Making Accurate and Consistent Wafer Measurements with Next Generation Guarded True-Kelvin MEMS DC Probes

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***Abstract*—Gate length down-scaling of silicon-based transistor results in very small on-state drain-source resistance, making it challenging for test engineers to perform precise and repeatable wafer measurements. Size reduction of aluminum-capped copper test pads to save on lithography, prototyping and production costs implies that it is very difficult to re-probe the same device with low contact resistance. Novel true-Kelvin MEMS analytical DC probes, new test and modelling strategies are proposed in this paper to address these emerging test challenges.**

***Keywords*—Device modeling, DC, CV, flicker noise, probe, MEMS probe, true-Kelvin probe, quasi-Kelvin probe, Kelvin, wafer measurements, contact resistance.**

I. INTRODUCTION

The semiconductor industry continues to pursue the relentless downscaling and development of new architectures for silicon-based transistor down to 2 nm and beyond. On-state currents of such advanced transistors are increasing, while off-state currents are kept very low to reduce power consumption. Smaller test pads to reduce lithography and prototyping costs, and the use of copper backend metallization have increased the difficulties for probes to have low and stable contact resistance as there are inadequate fresh pad metal available for deeper probe scrubs or re-probing.

These issues aggravate especially at elevated temperatures when pad aluminium cap layer has been probed and removed, and the exposed underlying copper oxidizes, hindering the ability to establish consistently good electrical contacts for every probe touchdown. The popular quasi-Kelvin analytical DC probes, widely used in the industry, are not able to cope with these challenges. In this paper, a novel coaxial guarded, true-Kelvin MEMS analytical DC probe with replaceable tips, is introduced to achieve precise and consistent device modelling wafer measurements. Despite recent low contact force and low contact resistance improvements on MEMS probe cards [1-4], they are excluded in the scope and discussions of this work because their probe tip layout is usually fixed, unable to support test structures with variable pad pitches.

II. DESIGN OF ENGINEERING ANALYTICAL DC PROBES WITH TRUE-KELVIN MEMS TIPS

For more than 20 years, the quasi-Kelvin, coaxial guarded, analytical engineering probe shown in Fig. 1, has been a very popular choice for engineers performing device wafer tests. This engineering probing solution usually consists of a ceramic blade with tungsten probe tip, coaxial guarded probe holder, probe arm, cables, Kelvin triaxial connectors and a XYZ positioner to allow accurate probing on the test pads. As channel resistance of advanced node device reduces, parasitic resistance of the quasi-Kelvin probe holder, shown in Fig. 2(a), is no longer negligible. This parasitic resistance also

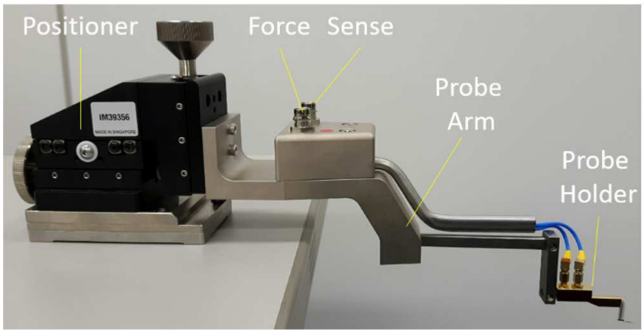
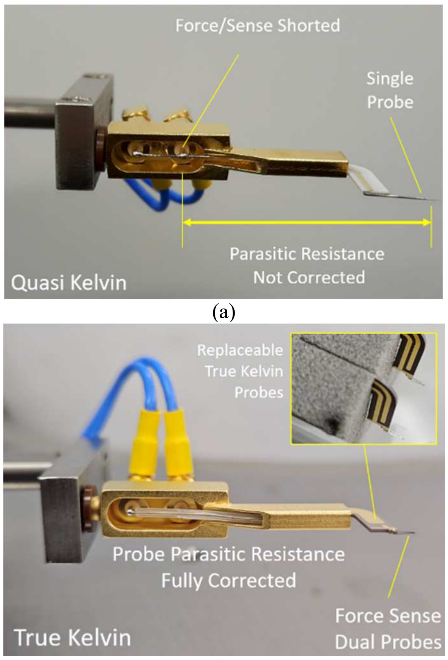


Fig. 1. DC probe supporting guarded and Kelvin wafer measurements.



