΔIg is plotted versus Bz for different values of Vg. There is an evident asymmetry for $Vg = -1.2$, -0.75, -0.45, and 0.0 V. All the curves cross each other and become equal to zero at $B = -175$ mT, $B = +0.75$ mT, and $B = +200$ mT. There is a perfect z-axis alignment of Ig and Bz at these three critical $Bcrit1$, $Bcrit2$, and $Bcrit3$ fields, which indicates a cancellation of the x–y components. When looking at the magnetomodulated channel current ΔIs, which is expected to be fully perpendicular to Bz, one should expect a symmetrical reduction of Is for negative and positive Bz fields as dictated by the magnetoconductance mechanism [4]. However, a remarkable anisotropy is also observed, as shown in Fig. 4. Compared to the ΔIg case, the ΔIs magnetomodulated current first increases for positive B fields in the -0.3 V $< Vg < -0.7$ V range and then rolls down to negative values for the $Vg > -0.8$ V range. For negative Bz fields, ΔIs has a complementary behavior (see Fig. 4). The change of slope from $m1$ to $m2$ at $Vg2$ in Fig. 2 correlates with the crossing of the extrapolated lines in Fig. 4. This crossing point at $Vg2$ corresponds with the diffusion-to-drift transition of the channel conductance (see Fig. 6), which indicates that the magnetic field Bz has a differentiated effect on the charge diffusion and the drift mechanisms.

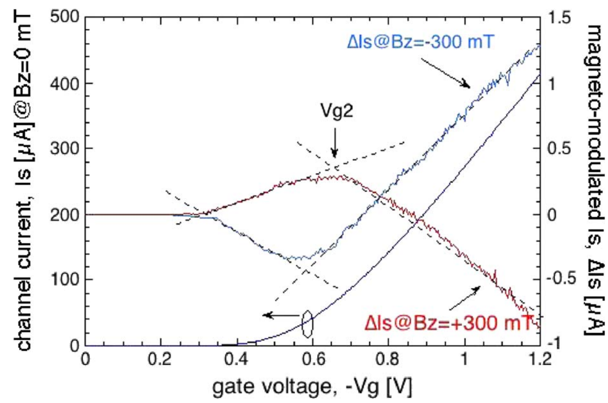

Fig. 4. Measured channel current Is and magnetomodulated channel current ΔIs for $Bz = \pm 300$ mT, for $Vsd = 1.0$ V.

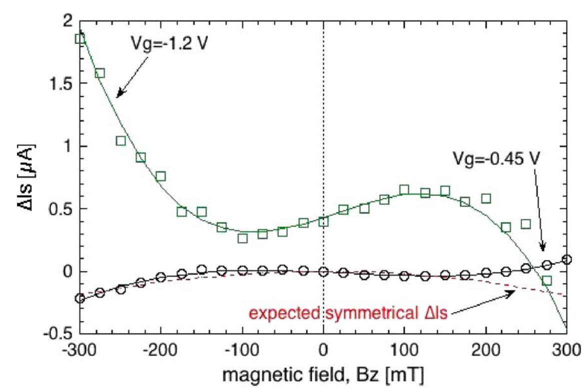

Fig. 5. Measured magnetomodulated channel current ΔIs versus Bz field for $Vg = -0.45$ and -1.2 V, for $Vsd = 1.0$ V. The dashed curve represents the expected symmetrical behavior of the $(\Delta Is–Bz)$ curve for $Vg = -0.45$ V.

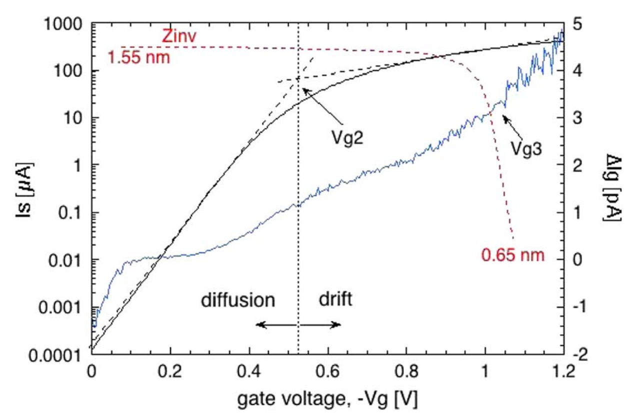

Fig. 6. Measured Is and ΔIg as a function of Vg for $Vsd = 1.0$ V. The inset of the dashed curve represents the simulated inversion hole channel centroid $Zinv$ varying from 1.55 nm at low Vg to 0.65 nm at high Vg.

The ΔIg magnetomodulated current is larger at high Vg voltages, which indicates that the Ig off-z-axis components are larger at high Vg voltages. The positive values of ΔIs in the -0.3 V $< Vg < -0.75$ V range for $+300$ mT and for the $Vg > -0.75$ V range for $Bz = -300$ mT indicate a hole flow into different crystal orientations with different mobilities along the channel. The variation in sign and magnitude of ΔIs as a function of Vg is explained as a hole channel flow diversion into different crystal orientations. The Bz field dependence of ΔIs for the diffusion ($Vg = -0.45$ V) and the drift ($Vg = -1.1$ V) regions is shown in Fig. 5.

