Keysight Technologies
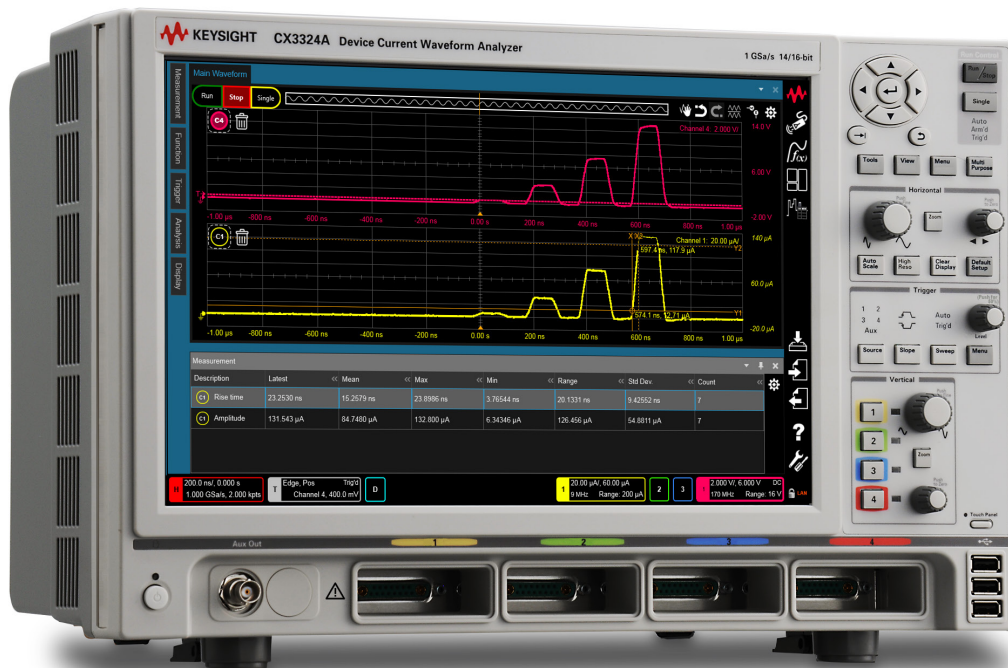## Accurate Current Waveform Measurements of Non Volatile Memory Devices using the CX3300

Application Note

![Keysight CX3324A Device Current Waveform Analyzer]

KEYSIGHT TECHNOLOGIES

Unlocking Measurement Insights

Introduction

The recent rise in demand for smartphone technology has increased the demands on non volatile memory (NVM) devices and the IoT continues to expand the application area of NVM. The flash memory is currently the mainstream for the storage device but extensive research is underway with the next generation of NVMs such as ReRAM, PRAM etc, looking at expanding applications for lower power storage, storage class memory and the replacement of conventional volatile memory through the improvement of speed, performance, power consumption, reliability and cost.

Keysight's CX3300 Device Current Waveform Analyzer, with its unique ultra-wideband low current sensing technology, allows you to quickly and interactively visualize a current waveform faster than µs and lower than µA. These are capabilities that are required in order to study a device's behavior and impedance changing mechanisms. The CX3300 supports the current sensors covering a wide range from 100 pA to 10 A with 1 GSa/s sampling rate, 200 MHz bandwidth, 14/16 bit dynamic range and 256 Mpts memory depth capabilities on a 2ch or 4ch mainframe model. The powerful dynamic current measurement capabilities enable you to analyze and debug the NVM device characteristics. This application note explains how to perform the measurement for NVM devices.