(a)

(b)

Fig. 2. Comparing cantilever quasi-Kelvin QK (a) and MEMS true-Kelvin TK (b) guarded probe holder with replaceable probe tips.

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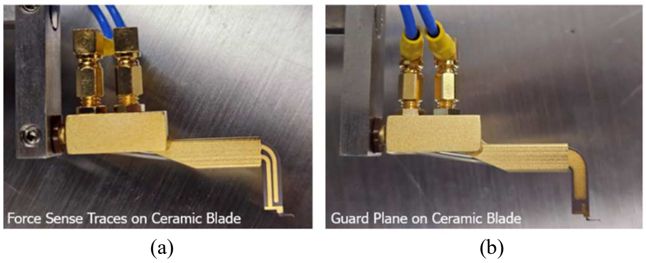


(a) (b)

Fig. 3. Force-Sense traces and guard plane on the replaceable ceramic blade of MEMS true-Kelvin probe tips.

increases with temperature, affecting the accuracy and repeatability of device's measured IV curves. To overcome these challenges, a novel true-Kelvin MEMS DC probe as shown in Fig. 2(b) and Fig. 3 is used. The innovative design consists of a new coaxial guarded true-Kelvin probe holder, extending force and sense connections to the removable ceramic probe blade having 2 separate MEMS tips. This facilitates true-Kelvin probe contacts on the device test pads, eliminating all parasitic resistances and inconsistencies in probe contact resistances for every probe touchdown on the test pads.

III. EXPERIMENTAL SETUP

QUASI-KELVIN PROBES VS TRUE-KELVIN PROBES

300mm probe station with automatic wafer loader and Keysight B1500 semiconductor parameter analyser are used to perform device measurements as depicted in Fig. 4. B1500 is utilized as it supports guarded low leakage, force-sense Kelvin measurements. Probe scrubs versus Z over-travel of the quasi-Kelvin cantilever probes and true-Kelvin MEMS probe are presented in Fig. 5. The probe scrub ratio of true-Kelvin MEMS probe is about 8% compared to quasi-Kelvin cantilever probes of 40%. The quasi-Kelvin cantilever probes require a probe scrub of at least 30μm or Z over-travel of about 60 to 70μm for good probe contact resistance.

Fig. 4. 300mm fully automatic probe system with cantilever quasi-Kelvin QK and MEMS true-Kelvin TK (b) probes for wafer-level device characterization.

On the contrary, true-Kelvin MEMS probe requires only 20μm Z over-travel for accurate and repeatable contact. This implies that it is able to support pad sizes smaller than 30×30μm as the probe scrub is only about 7 to 8μm. Fig. 6 shows the total resistance of 2 quasi-Kelvin cantilever probes on an aluminium-capped copper test pad at 25°C and 150°C for 100 contact cycles. This work was previously published in 2017 ICMTS [5]. The total parasitic resistance is observed to be about 1 and 5 Ω for 25°C and 150°C respectively on the first probe contact – such high test setup resistance limits the ability for test engineers to accurately characterize devices at high temperatures. Particularly, at 150°C, from 30th probe contact cycle onwards, the total parasitic resistance increases drastically and eventually became open circuit. This is due to repeated deep probing on test pad causing the aluminium cap layer to be removed, exposing the underlying copper metal layers which oxidize, eventually resulting in an open circuit.

