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Application Note Series

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An Ultra-Fast Single Pulse (UFSP) Technique for Channel Effective Mobility Measurement

Introduction

The channel effective mobility (μ_{eff}) influences the MOSFET performance through the carrier velocity and the driving current. It is one of the key parameters for complementary metal-oxide-semiconductor (CMOS) technologies. It is widely used for benchmarking different processes in technology development and material selection [1, 2]. It is also a fundamental parameter for device modelling [3]. With device scaling down to Nano-size regime and the introduction of new dielectric materials, conventional measurement technique for mobility evaluation encountered a number of problems described in the following section, leading to significant measurement errors. As a result, a new mobility extraction technique is needed.

This application note describes a novel Ultra-Fast Single Pulse technique (UFSP) [4, 5] for accurate mobility evaluation, including the technique principle, how to connect the device, and how to use the provided software in the Model 4200-SCS.

Conventional Mobility Measurement and Challenges

We use a p-channel device of gate length L and width W as an example. When the channel charge is fairly uniform from source to drain in the linear region, the channel effective mobility (μ_{eff}) can be written as

$$\mu_{eff} = \frac{L}{W} \cdot \frac{I_{ch}}{Q_i \cdot V_d} \qquad (1)$$

where V_d is a small bias applied on the drain terminal of the device, Q_i is the mobile channel charge density (C/cm²), and I_{ch} is the conduction current flowing in the channel.

Traditionally, I_{ch} is measured at the drain terminal of the device with the configuration shown in ***Figure 1(a)***. Q_i is extracted from integrating the measured gate-to-channel capacitance, C_{gc}, with respect to V_g, i.e.,

$$Q_i = \int_{+\infty}^{V_g} C_{gc}\, \mathrm{d}V_g$$

by using the connection configuration shown in ***Figure 1(b)***.

The principle of conventional mobility measurement is deceptively simple. However, many challenges and pitfalls are associated with this testing. Several sources of error are often ignored in the past.

Vd-dependence: The conventional technique applies a non-zero V_d (usually 50mV–100mV) for I_{ch} measurement but a zero V_d for Q_i measurement. This difference in V_d used in two measurements

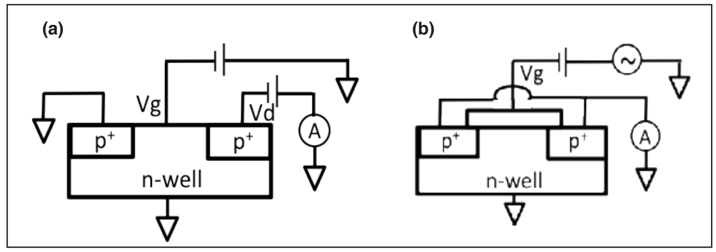

Figure 1. Configuration for (a) conduction current measurement and (b) gate-to-channel capacitance, C_{gc}, measurement.

can lead to significant errors in evaluating mobility for thin oxides, especially in the low electric field region. One example is given in ***Figure 2***, where a higher $|V_d|$ results in a substantial reduction of mobility near its peak. This is because $|V_g–V_d|$ reduces for high $|V_d|$, so that the real charge carrier density for the I_{ch} is smaller than the Q_i measured at $V_d = 0$.

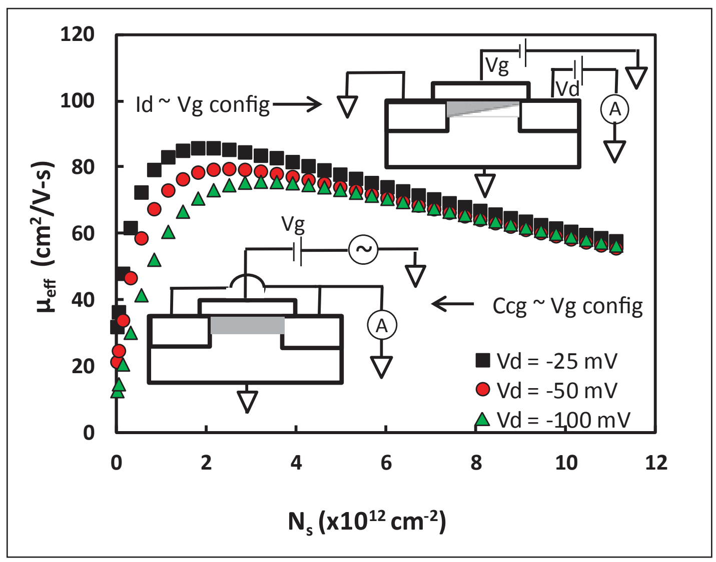

Figure 2. Effective channel mobility measured by conventional technique. I_{ch} was measured under various non-zero drain biases, V_{DS}, but Q_i was measured under $V_d = 0$. The extracted mobility clearly reduces for higher $|V_d|$. Insets illustrate the carrier distribution in the channel.