Measurement challenges and problems with present solutions

Many of new NVM memories are two terminal devices, the on and off states can be controlled by the set/reset pulse, and the on/off state is read by the reading pulse. Figure 1 below shows a typical voltage pulse waveform applied to the NVM device, and the set/reset pulse is typically less than 1 µs. The device impedance changes drastically during the set/reset pulse, and it varies according to the pulse parameters such as level, transient time and width, in addition to the material and fabrication process. Therefore, it is important to be able to measure how the impedance changes during the set/reset pulse and to study the device mechanisms and improve its performance, reliability and fabrication process or find suitable alternative materials.
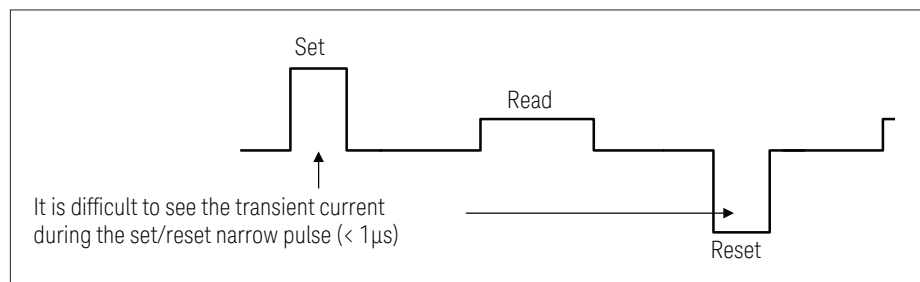

Figure 1. A typical pulse cycle for set-read-reset-read

Such high speed measurements are too fast to record using a conventional SMU and an oscilloscope is commonly used instead. However, there are a number of challenges when using an oscilloscope as follows:
  – An oscilloscope cannot measure the current directly. To convert the current to voltage, an I/V converter (e.g. 50 Ω input resistance, external shunt resistance, I/V amp, etc.) must be used.
  – Typical I/V converters limit the bandwidth for sensitivity or sensitivity for bandwidth. It is difficult for users to find or design appropriate I/V converters for their NVM devices.
  – The dynamic range of current measurement can be limited, for example , when using 50 Ω input resistance or external shunt resistance for I/V conversion.
  – An oscilloscope's dynamic range and noise floor is not sufficient for low current measurement.

Solution

The CX3300 Device Current Waveform Analyzer can be a new standard solution for NVM measurements. The CX3300 is designed specifically to enable you to easily and accurately visualize never before seen fast current waveform by integrating its powerful measurement capabilities, ultra-wideband low current sensing technology and easy to use software. The CX3300 benefits NVM characterization with the following features.

Benefits for NVM characterization:

– Visualize sub-µs/sub-µA ultra fast and low current waveform never before seen using conventional instruments.
– Quickly enable ultra-wideband low current measurement with advanced current sensors.
– Facilitate interactive and explorative measurements and debugging for finding measurement conditions.
– Provides better flexibility to use with any preferred external pulse generator compared to a source and measurement integrated product.

Key features:

– Ultra-wideband low current sensing technology based current sensors (CX1101A, CX1102A, CX1103A)
– Max. 200 MHz bandwidth (50 MHz, 100 MHz and 200 MHz options)
– Max. 1 GSa/s sampling rate
– Max. 256 Mpts memory depth (16 M, 64 M and 256 M options)
– 2ch / 4ch mainframe model. (Digital channel is available only for 4ch model)
– WGXA 14.1" LCD with multi touch screen helpful for interactive measurement and debugging
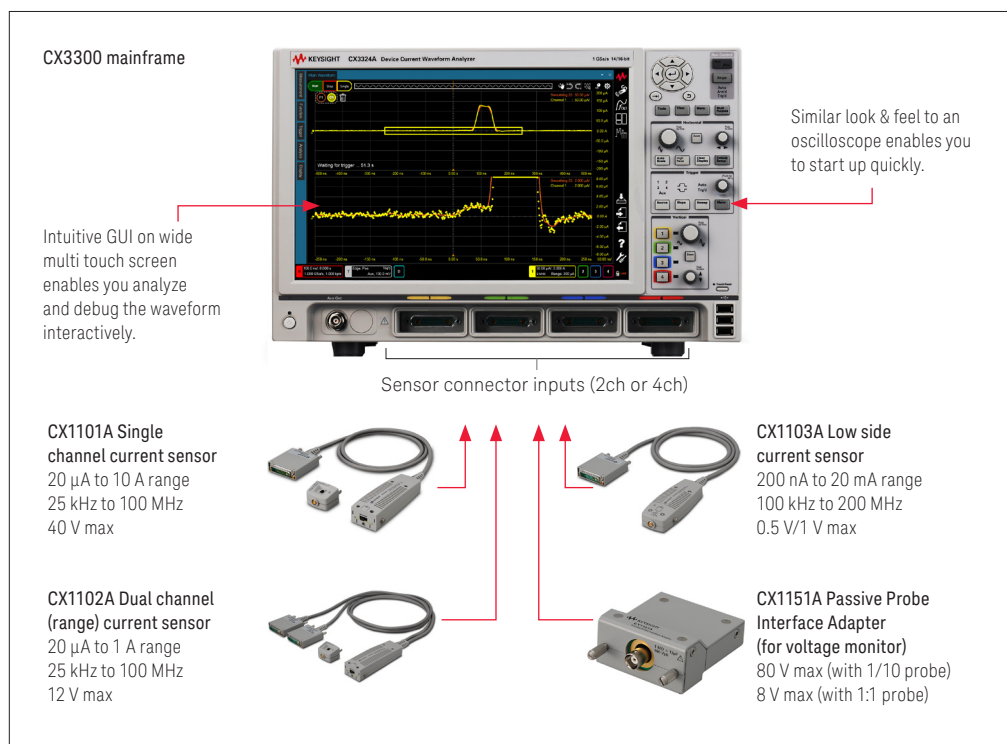

CX3300 mainframe

Similar look & feel to an oscilloscope enables you to start up quickly.

Intuitive GUI on wide multi touch screen enables you analyze and debug the waveform interactively.

Sensor connector inputs (2ch or 4ch)

CX1101A Single channel current sensor
20 µA to 10 A range
25 kHz to 100 MHz
40 V max

CX1103A Low side current sensor
200 nA to 20 mA range
100 kHz to 200 MHz
0.5 V/1 V max

CX1102A Dual channel (range) current sensor
20 µA to 1 A range
25 kHz to 100 MHz
12 V max

CX1151A Passive Probe Interface Adapter (for voltage monitor)
80 V max (with 1/10 probe)
8 V max (with 1:1 probe)

Figure 2. CX3300 Product Overview

An example of a fast dynamic transient current measurement using the CX3300 Device Current Waveform Analyzer

An example of a measurement setup using a discrete device

To understand the basic connections and check the CX3300 measurement performance, a simple pulsed IV measurement is performed with a 100 kΩ discrete resistance as shown in the following schematic.

Although any pulse generator can be used to apply the pulse, the B1525A HV-SPGU of the B1500A semiconductor device parameter analyzer is used in this example. The pulse is applied to the DUT via 50 Ω feed-thru which would be needed to prevent reflection when the pulse is narrow.

The current measurement is performed by the CX3300 with the CX1103A low side current sensor. The CX1103A supports multiple ranges from 200 nA (100 kHz BW) to 20 mA (200 MHz BW), and the 200 µA range (9 MHz BW) is chosen in this example, from the viewpoint of current sensitivity and bandwidth trade-off.

In addition to the current measurement, the CX3300 supports the monitoring of the voltage using the CX1151A Passive Probe I/F Adapter (1 MΩ input). It is helpful to compare the voltage and current at the same time. A tee connector is used to split the voltage to the DUT and the voltage monitor channel in the schematic.