As dictated by the magnetoresistance effect, a parabolic-like behavior (dashed curve) of the ΔIs–Bz curve is expected. However, as observed for both the ΔIg and ΔIs, there is an asymmetrical and nonmonotonic behavior, which is an indication of multidimensional flow of holes both along the channel and through the gate oxide. The data plotted in Fig. 6 confirm the correlation of the inflection $Vg2$ point with the diffusion-to-drift transition. Simulation of the hole inversion channel centroid $Zinv$ is also plotted as a function of Vg [7]. This simulation shows $Zinv$ decreasing with the increase of the absolute value of Vg, with a strong rolloff at $Vg = Vg3$. We conclude that the inflection $Vg3$ point and slope $m3$ of Fig. 1 are also correlated to the $Zinv$ position.

III. Conclusion

By using an externally applied magnetic field in conjunction with electrical characterization, we have measured the anisotropic and multicrystallographic nature of hole channel and gate currents in strained 28-nm pMOSFETs. The measured channel and gate magnetomodulated curves ΔIg–Vg and ΔIs–Vg show that the anisotropy and multicrystallographic hole transport is gate voltage dependent. The higher gate voltage leads to higher multicrystallographic hole flow. This is because most of the injected holes into the oxide, at large Vg's, come from the source and drain edges, where there is a considerably large x–y Ig component [5]. On the other hand, the random dopant fluctuation [8] also contributes to the magnetoasymmetry by making the channel charge asymmetrical. We believe that this magnetoconductance characterization technique provides a very powerful tool that contributes to the understanding of the complex charge transport in nanoscaled semiconductor devices such as single-gate and multigate MOSFETs, Fin-FETs, and quantum wires and dots.

Acknowledgment

The first author would like to thank IBM for providing the test samples and A. Torres for his insight and very fruitful technical discussions.

References

[1] F. Arnaud, A. Thean, M. Eller, M. Lipinski, Y. W. Teh, M. Ostermayr, K. Kang, N. S. Kim, K. Ohuchi, J.-P. Han, D.R. Nair, J. Lian, S. Uchimura, S. Kohler, S. Miyaki, P. Ferreira, J.-H. Park, M. Hamaguchi, K. Miyashita, R. Augur, Q. Zhang, K. Strahrenberg, S. ElGhouli, J. Bonnouvrier, F. Matsuoka, R. Lindsay, J. Sudijono, F. S. Johnson, J. H. Ku, M. Sekine, A. Steegen, and R. Sampson, "Competitive and cost effective high-k based 28 nm CMOS technology for low power applications," in *IEDM Tech. Dig.*, 2009, pp. 651–654.

[2] H. Ohta, Y. Kim, Y. Shimamune, T. Sakuma, A. Hatada, A. Katakami, T. Soeda, K. Kawamura, H. Kokura, H. Morioka, T. Watanabe, J. Oh, Y. Hayami, J. Ogura, M. Tajima, T. Mori, N. Tamura, M. Kojima, and K. Hashimoto, "High performance 30 nm gate bulk CMOS for 45 nm node with Σ-shaped SiGe-SD," in *IEDM Tech. Dig.*, 2005, pp. 240–243.

[3] M. Yang, E. P. Gusev, M. Ieong, O. Gluschenkov, D. C. Boyd, K. K. Chan, P. M. Kozlowski, C. P. D'Emic, R. M. Sicina, P. C. Jamison, and A. I. Chou, "Performance dependence of CMOS on silicon substrate orientation for ultrathin oxynitride and HfO_2 gate dielectrics," *IEEE Electron Device Lett.*, vol. 24, no. 5, pp. 339–341, May 2003.

[4] P. Y. Yu and M. Cardona, *Fundamentals of Semiconductors*. New York: Springer-Verlag, 1996, ch. 5, pp. 222–223.

[5] V. H. Vega-G., "Quantum mechanical analysis and modeling of sub-65 nm MOSFETs under the influence of a magnetic field," Ph.D. dissertation, INAOE , Puebla, Mexico, Oct., 2011.

[6] E. A. Gutiérrez-D. and F. Guarin, "Experimental evidence of unconventional room-temperature quantum Hall effect (RTQHE) in 65 nm Si nMOSFETs at very low magnetic fields," in *Proc. ESSDERC*, 2010, pp. 178–181.

[7] J. A. Lopez-Villanueva, P. Cartujo-Cassinello, F. Gamiz, J. Banqueri, and A. J. Palma, "Effects of the inversion-layer centroid on the performance of double-gate MOSFETs," *IEEE Trans. Electron Devices*, vol. 47, no. 1, pp. 141–146, Jan. 2000.

[8] K. J. Kuhn, M. D. Giles, D. Becher, P. Kolar, A. Kornfeld, R. Kotlyar, S. T. Ma, A. Maheshwari, and S. Mudanai, "Process technology variation," *IEEE Trans. Electron Devices*, vol. 58, no. 8, pp. 2197–2208, Aug. 2011.