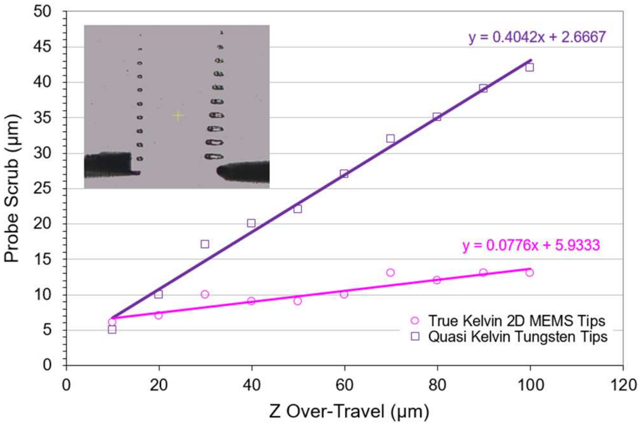


Fig. 5. Probe scrub versus Z Over-Travel for cantilever quasi-Kelvin (QK) and MEMS true-Kelvin (TK) probes.

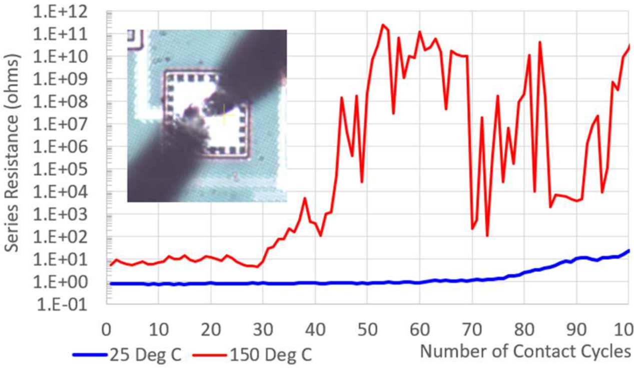


Fig. 6. Series resistance of 2 cantilever quasi-Kelvin (QK) probes on aluminium-capped copper test pad over 100 contact cycles.

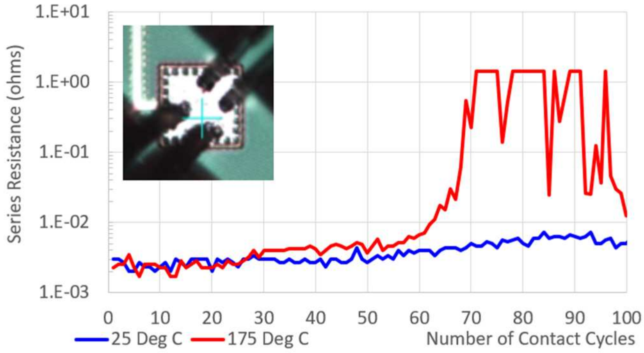


Fig. 7. Series resistance of 2 MEMS true-Kelvin (TK) probes on aluminium-capped copper test pad over 100 contact cycles.

Such experimental result reveals the difficulties and challenges to have consistency and accuracy when measuring device characteristics with these aluminium-capped copper test pads. When the same experiment is repeated with the proposed true-Kelvin MEMS probes, the total parasitic resistance shown in Fig. 7 remains low, less than 10 mΩ at 25°C. The total parasitic resistances at 25°C and 175°C are comparable, less than 5 mΩ for the first 50 contact cycles, with no large gaps observed. Since true-Kelvin MEMS probe requires Z over-travel of only 20µm, less pad damage has been inflicted and therefore little underlying copper oxidation and no open circuit has been observed. Fig. 8 shows the parasitic resistance of 2 true-Kelvin probes on gold pads. It is observed that at 25°C and 175°C, the average total parasitic resistances are consistently low at 1.4 and 2.2 mΩ respectively over 100 probe contact cycles since there is no metal oxidation observed during these tests. Fig. 9 shows the leakage current for the guarded true-Kelvin probe when 10V is applied, with probe tips in the air at 250µm above the wafer. The probe leakage current is less than ±5 and ±10 fA at temperatures of 25 and 175°C respectively. Such excellent probe leakage performance is required to characterize a single transistor with typical off-state current in the pico-ampere range.