It is simple to perform the synchronized measurement with the applied pulse. The CX3300 can be triggered just like an oscilloscope, and the measurement can be triggered by the current input, voltage input or AUX trigger input. Unless the current condition is known, triggering by the voltage monitor or AUX input may be useful.
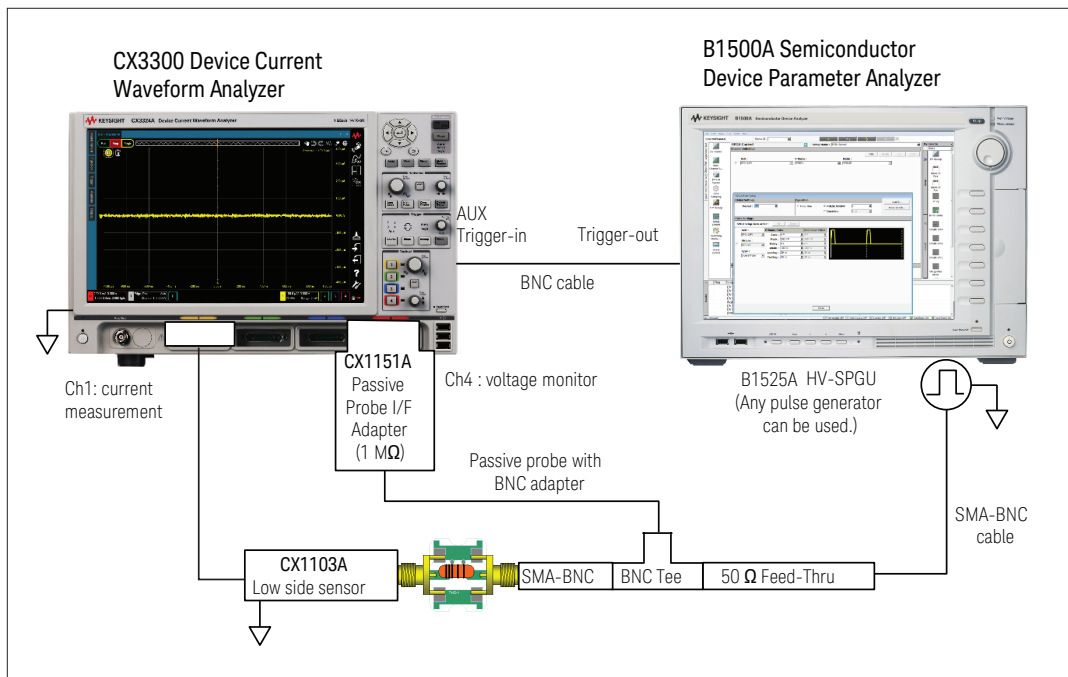

Figure 3. An example of a measurement setup using a discrete device.

Measurement of the current response to a narrow pulse

As discussed, typically the applied pulse can be less than 1 µs for set/reset pulse. To see how fast current waveform can be seen using the CX3300, let's try to apply the 100 ns narrow pulse steps from 500 mV to 13 V as follows, then measure the current response as shown in the previous example measurement setup.
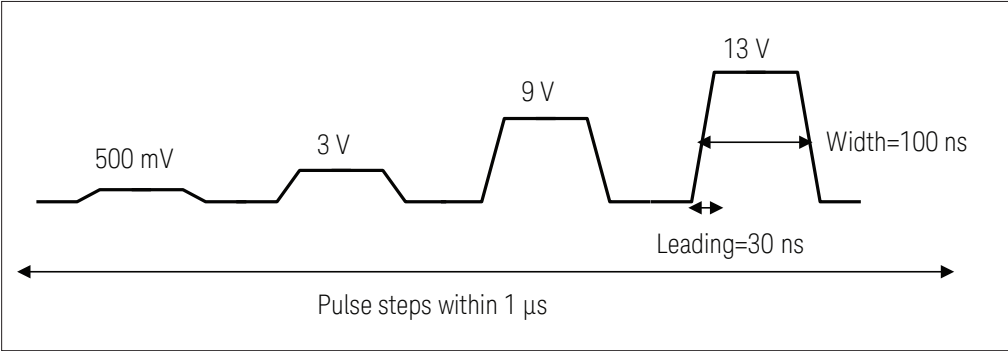