Charge trapping: The conventional technique used slow measurement with typical measurement time in seconds. The fast charge trapping becomes significant for both thin SiON and high-k dielectric. For slow measurements, trapping can respond during the measurement and give rising to hysteresis and stretch-out of the $C_{gc}–V_g$ curve and a reduction of I_{ch}. This results in an underestimation of mobility.

Leaky dielectric: As gate oxide downscales, high gate leakage current becomes a main challenge for mobility extraction. It affects both I_{ch} and Q_i measurements and in turn the mobility. To minimize its impact on C_{gc} measurement, frequency up to gigahertz has been used, which requires devices with RF structure. The RF structure requires more processing and die space and is not always available.

Cable switching: The conventional technique involves cable changing between I_{ch} and Q_i measurements. This slows down the measurement and can potentially cause breakdown of the device under test.

The Ultra-Fast Single Pulse Technique (UFSP Technique)

To overcome the challenges mentioned above, a novel technique called the Ultra-Fast Single Pulse technique (UFSP) is developed and described below.

A p-channel device is used here for illustrating the working principle of the UFSP technique as shown in ***Figure 3***. The considerations for n-channel devices are similar. To perform the UFSP measurement, a single pulse with edge time of several micro-seconds is applied on the gate terminal of the device. The gate voltage sweeps toward negative during the falling edge of the pulse and turns the device on. The transient currents are recorded at both the source and the drain terminal of the device. The device is then switched off during the subsequent rising edge where gate voltage are swept toward positive. The corresponding transient currents are also to be recorded. Channel effective mobility can be extracted from these four transient currents measured within several micro-seconds.

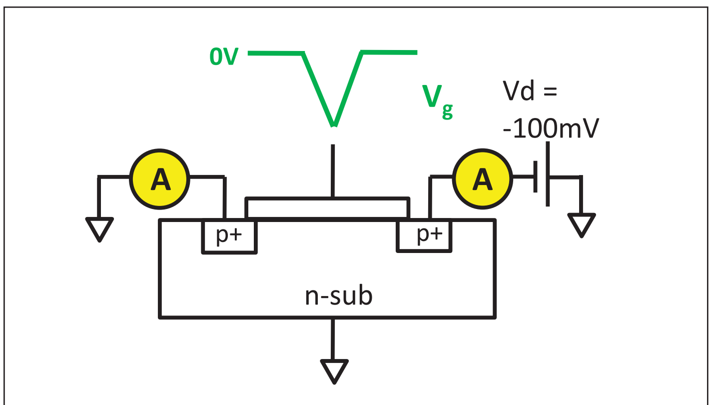

Figure 3. Illustration of the working principle of UFSP technique.

To facilitate the analysis, we define currents measured at drain and source terminal during switching on and off as I_d^{on}, I_s^{on}, I_d^{off}, and I_s^{off}. The current flow in the channel during the transient measurement is shown in ***Figure 4 (a)*** and ***(b)***. Three types of current are present: channel conduction current, I_{ch}, displacement current between gate and source/drain, I_{dis_s} and I_{dis_d}, and the leakage current between gate and source/drain, I_{g_s} and I_{g_d}. When device is switched off-to-on, the direction of I_{dis_s} and I_{dis_d} is toward the channel centre: I_{dis_s} has the same direction as I_{ch} at the source, but I_{dis_d} is in opposite direction to I_{ch} at the drain. When device is switched on-to-off, I_{dis_s} and I_{dis_d} change direction, but Ich does not. I_{g_s} and I_{g_d} are independent of V_g sweep direction and always flow from the source and drain towards gate under negative V_g. Based on the above analysis, channel current, I_{ch}, gate current, I_g, and displacement current, Idis can be separated by using Equations (2)–(4). C_{gc} can be calculated using (5).