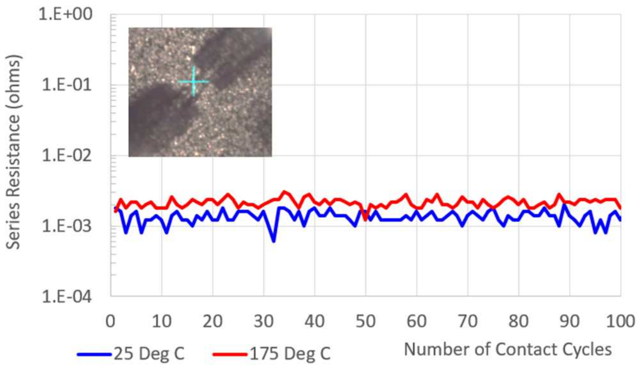


Fig. 8. Series resistance of 2 MEMS true-Kelvin (TK) probes on gold pad over 100 contact cycles.

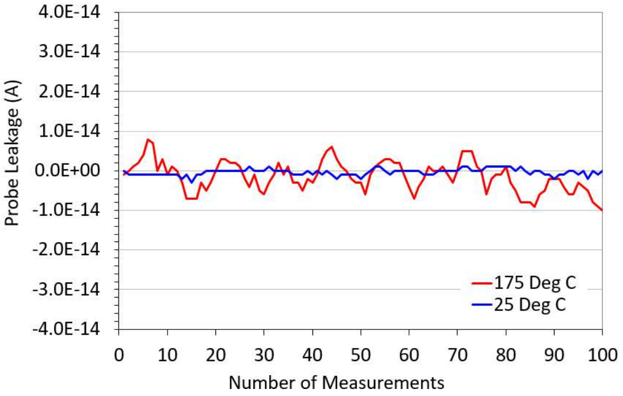


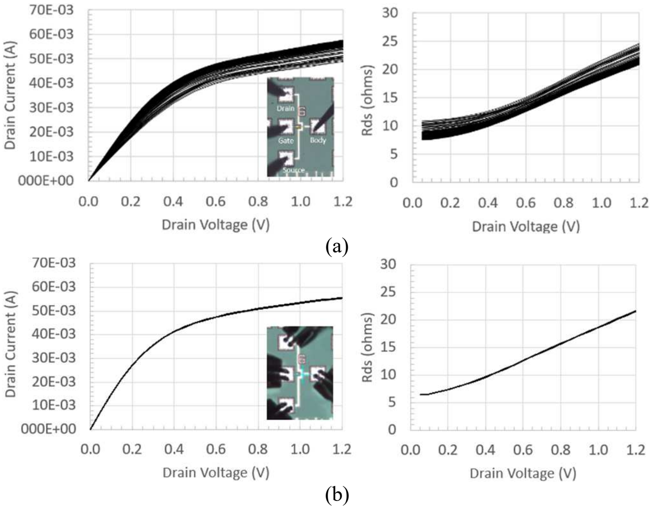
Fig. 9. Probe leakage current for MEMS true-Kelvin (TK) probe when 10 V is applied, probe is 250 µm above the wafer surface at 25 and 175°C.

IV. TEST STRUCTURES AND DEVICE TEST RESULTS

NMOSFETs with size of width/length=100/0.06µm are used for device tests to compare performance of cantilever quasi-Kelvin and MEMS true-Kelvin probes. The NMOSFET test structures consist of both standard 4-pad and true-Kelvin 6-pad layout and the test pads are 50×50µm in size.

A. Current-Voltage (IV) Measurements

Characterizing the NMOSFETs with quasi-Kelvin cantilever probes, inconsistent drain current, Ids and drain-source resistance, Rds have been obtained when Vds is swept from 0 to 1.2V while the gate is biased at 1.2V over 100 probe contact cycles, as shown in Fig. 10 (a). This is due to the parasitic resistance of quasi-Kelvin probe body and the unstable probe-pad contact resistance. On the contrary, true-Kelvin MEMS probes provided extremely good repeatability in the same test. Fig. 10 (b) and Fig. 11 show identical Ids and Rds versus Vds plots over 100 probe contact cycles at 25°C and 175°C correspondingly, demonstrating accuracy, repeatability and real-time parasitic resistance corrections by B1500 for every measurement. The true-Kelvin MEMS probe requires only 20µm Z over-travel, demonstrating ability to handle small test pads. It also requires minimal probe tip maintenance – only cleaning that is necessary to prevent force and sense tips from shorting together.



