Ultra Low Current Measurement Technologies Employed in the Agilent 4073A Ultra Advanced Parametric Test System

Product Note

- **High-Resolution SMU**
- **High-Resolution Pin Board**
- **Ultra-Low Leakage Probe Card**
- **Optimization of Integration Time**
- **Comparison of Settling Time for the 4073A and 4072A**

Introduction

The trend in semiconductor devices is toward lower cost and lower power consumption with better operating speed and functions. To address this trend, deep sub-micron and low-power consumption processes have been developed, which are evaluated by low-current and low-voltage measuring instruments. For example, DRAM cell evaluation now requires ultra low-current measurement below 100 fA.

Both resistance evaluation of advanced Cu interconnect and matching tests for new analog devices need sub-1 µV measurement capability. Further, the measurement must be fast, especially at production facilities.

To meet these needs, the Agilent 4073A Ultra Advanced Parametric Test System measures low current and low voltage down to the femtoampere (fA) and micro-volt (µV) levels, without losing test speed. This is the very performance semiconductor process development engineers need.

Semiconductor fabricators will also benefit from the 4073A because its high throughput supports an integrated process monitoring environment from development to production.

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This product note describes how the 4073A attains such high performance by focusing on the following items: high-resolution SMU, high-resolution pin board, ultra-low leakage probe card, optimization of integration time, and comparison of settling time for the 4073A and 4072A.

High-Resolution SMU

The high-resolution SMU (HRSMU) is newly designed to achieve ultra low-current measurements. Power coverage of the HRSMU is the same as that of the MPSMU but the lower-current ranges of 100 pA and 10 pA are supported by the HRSMU, as illustrated in Table 1.

Table 1 shows the differences in the low-current measurement capabilities of the 4073A using an HRSMU and the 4072A using an MPSMU. The MPSMU's lowest measurement range is 1 nA, compared with 10 pA for the HRSMU. In addition, both force and measure resolutions are improved to 1 fA for the HRSMU, allowing the 4073A to measure low current more precisely than the 4072A. Accuracy is also improved.

Table 1. Comparison of 4073A and 4072A Key Specifications

Key Specifications	4073A HRSMU	4072A MPSMU
Lowest Current Range	10 pA	1 nA
Resolution of Current Force	1 fA (at 10 pA range)	50 fA (at 1 nA range)
Resolution of Current Measure	1 fA (at 10 pA range)	10 fA (at 1 nA range)
Accuracy of Current Force and Measure[1]	4% + [4.0 + (0.0001×Vo)]% + (500 fA + 1 fA/V×Vo) at 10 pA range	1% + [0.1 + (0.0005×Vo)]% + (3 pA + 2 pA/V×Vo) at 1 nA range

[1]Accuracy: ±(% of reading + % of range + amp)

Figure 1 shows an example of the Id-Vg measurement of an N-channel MOSFET on a wafer. The HRSMU is connected to the drain terminal of the MOSFET and another SMU is connected to the gate terminal. Source and substrate terminals are connected to the GNDU. Drain voltage is set to a constant 2 V, gate voltage is swept from –250 mV to 250 mV in 12.5 mV steps, and drain current is measured for each step in the 10 pA range. The integration times are 16 power line cycles (PLC). This example shows that the fA level low current is measured in a stable manner.

Low-current measurement to the fA level can be achieved by using the 10 pA range of the HRSMU. Some program statements are necessary to use the 10 pA range.