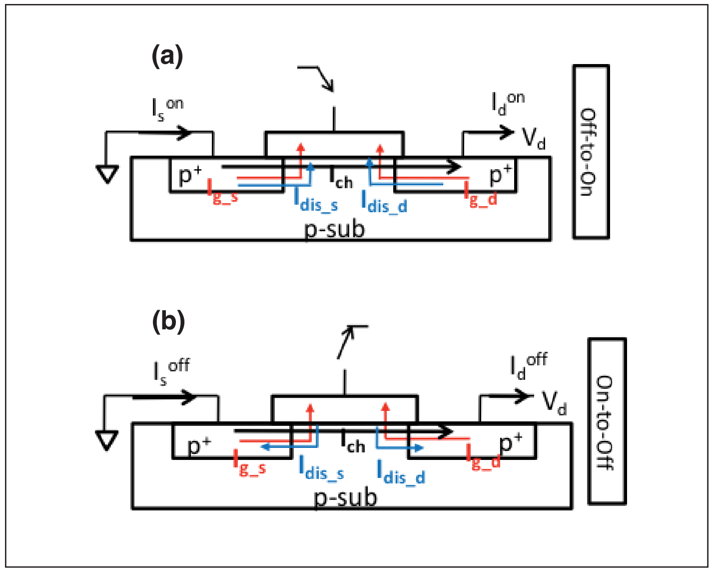

Figure 4. Schematic diagram of current flow during the transient measurement.

$$I_{CH} = \frac{I_D^{ON} + I_D^{OFF} + I_S^{ON} + I_S^{OFF}}{4} \tag{2}$$

$$I_G = I_{G\_S} + I_{G\_D} = \frac{I_S^{ON} + I_S^{OFF} - I_D^{ON} - I_D^{OFF}}{2} \tag{3}$$

$$I_{DIS} = I_{DIS\_S} + I_{DIS\_D} = \frac{I_D^{OFF} - I_D^{ON} + I_S^{ON} - I_S^{OFF}}{2} \tag{4}$$

$$C_{GC} = \frac{I_{DIS}}{dV_G/dt} \tag{5}$$

To calibrate the UFSP technique, a p-channel MOSFET with thick oxide is used which has negligible I_G current. The measurement time (=edge time) is set at 3μs. the measured four currents are shown in ***Figure 5***. The extracted I_{ch}, I_g and C_{gc} by using Equations (2) to (5) are shown in ***Figure 6(a)***. Once C_{gc} and I_{ch} are evaluated accurately, Qi can be obtained by integrating C_{gc} against V_g and channel effective mobility, μeff, is calculated through Equation (1) as shown in ***Figure 6(b)***.

Since the UFSP measured I_{ch} and C_{gc} under the same V_d, μ_{eff} should be independent of V_d. The μ_{eff} evaluated under three different V_d biases is compared in ***Figure 7***. Good agreements are obtained confirming the errors induced by V_d for the conventional techniques has been removed.

The UFSP also works well on leaky gate dielectric of standard structure. When it was applied on one 'leaky' n-channel MOSFET with an EOT of 1.28nm, the four currents measured from the source and drain terminals corresponding to the off-to-on and on-to-off V_G sweep are shown in ***Figure 8(a)***. By using Equations

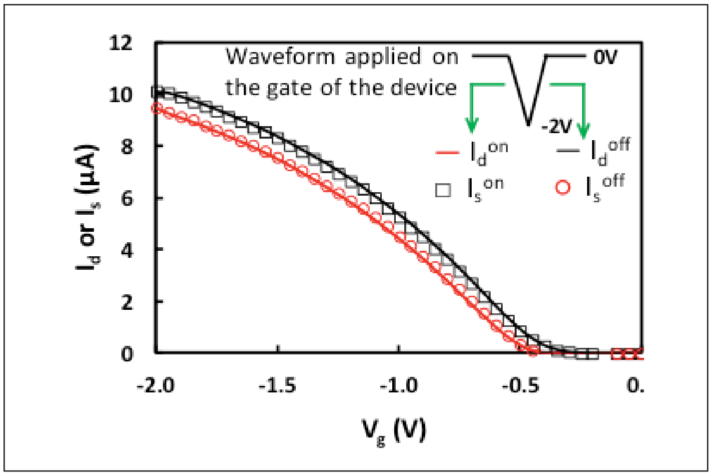

Figure 5. Four currents measured from source and drain corresponding to the off-to-on and on-to-off Vg sweep. Schematic Vg waveform is shown in inset.

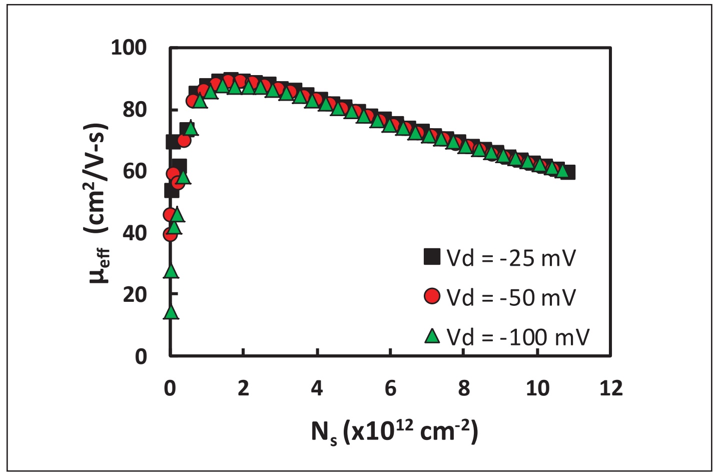

Figure 7. The effective channel mobility, μ_{eff}, extracted under three different V_d by using UFSP technique.