(a)

(b)

Fig. 10. Id and Rds for 100/0.06µm NMOSFET measured repeatedly over 100 contact cycles with cantilever quasi-Kelvin probes (a) and MEMS true-Kelvin probes (b) at 25°C in a 4-pad test layout.

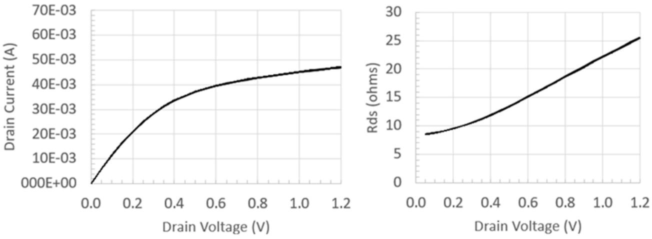
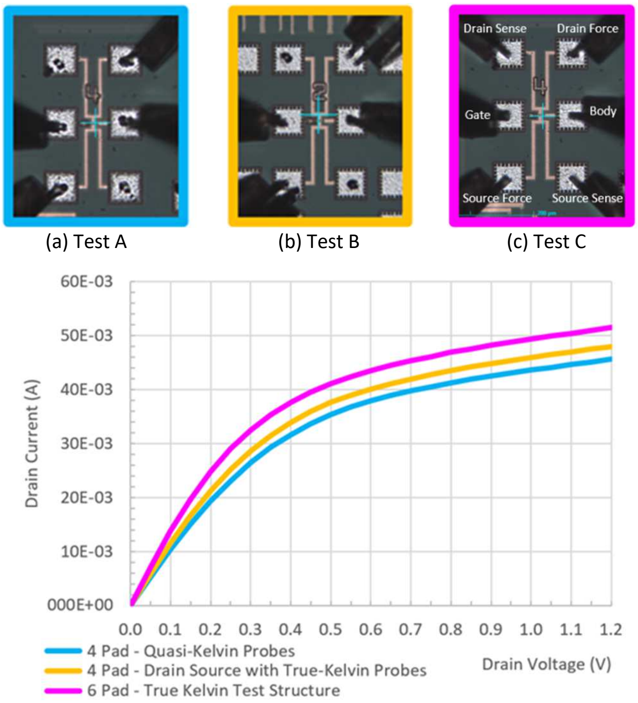


Fig. 11. Id and Rds for 100/0.06µm NMOSFET measured over 100 contact cycles with MEMS true-Kelvin probes at 175°C.

Quasi-Kelvin probe with one single MEMS probe tip instead of cantilever tungsten tip is also fabricated in this work. Together with true-Kelvin MEMS probes, 6-pad true-Kelvin NMOSFET test structures are characterized to establish the correlations between measurement accuracy, true-Kelvin MEMS probes versus quasi-Kelvin MEMS probes and 4 versus 6-pad layout configurations. Fig. 12 (a) shows Test A with 4 quasi-Kelvin MEMS probes on 4 test pads of the NMOSFET device. Fig. 12 (b) depicts Test B with NMOSFET characterize by 2 quasi-Kelvin MEMS and 2 true-Kelvin MEMS on drain and source terminals. Fig. 12 (c) shows 6 quasi-Kelvin MEMS probes on a 6-pad true Kelvin device test structure as Test C. Ids versus Vds plots for the 3 test configurations are compared in Fig. 12 (d).

Test C with a 6-pad true Kelvin test structure yielded the highest current and accuracy because parasitic resistances associated with the drain source test leads are fully corrected during the measurements. Test A resulted in the lowest Ids. Compared to Test C, Test B is recommended instead because true-Kelvin probes are able to correct for probe contact resistances in a 4-pad layout with 33% reduction in test structure size. Test B setup in a 4-pad layout is also preferred for capacitance-voltage as well as 1/f noise measurements



(a) Test A (b) Test B (c) Test C

(d)

Fig. 12. Die photos showing MEMS quasi-Kelvin and MEMS true-Kelvin probes on 4-pad and 6-pad test configurations - 4 quasi-Kelvin probes Test A (a), 2 quasi-Kelvin 2 true-Kelvin probes Test B (b), 6 quasi-Kelvin probes Test C (c) and their respective Id versus Vd plots (d).

because it does not have the additional source and drain sense test pads. The device test leads should be designed with short, wide top metallization to minimize parasitic resistances. At various temperatures, characterizing additional de-embedding test structures with the source and drain test leads shorted together, allows source and drain parasitic test-lead resistor models to be developed. Having these resistor models in SPICE simulators while extracting the MOSFET model parameters will result in highly accurate MOSFET SPICE models.

