Institution: Liverpool John Moores University

Unit of Assessment: 13 Electrical and Electronic Engineering, Metallurgy and Materials

Title of case study: Impact of research into transistor carrier mobility measurement on globally used instruments

1. Summary of the impact

Carrier mobility is a key parameter for the semiconductor industry, but its measurement is characterised by poor accuracy and unreliability for advanced transistors. The Microelectronics Research Group (RG1), working with the Logic Devices Consortium at IMEC (Inter-University Microelectronics Research Centre in Leuven, Belgium), developed a new technique that overcomes these problems, implemented it on industrial-standard equipment provided by Keithley Instruments (a US company based in Cleveland, Ohio), and prepared the application notes and software. This benefits test engineers in the semiconductor industry through significant improvement in the accuracy, reliability, cost, and efficiency of measurements. Keithley is disseminating information to its global customer base and is highlighting it as strength of its instruments in the promotion.

2. Underpinning research

Ever since computers were invented, their speed has increased by developing smaller and faster transistors. Transistor speed is characterised by the electron mobility, so that its measurement is essential for evaluating new materials and processes in the semiconductor industry. The standard measurement technique is based on the split capacitance-voltage (Split-CV), but it increasingly suffers from poor accuracy and unreliability as transistors become smaller. Smaller transistors cause problems, since they have higher <u>gate leakage</u> and use materials with higher <u>charge trapping</u>. Moreover, the existing techniques measure the capacitance and conduction current under different drain voltages, and this <u>drain voltage mismatch</u> introduces unacceptable errors for the small transistors operating at low voltage.

Early attempts to resolve these problems only had limited successes and required expensive set-up and complex procedures [R2.1]. During this REF period, a new technique has been developed and demonstrated, which overcomes the shortcomings mentioned above without using expensive set-up, as detailed below.

<u>Drain voltage mismatch:</u> To extract mobility, one needs both the conduction current and the mobile charge. In principle, they should be measured under the same drain voltage. The existing technique, however, measures conduction current with non-zero drain voltage, while mobile charge is measured with zero drain voltage, because the signal for mobile charge would be buried by conduction current if non-zero drain voltage were applied. This drain voltage mismatch leads to unacceptable errors for advanced transistors [R2.1, R2.2].

An early career researcher from the Microelectronics Research Group, Z.Ji, made a breakthrough by proposing and demonstrating, for the first time ever, that conduction current and mobile charge could be measured simultaneously under the same drain voltage, eliminating the drain voltage mismatch. By raising the ramping rate of gate bias one million times over its conventional level through applying an ultra-fast pulse, the displacement current becomes high enough for measuring mobile charge and will no longer be buried by conduction current [R2.1, R2.2].

<u>Gate Leakage:</u> As the gate oxide is downscaled close to one nano-meter, large gate leakage buries the signal of high frequency capacitance meter used for the split-CV [R2.3, R2.4], making the measurement unreliable. To make signal strong enough, the frequency has to rise to the radio frequency (RF) or even GHz range. This, however, requires the costly RF probe station, the network analyser, and complex test structure. In the new technique, the effect of gate leakage on capacitance was cancelled out by subtracting the displacement current at the two pulse edges. The measured capacitance becomes inherently independent of the gate leakage, overcoming a major obstacle without using expensive set-up.

<u>Charge trapping:</u> As high-k dielectric replaces the conventional SiON, charge trapping in gate

dielectric increases. The slow conventional technique gives time for the trapping to take place during measurement and, consequently, the measured mobile charge includes the trapped charges. Since the trapped charges are immobile, they will not contribute to the current. This leads to an underestimation of mobility. In the new technique, the ultra-fast pulse used is too quick for trapping to occur [R2.5, R2.6], suppressing the trapping.

The work was carried out in collaboration with the Logic Devices Consortium at IMEC, whose roles included identifying the shortcomings of existing techniques, supplying test samples, and verifying the proposed technique as users. The impact, however, was delivered mainly through Keithley Instruments, with IMEC playing a complementary role, as detailed in section 4.