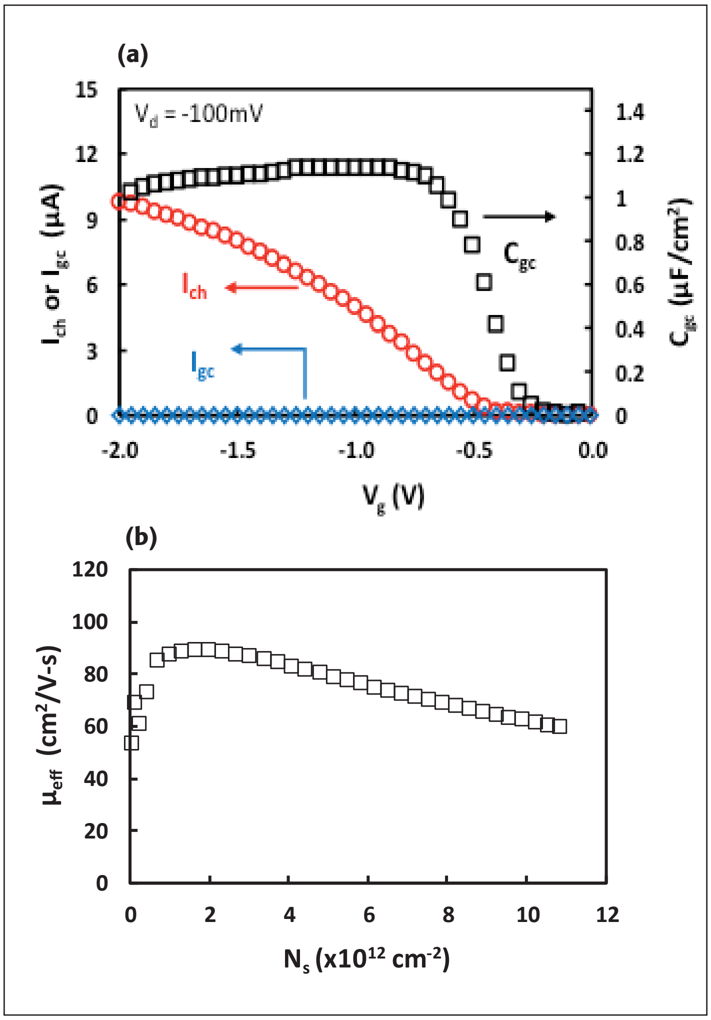

Figure 6.

(a). I_{ch}, I_g, and C_{gc} extracted simultaneously from the currents in Figure 5 by using Equations (2)–(5).

(b) Channel effective mobility extracted from I_{ch} and C_{gc} from (a).