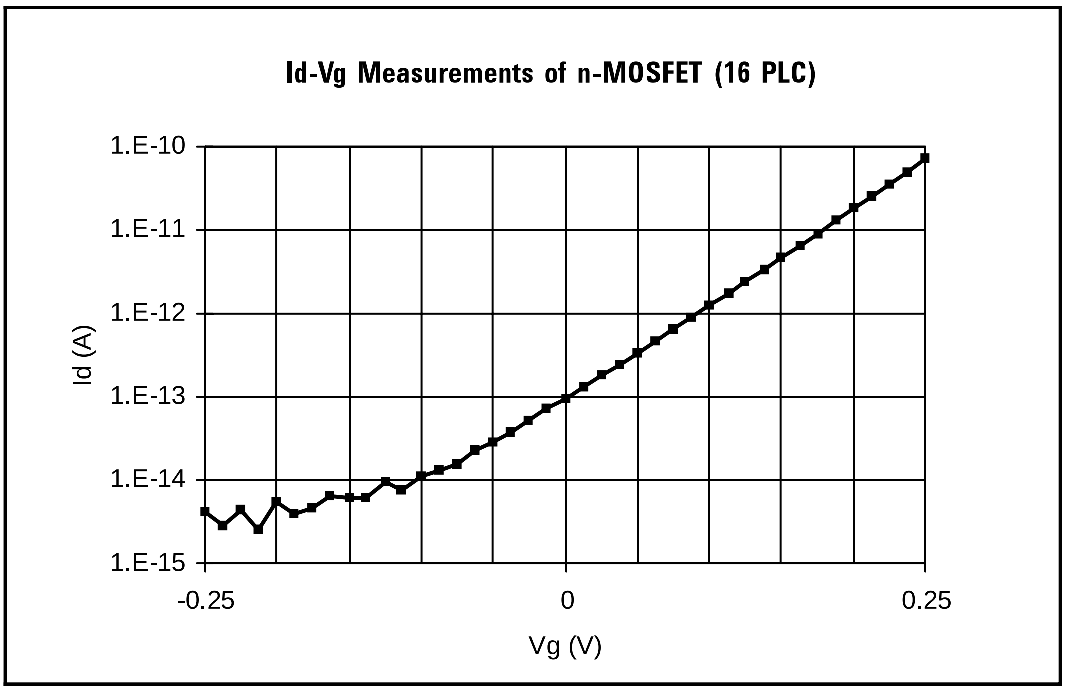

Figure 1. Id-Vg Measurements with the 4073A

When limited auto range mode is used, the 10 pA range must be specified as shown in the example at the right.

`Force_v(FNPort(0,2),Vf)`	*Force a voltage (Vf) from SMU2.*
`Measure_i(FNPort(0,2), Im,`**`1.E-11`**`)`	*Measure a current (Im) at SMU2 with 10 pA limited auto range mode*

When auto range mode is used, ranges lower than 1 nA must be enabled by using the `Set_rangemode` statement. The minimum current range of the auto range mode is 1 nA (the default setting) in order to maintain compatibility among the 4073A, 4072A, and 4071A. (Note that the lowest available current range for the 4071A and 4072A is 1 nA.) To enable lower ranges (10 pA and 100 pA) on the 4073A, a `Set_rangemode` statement is used, as shown in the example at the right.

`Set_rangemode(1)`	*Enable 10 pA and 100 pA ranges.*
`Set_adc_i(1,3)`	*Set LONG mode to high-resolution ADC.*
`Set_smu_ch(FNPort(0,2),1)`	*Set high-resolution ADC to SMU2 (HRSMR).*
`Force_v(FNPort(0,2),Vf)`	*Force a voltage (Vf) from SMU2.*
`Measure_i(FNPort(0,2),Im,0)`	*Measure a current (Im) at SMU2 with auto range mode.*

The HRSMU enables the low-current measurements as shown in Figure 1 on page 3. Note that the high-resolution pin board and ultra low leakage probe card, which are discussed in the following sections, contribute to this low-current measurement capability.

High-Resolution Pin Board

The 4073A uses high-resolution (HR) pin boards, which consist of new relays configured to minimize drift of thermo-electromotive force for the matrix switches. This allows the 4073A to achieve better low-current and low-voltage measurements than the 4072A. The low-current measurement capability is shown in Figure 1 on page 3.

This performance improvement is apparent in the digital volt meter (DVM) accuracy of the specifications and Table 2 shows a comparison of the DVM accuracy for the 4073A and 4072A. Note that the lower range of 0.1 V is supported by the 4073A and the offset voltage in the accuracy column is 100 µV, while the 4072A has an offset voltage of 300 µV.