Figure 4. Sample narrow step pulses

The following figure shows the screen capture of the current response waveform. The applied voltage pulse is displayed as channel 4's waveform in magenta. The current waveform is displayed as channel 1's waveform in yellow. As shown in this figure, the CX3300's advanced features such as 1 GSa/s sampling rate, 200 MHz bandwidth and superior low current sensitivity enable you to visualize the 100 ns pulse current clearly with current sensitivity with 3 digits from 5 µA to 130 µA. This ultra wideband low current sensing technology enables you to thoroughly analyze the NVM device behavior from primitive device research to the fabricated device debugging.
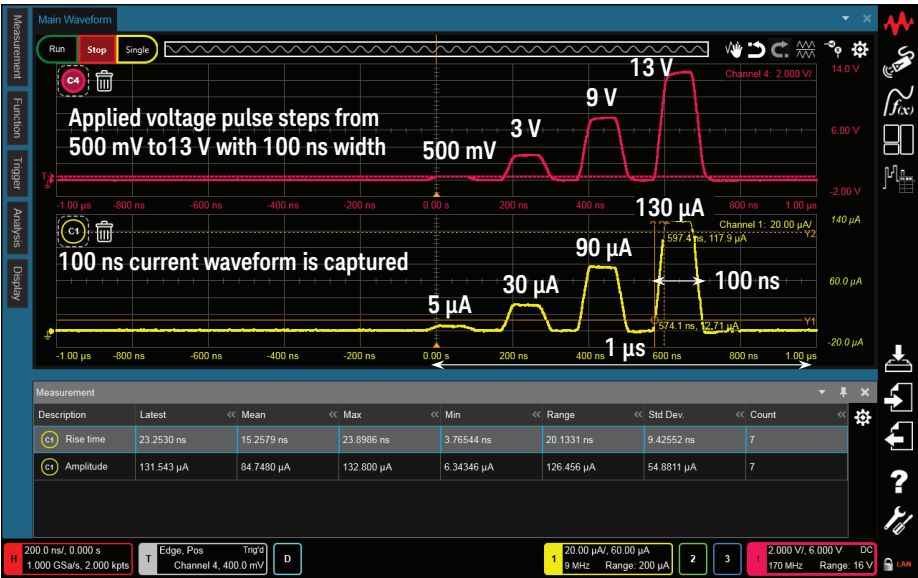

Figure 5. 100 ns current waveform is visualized

Measurement of impedance changes from off to on (from high Z to low Z)

According to the device impedance change, the flowing current can change drastically during a narrow pulse, as shown in Figure 6 below. For understanding the device mechanism, you may want to see only the area where the impedance changes from high to low, rather than entire pulse cycle.
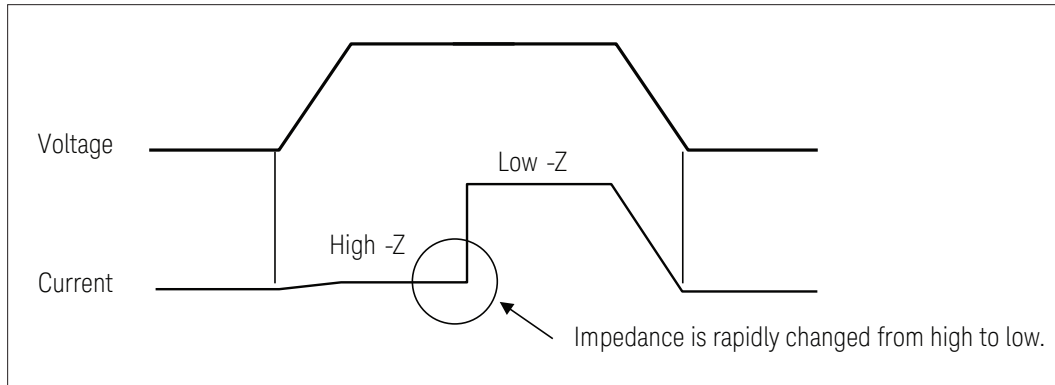

Figure 6. Dynamic current changes in a pulse

Figure 7 below shows a measurement example of transient current response. To simulate the current changes of NVM, the applied pulse to DUT(100 kΩ) is changed from 150 mV to 15 V within 200 ns using a pulse generator. The CX3300 enables you to visualize the transient current in 3 digit from 1.5 µA to 150 µA as expected using 200 µA range, as shown in the figure. The anywhere zoon function is useful to magnify and analyze the waveform precisely.