B. Capacitance-Voltage (CV) Measurements

Apart from IV measurements, to qualify as a device characterization and modelling probe, the proposed true-Kelvin MEMS probe must be able to support CV and flicker noise wafer measurements. In CV tests with a LCR meter, as each true-Kelvin MEMS probe has 2 force-sense probe tips, it is possible to connect one MEMS tip or have both MEMS tips shorted to each of the "high" and "low" test terminals of the LCR meter. To validate the CV measurement performance of the true-Kelvin probes, Keysight 4284 LCR meter is used to measure the gate capacitance of the 100/0.06µm NMOSFET in a 4-pad test layout. The source and drain of the transistors are shorted together and the gate voltage is swept from -2 to 2V.

Shorting both force and sense probe tips together and connecting them to each of the instrument test terminals, Fig. 13 shows excellent correlations, with almost identical values of NMOSFET gate capacitance measured with MEMS true-Kelvin and cantilever quasi-Kelvin probes. On other hand, it is interesting to note that when only 1 tip is connected to each of the LCR meter test terminals, after an OPEN calibration, there is a systematic error with larger capacitance of about 0.01pF. This is likely due to additional capacitance introduced by the floating tip that was not corrected during the OPEN in air capacitance calibration but was measured by the LCR meter in the device measurements when this floating tip comes into electrical contact with the test pad.

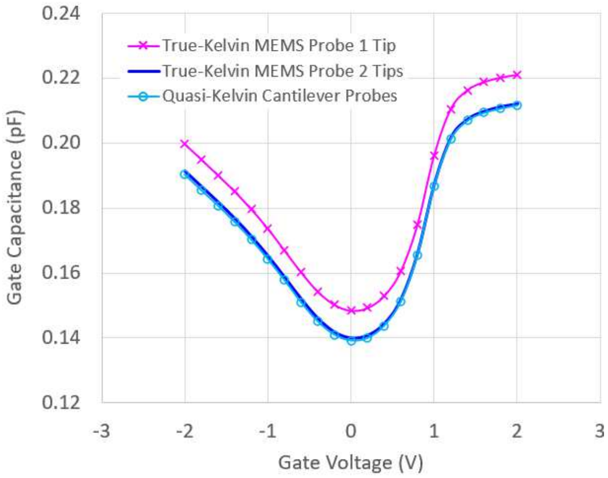
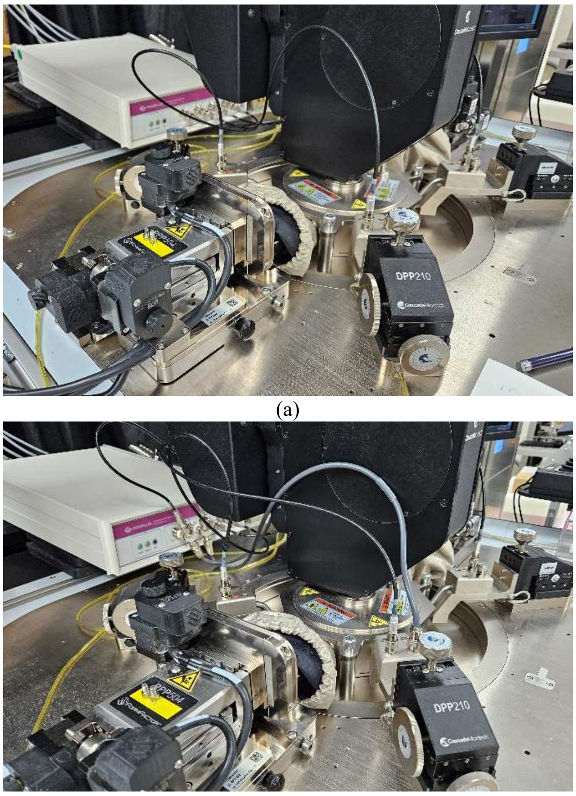