Table 2. Comparison of 4073A and 4072A DVM Specifications

Model	Full Scale Voltage Range	Resolution	Accuracy ± (% of reading + volt)
Agilent 4073A	0.1 V	0.1 µV	0.01% + <u>100 µV</u>
	1 V	1 µV	0.01% + <u>100 µV</u>
	10 V	10 µV	0.01% + 200 µV
	100 V	100 µV	0.02% + 1 mV
Agilent 4072A	1 V	1 µV	0.01% + <u>300 µV</u>
	10 V	10 µV	0.01% + 300 µV
	100 V	100 µV	0.02% + 1 mV

Ultra Low Leakage Probe Card

The ultra low leakage probe card, jointly developed by probe card vendors and Agilent, is designed so that force and sense pads for each measurement pin are surrounded three-dimensionally by the guard conductor. This reduces dielectric absorption on the probe card.

Figure 2 shows the settling time difference between an ultra low leakage (new) and conventional (old) probe card. Nothing is connected at the probing needles and forced voltage is 100 V. The measurement range is 1 nA and integration time is 16 PLC. Since the dielectric absorption of the ultra low leakage probe card is very small, a current less than 100 fA flows after 100 V is forced.

In general, the current caused by the dielectric absorption is relative to the forced voltage. For example, when the forced voltage is 10 V, the current is less than 10 fA.

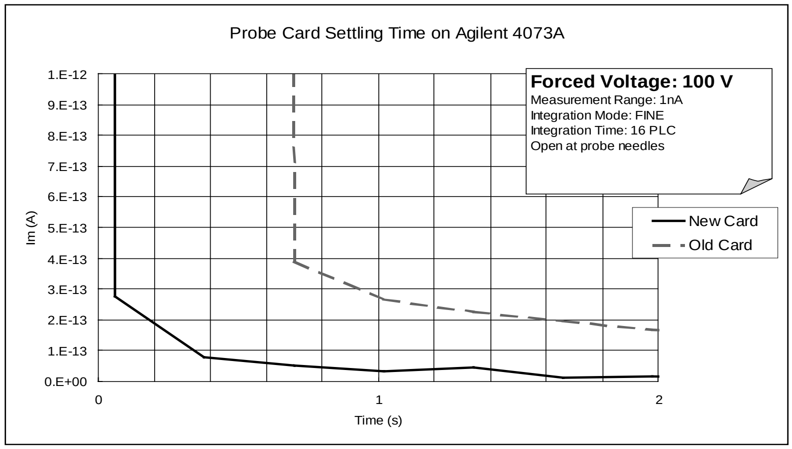

Figure 2. Comparison of Settling Time for New and Old Probe

Optimization of Integration Time

New methods for optimizing integration time are supported by the 4073A. These techniques utilize a new integration mode called SMART and an additional integration time setting. The SMART mode and additional integration time setting can reduce unnecessary integration time to improve measurement throughput.

SMART Mode

SMART mode automatically reduces the integration time for a region of current measurement value without spoiling the measurement accuracy. In general, the measurement time with SMART mode is shorter than or equal to that with LONG mode.

Measurements close to the full scale of a range have enough resolution to obtain stable measurements with shorter integration time. The integration time is automatically reduced by the PLC for the measured value close to the full scale of the range. The minimum integration time is one PLC.

In SMART mode, the integration value can be made the same as for LONG mode and the unit of measure is PLC, with the default setting being 16 PLC.

To specify SMART mode in a measurement program the `Set_adc_i` statement is used, as shown in the example below. The second parameter of the `Set_adc_i` statement is referred to as *integ mode*, and the number 4 means SMART mode.

`Set_adc_i(1,4)`	*Set SMART mode to high-resolution ADC.*
`Set_smu_ch(FNPort(0,2),1)`	*Set high-resolution ADC to SMU2.*

Additional Integration Time Setting

In general, longer integration time is necessary for accurate and repeatable lower-current measurements, while shorter integration time is enough for accurate and repeatable higher-current measurements. For example, 16 PLC is needed for the integration time in Table 2 to measure about 100 fA low current with fA level of error. When wide range sweep measurements are made from lower to higher current, a long integration time setting is necessary for the lower current measurements. This long integration time setting is unnecessary, however, for the higher current measurements made during the sweep.