Current sensitivity is limited by the instrument and sensor intrinsic noise floor and other noise in the measurement system. Although the RMS noise must be referred to the data sheet, it can be roughly estimated 1/1000 of the range and a 3 digit measurement in the range is realistic as shown in the example in Figure 7. The current sensitivity and bandwidth is trade-off, so it is important to choose the appropriate range for your measurement. It is recommended that the device maximum current does not exceed the range. If a wider dynamic range is necessary, the CX1102 dual range sensor can be used. Although it is also possible to use the lower current range of the sensor to measure the low current in more detail, the sensor reaches 'over range' status if the current is exceeded. Further details on this status can be found in a later section of this application note.
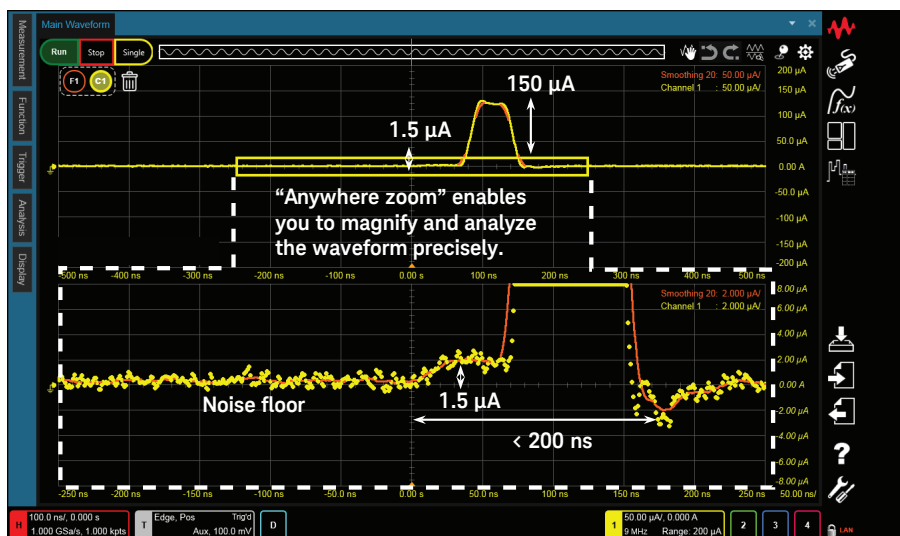

Figure 7. Low current behavior can be unveiled by sensing technology and anywhere zoom.

On-wafer Measurement Setup Example

Since a NVM device is typically fabricated and measured on a wafer, the CX3300 may be used with a wafer prober. The basic schematic is the same as the previous setup, but Figure 8 below shows an example set up with a wafer prober for interactive manual measurement. The N2787A 3D positioner and the CX1905A attachment help you to position and connect the sensor as shown in the figure. The pulse generator output and sensor input are connected by an SMA-SSMC cable which is connector furnished with a probe manipulator. It is recommended that you place only one sensor out of the CX1101A, CX1102A and CX1103A at low side (circuit common) in the measurement path. It can reduce the influence of the charge current to the sensor stray capacitance, and also prevent the influence of the insertion of additional sensors.