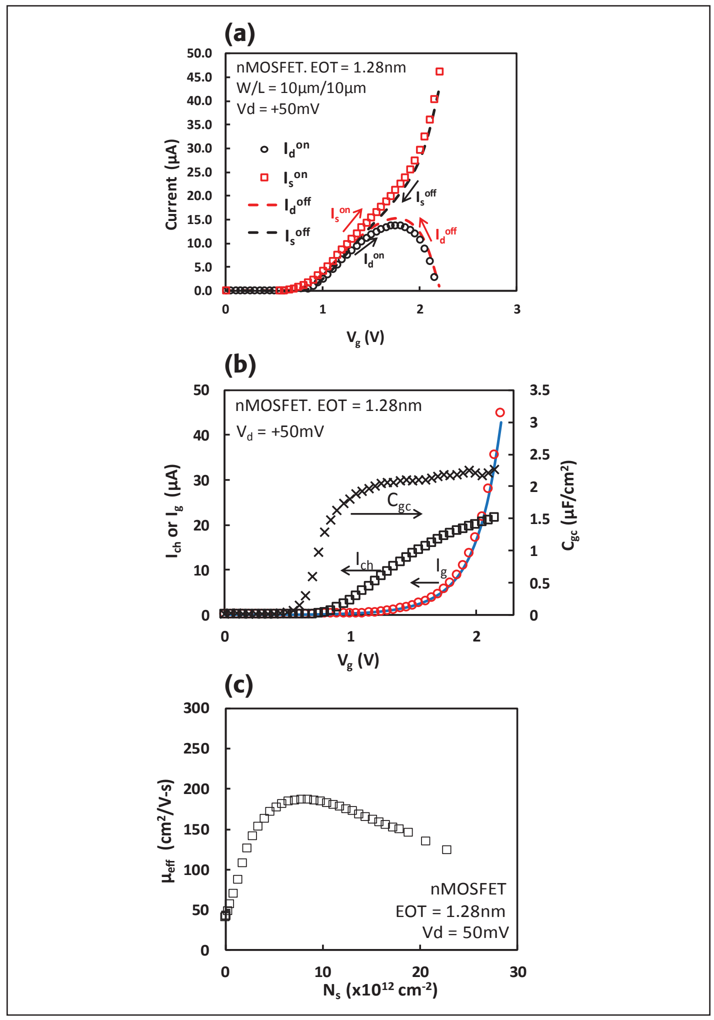

Figure 8.

(a) Four currents measured from the source and drain corresponding to the off-to-on and on-to-off V_g sweeps by UFSP technique on an nMOSFET with EOT of 1.28nm.

(b) I_{ch} ('□'), I_g ('o') and C_{gc} ('x') are extracted from the currents in (a) with Equations (2)-(5). The blue line is the leakage current obtained by DC measurement.

(c) Channel effective mobility, μeff, is calculated by using the extracted Ich and C_{gc} with Eqn (1).

(2)–(5), I_{ch} ('□'), I_g ('o') and C_{gc} ('x') are extracted and plotted in ***Figure 8(b)***. I_g from DC measurement is also plotted for comparison in ***Figure 8(b)***. Good agreement is obtained. ***Figure 8(c)*** shows that electron mobility can be reliably measured for this leaky device where I_g is as high as 45A/cm². Since the UFSP can tolerate high gate leakage, it does not need using the special RF structure for mobility evaluation.

To demonstrate the applicability of UFSP to devices with significant charge trapping, one pMOSFET with HfO_2/SiO_2 stack was used. Large amount of traps locate close to the Si/SiO_2 interface in this dielectric stack and they can exchange charges with substrate rapidly. The conventional technique takes seconds, making them indistinguishable from channel mobile charges. As a result, inversion charges will be overestimated and in turn the channel effective mobility will be underestimated. The UFSP technique only takes microseconds, minimizing charge trapping effect. ***Figure 9*** compares the mobility extracted by these two techniques. It clearly shows that after suppressing the trapping, the mobility extracted from the UFSP is considerably higher than that by the conventional technique.

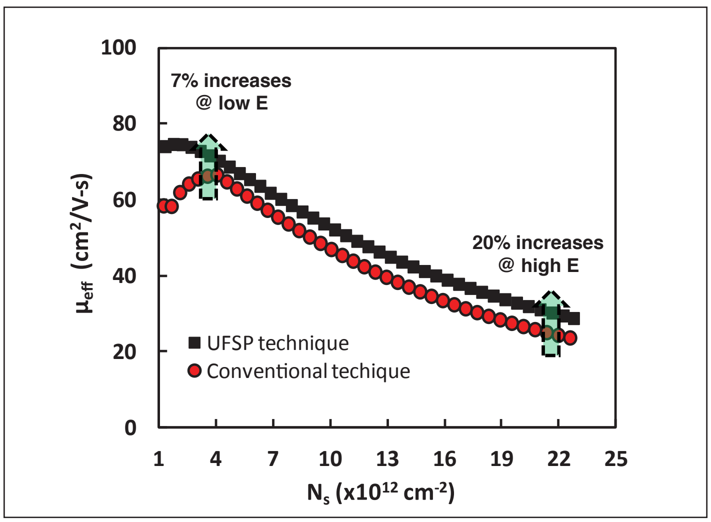

Figure 9. A comparison of mobility extracted by UFSP and conventional technique for a device with HfO_2/SiON dielectric of considerable fast trapping.

Required Hardware for UFSP Measurement

Selecting appropriate measurement equipment is critical to the success implementation of ultra-fast single pulse method. The following hardwares are required: Two Keithley Ultra-Fast I-V Modules (4225-PMU);

- Two Keithley Ultra-Fast I-V Modules (4225-PMU);
- Four Remote Amplifier/Switch (4225-RPM);
- 4 sets of high Performance Triaxial Cable Kit (4210-MMPC-C).