The 4073A allows an additional integration time setting that reduces unnecessary integration time for higher-current measurements in a sweep. Integration time can be set for lower and higher current ranges individually by specifying an additional integration time setting.

The additional integration time setting consists of three parameters: boundary range, additional integration mode, and the integration value. The boundary range is used to separate the higher range and lower range groups. The additional integration mode and integration value are used for the higher range group that is greater than or equal to the boundary range.

For example, the following statements specify SHORT mode for the higher range group and SMART mode for the lower range group by using the `Set_adc_i` statement as shown in the example below.

`Set_adc_i(1,4,0,0,1.E-6,1)`	*Set SHORT (1) mode for the additional integration time with the boundary of 1 µA range.*
`Set_smu_ch(Drain,1)` `.........`	*Set high-resolution ADC to Drain.*
`Set_iv(Gate,1,0,Vstart,` `Vstop,Nstep)`	*Set sweep source parameters.*
`Sweep_iv(Drain,2,0,Id(*))`	*Start the sweep measurement.*

SMART (4) mode with the default integration value (= 16 PLC) is specified by the second and third parameters in the `Set_adc_i` statement above. The 1 µA range is specified as the boundary range by the fifth parameter. SHORT (1) mode is specified by the sixth parameter. Since the seventh parameter is omitted, the default integration value (= 480 µs) is used for SHORT mode.

Comparison of 4073A and 4072A Settling Time

The previous sections describe how dielectric absorption in the switching matrix part and the probe card are improved by the HR pin board and ultra low leakage probe card. To show the performance of dielectric absorption, settling time measurements can be used. Here the actual comparison data is shown to illustrate the improvement of the dielectric absorption performance of the 4073A.

Figure 3 shows the measurement results of the settling time for the 4073A with an ultra low leakage probe card and ceramic-blade needles and for the 4072A with a conventional probe card and ceramic-blade needles. The measurement conditions are as follows:

- Forced voltage: 100 V
- Current compliance: 1 nA
- Measurement range: 1 nA
- Integration time: 16 PLC
- No DUT is connected to the probe needles.

The current slowly flows down to the converged value because of the dielectric absorption. One second after the 100 V is forced, 50 fA is flowing with the Agilent 4073A, while 400 fA is flowing with the Agilent 4072A.

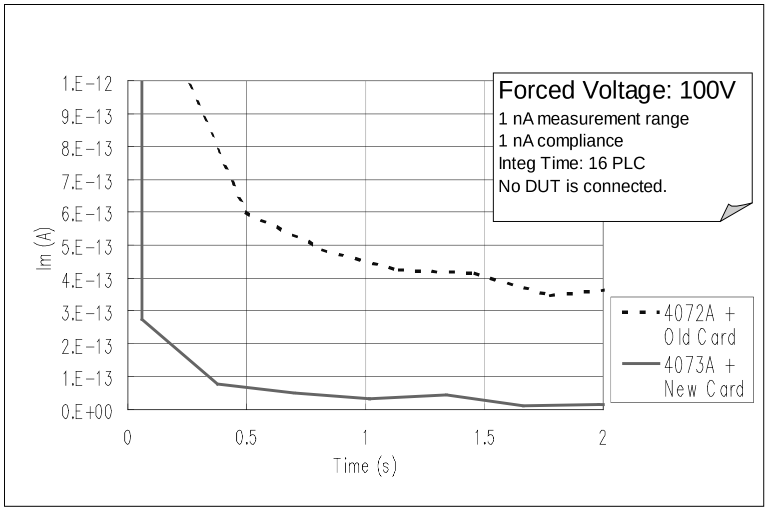

Figure 3. Comparison of 4073A and 4072A Settling Time

Summary

The new technologies employed in the Agilent 4073A enable femto-ampere (fA) and micro-volt (µV) levels of low-current and low-voltage measurement with greater accuracy and stability, which are required for state-of-the-art semiconductor process technologies. Also, measurement optimization techniques speed up measurement by reducing unnecessary integration time.

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