Since this high bandwidth measurement is different from DC measurement, unexpected disturbances such as noise, influence from residual capacitance/inductance, etc. may be observed in addition to the device characteristics that you are trying to identify. To reduce these disturbances, it is important to shorten the cables, the position, and to connect the sensor and unify a common circuit (potential reference point) among all other measurement components at a point as close as possible to the DUT.
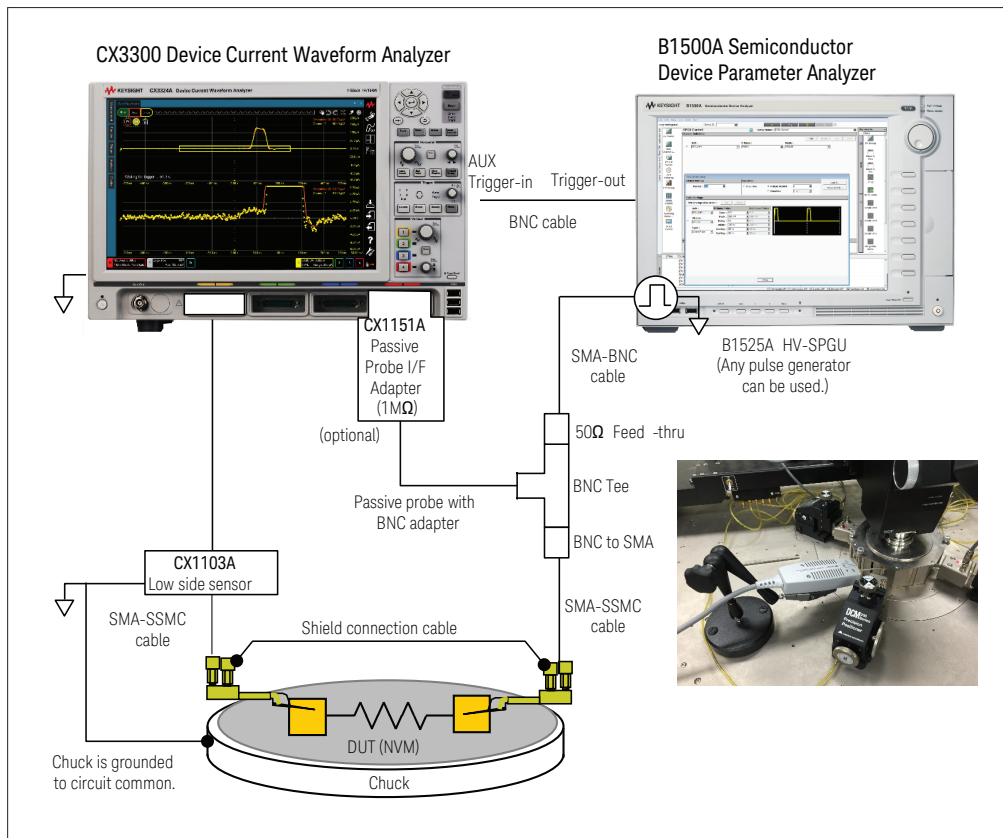

Figure 8. On-wafer measurement setup example

Measurement Tips

Flexible selection of the current sensor and ranges for max current, sensitivity and bandwidth requirements

The CX3300 supports three sensors, CX1101A, CX1102A and CX1103A, differentiated by the bandwidth, current coverage and sensitivity to satisfy various needs, as shown in Figure 9 below.

In addition to the bandwidth and range, the sensors are also differentiated by the max common voltage, input impedance and so on. Since it is recommended that you place only one sensor at the low side (circuit common), it is important to choose the appropriate sensor for your requirements. The following are example applications for each sensor.

CX1101A: This sensor supports 100 MHz (sensor standalone) wide bandwidth from 2 mA (3 µArms) to 1 A (2 mArms) ranges. Since its common mode voltage can be up to 40 V, it can be used for breakdown measurement, for example.

CX1102A: As well as CX1101A, 100 MHz (sensor standalone) wide bandwidth is available from 2 mA (3 µArms) to 1 A (2 mArms), but the common mode voltage can be up to 12 V. This sensor provides dual range, primary and secondary ranges, to support a measurement across a wide dynamic range. Note that secondary range is fixed as 1/1000 of primary range except for 1A range, and each range occupies the measurement channel respectively.