A photo of the cabling configuration for the test is shown in ***Figure 10***. 4225-PMU is the latest addition to the growing range of instrumentation options for the Model 4200-SCS Semiconductor Characterization System. The module integrates ultra-fast voltage waveform generation and signal observation

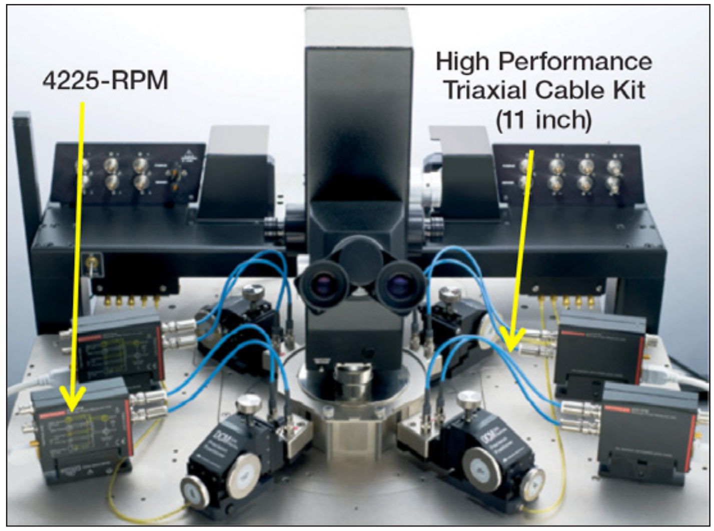

Figure 10. Photo of the UFSP technique setup using Keithley instruments.

capabilities into the Model 4200-SCS's already powerful test environment to deliver unprecedented I-V testing performance. It makes ultra-fast I-V sourcing and measurement as easy as making DC measurements with a traditional high resolution Source-Measure Unit (SMU). Each plug-in Model 4225-PMU module provides two channels of integrated sourcing and measurement. Each channel of the Model 4225-PMU combines high speed voltage outputs (with pulse widths ranging from 60 nanoseconds to DC) with simultaneous current and voltage measurements. 4225-RPM Remote Amplifier/Switch further expands the Model 4225-PMU's capabilities by providing ultra-low current measurement (below 100 nA) and reducing cable capacitance effects.

Connections to the Device

The connection for the UFSP measurement is shown in ***Figure 11***. Each terminal of the device is connected to one 4225-RPM using two 11-inch blue cables (provided in the cable set 4210-MMPC-C). Then each 4225-RPM is connected to one channel of PMU using two tri-axial cables. All the measurements are controlled by the Keithley KTEI software.

Using the KTEI Software to Perform UFSP measurement

Performing UFSP for channel effective mobility measurement using Keithley 4200-SCS system is quite simple. One example project can be downloaded from http://www.keithley.com/data?asset=57747. As shown in ***Figure 12***, each terminal of the device is connected to one channel of PMU. Users can modify the parameters for each PMU channel in the definition tab. ***Table 1*** lists one set of user-defined parameters for a p-channel MOSFET.

In the timing tab, users can input the desired measurement speed which is the edge time of the pulse. The recommended values are listed in ***Table 2***.