3. References to the research

('**' denotes the three papers that best illustrate the quality of the underpinning research)

[R2.1] **Z. Ji, J. F. Zhang, and W. Zhang, "A new mobility extraction technique based on simultaneous ultra-fast Id-Vg and Ccg-Vg measurements in MOSFETs," *IEEE Transactions on Electron Devices*, vol. 59, pp. 1906-1914, 2012 (d.o.i.: 10.1109/TED.2012.2196519).

[R2.2] Z. Ji, J. Gillbert, J. F. Zhang, and W. Zhang, "A new Ultra-Fast pulse technique (UFSP) for channel effective mobility evaluation in MOSFETs," *Proc. IEEE 26th International Conference on Microelectronic Test Structures*, Osaka, Japan, pp. 64-69, 2013 (d.o.i.: 10.1109/ICMTS.2013.6528147).

[R2.3] L. Lin, Z. Ji, J. F. Zhang, W. D. Zhang, B. Kaczer, S. De Gendt, and G. Groeseneken, "A single pulse charge pumping technique for fast measurements of interface states," *IEEE Transactions on Electron Devices*, vol. 58, pp. 1490-1498, 2011 (d.o.i.: 10.1109/TED.2011.2115244).

[R2.4] **Z. Ji, J. F. Zhang, W. Zhang, B. Kaczer, S. De Gendt, and G. Groeseneken, "Interface states beyond band gap and their impact on charge carrier mobility in MOSFETs," *IEEE Transactions on Electron Devices*, vol. 59, pp. 783-790, 2012 (d.o.i.: 10.1109/TED.2011.2177839).

[R2.5] Z. Ji, J. F. Zhang, M. H. Chang, B. Kaczer, and G. Groeseneken, "An analysis of the NBTI-induced threshold voltage shift evaluated by different techniques," *IEEE Transactions on Electron Devices*, vol. 56, pp. 1086-1093, 2009 (d.o.i.: 10.1109/TED.2009.2016400).

[R2.6] **Z. Ji, L. Lin, J. F. Zhang, B. Kaczer, and G. Groeseneken, "NBTI lifetime prediction and kinetics at operation bias based on ultrafast pulse measurement," *IEEE Transactions on Electron Devices*, vol. 57, pp. 228-237, 2010 (d.o.i.: 10.1109/TED.2009.2037171).

4. Details of the impact (indicative maximum 750 words)

This case study gives an example how the RG1 provides solutions to practical problems by direct engagement with industrial partners. The main beneficiaries are test engineers (e.g. those in the Logic Devices Consortium at IMEC) and equipment suppliers (e.g. Keithley Instruments). The details of the impact for each are given in what follows.

Keithley Instruments: Keithley, as a global prime test equipment supplier, played a leading role in disseminating the new technique. After demonstrating the new technique on the home-made facility [R2.1], the RG1 made an effort to maximise its reach and impact by working with Keithley. By implementing the technique on the industrial-standard equipment, it opened a channel for its dissemination to the Keithley's world-wide customer base.

The RG1's activities in developing new measurement techniques have been noted by Keithley and an agreement was signed with Keithley to implement these new techniques on Keithley's instruments in 2010 [C2.1]. After the take-over of Keithley by Tektronix, the collaboration agreement was renewed in 2013 [C2.2]. Following the publication of the new technique for mobility in 2012 [R2.1], Keithley noticed its advantages and "believes that equipping its instrument with such advanced techniques will give it a competitive edge" [C2.2], "as it demonstrates the capability of 4200-SCS and explores its application potential" [C2.1]. Keithley provided its most advanced ultra-fast pulse test module 4225 to the University to implement this technique [C2.2]. By working together with Keithley, the RG1 made the following key contributions:

- It demonstrated that the new technique can be implemented on the industrial standard equipment, as reported in March 2013 [C2.3].
- It prepared the application note no. 3236, authored by Z.Ji from the RG1 [C2.1, C2.4]; the application note is available at Keithley's website addresses given in [C2.4].
- It prepared the control software [C2.1, C2.5], available through Keithley's website given in [C2.5].