Fig. 13. Gate capacitance versus gate voltage for the 100/0.06µm NMOSFET, measured with MEMS true-Kelvin probe with 1 tip or 2 tips shorted to each of the test terminals of the LCR meter versus quasi-Kelvin cantilever probe.

C. Flicker Noise (1/f Noise) Measurements

The Primarius 9812DX(HV) flicker noise measurement system is used to qualify the true-Kelvin MEMS probes for device characterization and modelling applications. Similar to the CV test setup, there are 2 ways to connect the true-Kelvin probes. Fig. 14(a) shows the sense tip floating and only the force tip is connected to the Amplifier Filter Unit (AFU) of the flicker noise test setup using 1 single test cable each for the drain and source device terminals. Another possible setup is to short the force and sense probe tips with 2 separate test



(a)

(b)

Fig. 14. Photos showing the source drain test terminals with 1 test cable (a) and 2 test cables (b) connected to the Amplifier Filter Unit (AFU) of the Primarius 9812DX(HV) flicker noise test system.

cables to the measurement channel on the AFU as shown in Fig. 14(b). This method reduces the cabling resistance but increases the parasitic capacitances of the test setup which will likely cause an early roll-off in the measured noise spectrum if a very large load resistor is selected for more accurate noise measurements. In this study, to facilitate a fair comparison to quasi-Kelvin cantilever probe, only the force tip is connected to the AFU using 1 test cable and sense tip is left floating.

Fig. 15 shows the noise spectrum, Sid versus frequency plots for a W/L=20/0.06µm NMOSFET device in a 4-pad test layout. A smaller device with lower bias currents is selected so that the device noise spectrum will be low, allowing the true-Kelvin MEMS probes to be carefully evaluated. It is observed that the noise spectrums measured by the quasi-Kelvin cantilever probes and true-Kelvin MEMS probes are well correlated. At low current levels of 6.5µA and 50µA, it is noted that the true-Kelvin MEMS probes have smaller fluctuations in the measured Sid compared to the quasi-Kelvin probes. This could be attributed to an ultra-stable MEMS probe-to-pad contact and well-matched characteristics impedance for the true-Kelvin MEMS probe. Both features are critical in allowing fluctuations of the drain current to be accurately captured by the instruments, over time, during low frequency noise characterization of these silicon-based transistors.

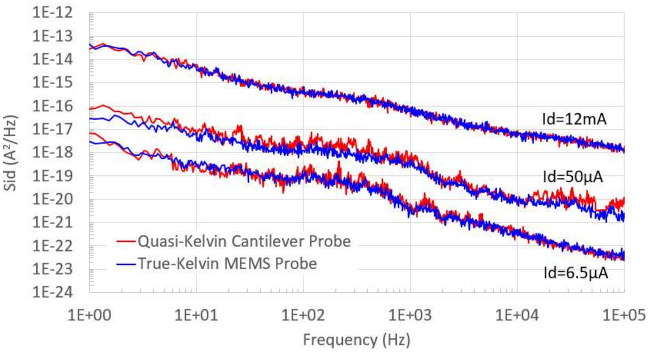


Fig. 15. Sid noise spectrum for the W/L=20/0.06µm NMOSFET biased at Vg=Vd=0.3V (Id=6.5µA), Vg=0.3V Vd=1.2V (Id=50µA) and Vg=Vd=1.2V (Id=12mA), measured with cantilever quasi-Kelvin probes and MEMS true-Kelvin probes.

V. CONCLUSION

A novel low-leakage DC MEMS probe with ultra small probe scrubs and true-Kelvin force-sense probe tips has been successfully demonstrated to address the test challenges of making precise and consistent device modelling wafer measurements for advanced node silicon-based transistors.

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