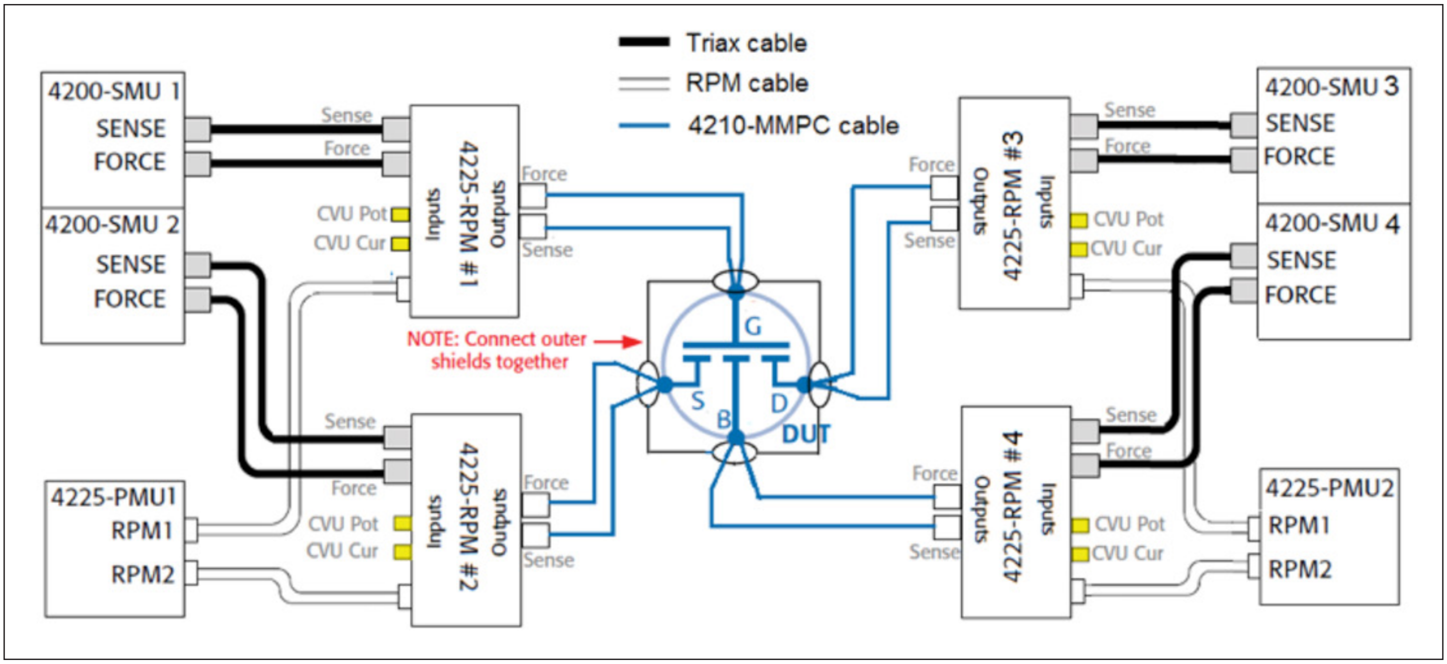

Figure 11. Experiment connection for the Ultra-fast Single Pulse (UFSP) technique. Two Keithley dual-channel 4225-PMUs are used for performing transient measurements. Four Keithley 4225-RPMs are used to reduce cable capacitance effect and achieve accurate measurement below 100nA.

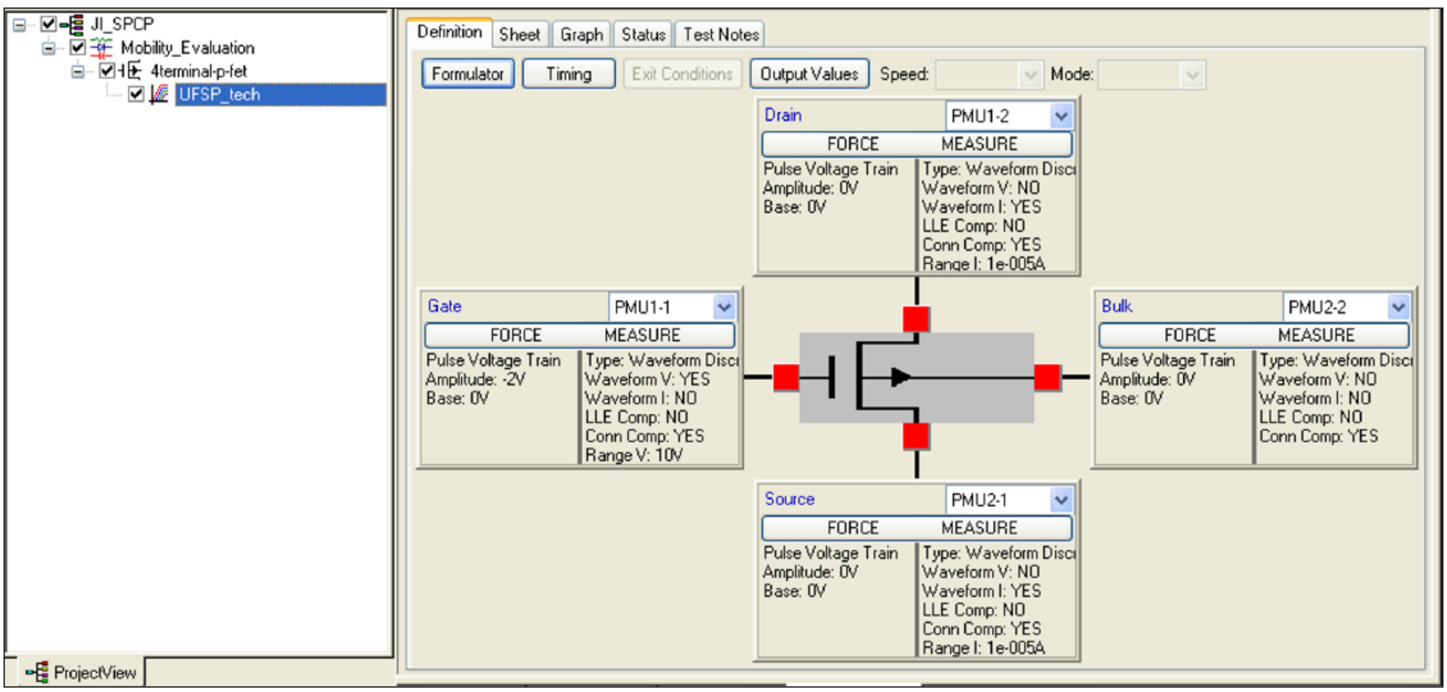

Figure 12. Example project in KTEI software for UFSP measurement. Each of the four terminals of the device is connected to one channel of PMU respectively.