Keithley has been disseminating information about this technique to its world-wide customers by highlighting it in its quarterly newsletter "Test Patterns", which was also sent to its global customers by email [C2.6]. It is drawing attention to this technique as one of the strengths for its award-winning 4200-SCS instruments in its sales promotion [C2.1]. These activities provide mechanisms for a global reach and impact. According to the data provided by Keithley, 67 customers downloaded the application notes on the same day when they received the email notification regarding the new feature. Each 4200 instrument costs US$ 80k, but it offers multi-functionality and it is difficult for Keithley to tell how many customers purchased it just because of this new feature.

<u>The Logic Devices Consortium at IMEC:</u> The members of this Consortium include Intel, Global Foundries, TSMC, Sony, Panasonic, and Xilinx. The RG1 has collaborated with it for 20 years [C2.7].

The Consortium supported the research into a new technique by providing three sets of test samples requested by the RG1: one set (2.3-nm SiO_2) as the benchmark and two sets for testing the applicability of the new technique to samples of high trapping (1.65-nm HfSiON/SiON) and high gate leakage (1.28-nm HfSiON/SiON). These samples were the same as those used by the Consortium for technology development [C2.7].

As the users of the new technique, IMEC [C2.7] corroborates that "the new mobility measurement technique simplifies the test procedure without using the expensive RF setup, has better accuracy and efficiency". The significance of the improvement is supported by the following quantitative information:

<u>(i) Reduced cost:</u> The quotations received by the RG1 show that a typical RF probe station costs approximately £130k and it also requires network analyser, such as Agilent PNA, costing over £70k. In addition, the test devices should have special RF structures, whose cost is manufacturer-specific. All of these are not required for the new technique.

<u>(ii) Improved reliability:</u> The commercial capacitance metre can only tolerate gate leakage below 10 A/cm^2, which is lower than the gate leakage in advanced transistors. The capacitance measured by the new technique is independent of gate leakage and it has been demonstrated that mobility can be extracted with a gate leakage as high as 40 A/cm^2 [R2.1, R2.2].

<u>(iii) Better accuracy:</u> The drain voltage mismatch induces an error over 20% and the charge trapping can cause an additional 20% error [R2.1, R2.2]. These errors were eliminated by the new technique.

<u>(iv) Improved efficiency:</u> The existing technique measures current and mobile charges separately, whilst the new technique measures them simultaneously, so that the number of tests is halved [R2.1, R2.2].

5. Sources to corroborate the impact

[C2.1] Statement from the Keithley Instrument Inc., available at http://www.ljmu.ac.uk/ENG/ENG_Docs/C2.1_-_Statement_from_Keithley_on_Mobility_-Case.pdf. Contact Identifier Number: 1.

[C2.2] The renewed collaboration agreement between LJMU and Keithley Instrument, available at http://www.ljmu.ac.uk/ENG/ENG_Docs/C2.2_-_Collab_-_Agreement_-_Keithley.PDF.

Contact Identifier Number: 1.

[C2.3] The paper reporting the successful implementation of the new technique in Keithley's instruments: Z. Ji, J. Gillbert, J. F. Zhang, and W. Zhang, "A new Ultra-Fast pulse technique (UFSP) for channel effective mobility evaluation in MOSFETs," *Proc. of IEEE 26th International Conference on Microelectronic Test Structures*, Osaka, Japan, pp. 64-69, 2013 (d.o.i: 10.1109/ICMTS.2013.6528147), available at http://dx.doi.org/10.1109/icmts.2013.6528147.

[C2.4] The Application Note, directly accessible at http://www.keithley.com/data?asset=57662 and also accessible from the list of application notes at Keithley's web-site http://www.keithley.com/products/semiconductor/parametricanalyzer/characterizationsolutions/?path=4200-SCS/Documents#1 .

[C2.5] The control software: http://www.keithley.com/data?asset=57747 .

[C2.6] Keithley's quarterly newsletter highlighting the new technique: http://www.ggcomm.com/client/Keithley/Newsletters/TestPatterns-Sep13/TP_Sep13_US.html

[C2.7] Statement from IMEC, available at http://www.ljmu.ac.uk/ENG/ENG_Docs/C2.7_-_Statements_from_IMEC_on_Mobility_Case.pdf. Contact Identifier Number: 2.