Table 1. Recommended setting in the definition tab for each channel of PMU.

PMU Setting for Gate Terminal			
Parameters		**Value**	**Description**
Pulse Train Settings	Forcing Function	Pulse Train	To generate a single pulse or a pulse train with same shape
	Voltage Amplitude	–2V	To define the Vg sweep range
	Voltage Base	0V	
Measurement Range	Vrange	10V	Maximum possible voltage applied on the gate
	Irange	10µA	Measurement range for current
Measurement Setting	Sample I waveform	untick	Do not record current at the gate
	Sample V waveform	tick	Record applied voltage at the gate
	Timestamp	tick	Record total time for the measurement

PMU Setting for Drain Terminal			
Parameters		**Value**	**Description**
Pulse Train Settings	Forcing Function	Pulse Train	To generate a single pulse or a pulse train with the same shape
	Pulse Train Settings	DC voltage	To apply a constant Vd bias used for mobility measurement
	Voltage base (V)	–0.1	
Measurement Range	Vrange	10V	Maximum possible voltage applied on the gate
	Irange	10µA	Measurement range for current
Measurement Setting	Sample I waveform	tick	Record current at the drain
	Sample V waveform	untick	Do not record applied voltage at the drain
	Timestamp	untick	Do not record total time for the measurement

PMU Setting for Source Terminal			
Parameters		**Value**	**Description**
	Forcing Function	Pulse Train	To generate a single pulse or a pulse train with the same shape
	Pulse Train Settings	DC voltage	To apply a zero Vs bias used for mobility measurement
	Voltage base (V)	0	
Measurement Range	Vrange	10V	Maximum possible voltage applied on the gate
	Irange	10µA	Measurement range for current
Measurement Setting	Sample I waveform	tick	Record current at the source
	Sample V waveform	untick	Do not record applied voltage at the source
	Timestamp	untick	Do not record total time for the measurement

PMU Setting for Bulk Terminal			
Parameters		**Value**	**Description**
	Forcing Function	Pulse Train	To generate a single pulse or a pulse train with the same shape
	Pulse Train Settings	DC voltage	To apply a zero Vbulk bias used for mobility measurement
	Voltage base (V)	0	
Measurement Setting	Sample I waveform	untick	Do not record current at the bulk
	Sample V waveform	untick	Do not record applied voltage at the bulk
	Timestamp	untick	Do not record total time for the measurement

Table 2. Recommended setting in the timing tab.

Parameters	Value	Description
Test Mode	Waveform capture	
Measurement Mode	Discrete Pulses	Discrete Pulse and Average pulses, then you need to input number of Pulses, 10 is enough.
Sweep parameter	None	No sweeping required
Period (s)	5.00E-05	Period of the pulse
Width (s)	6.00E-06	Pulse width
Rise Time (s)	3.00E-06	Pulse rise time
Fall Time (s)	3.00E-06	Pulse fall time, set to be the same as rise time
Pulse Delay (s)	2.00E-06	Pulse delay time, keep the same as rise time

Once the test is executed, transient currents during switching on and off at source and drain terminals will be recorded and stored in the sheet tab and can be saved as an .xls file. These currents can also be plotted on the graph tab. From these currents, the channel effective mobility can be extracted based on Equations (2) to (5).

Conclusion

Channel carrier mobility is a key parameter for material selection and process development. The conventional technique suffers from several shortcomings: slow speed and vulnerability to fast trapping, V_d-dependence, cable-changing, sensitivity to gate leakage, and complex procedure. An ultra-fast single pulse technique (UFSP) has been proposed and developed to overcome these shortcomings. I_{CH} and Q_i can be simultaneously measured within several micro-seconds without cable switching. UFSP measurement can be easily performed using the Keithley 4200-SCS system with four 4225-RPMs. It provides a complete solution for robust and accurate mobility evaluation in a convenient way and serves as a tool for process development, material selection, and device modelling for CMOS technologies.

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