CX1103A: This sensor supports ultra-wideband and superior sensitivity across the frequency range, and provides you with the flexible choice according to your needs. This sensor can only be used at low side, and max common mode voltage is limited to less than 1V. It can be used for the transient measurement focusing on switching behavior, for example.
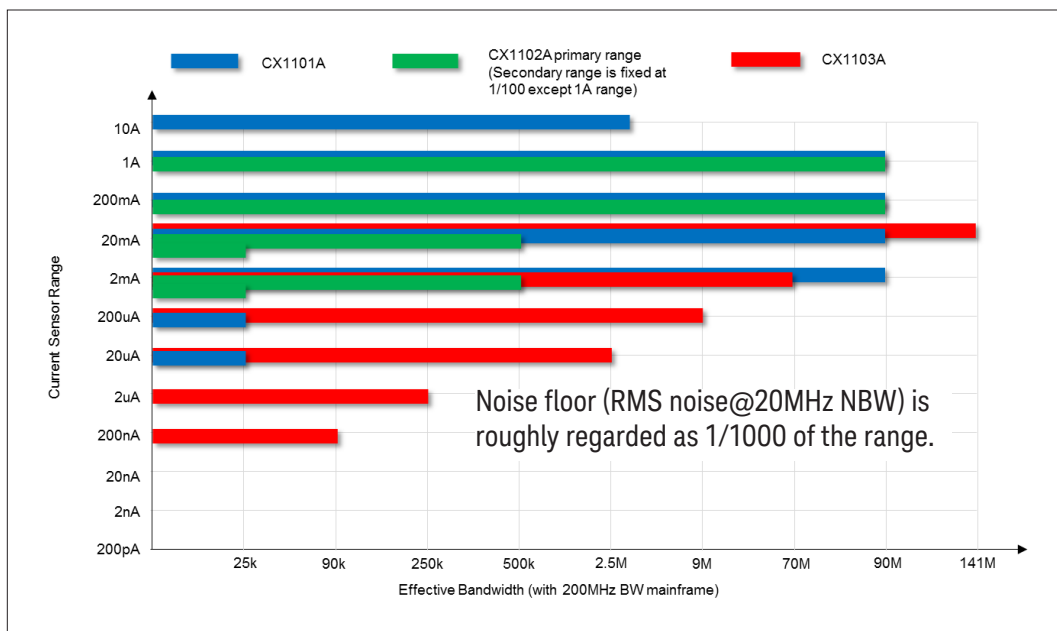

Figure 9. Three sensors cover a wide range of bandwidth and current requirements

Considerations for appropriate measurement

- Current sensitivity and max flowing current of device

Since the current measurement is limited between the upper limit and noise floor of the range, it is very important to select the appropriate range. In general, the noise floor can be estimated 1/1000 of the full scale of a range and approximately 3 digit sensitivity is achievable in a single range, though actual noise floor can be influenced by the environmental noise and the measurement condition.

To select the appropriate sensor and range, the max current, sensitivity and bandwidth must be considered, but it is recommended that you choose the minimum current range which can cover the max device flowing current (e.g. 20 µA range, if the device current is 10 µA), as the first step. Then, check the bandwidth of the range, and choose upper range if the bandwidth is not sufficient.

In order to observe the low current domain in more detail, a current range that is lower than the device max current can be selected. If the current exceeds the upper range limit, the sensor reaches 'over range' status. As long as the current remains less than the fuse protected current, the 'over range' status will not break down the sensor but the sensor circuit might influence the measurement condition and it can take longer for the device to recover from reaching 'over range' status. The measurement data may also not be accurate during and immediately after 'over range' status.

- Bandwidth and pulse parameter

Bandwidth is also an important factor when choosing the appropriate sensor according to your measurement. The bandwidth is specified for the mainframe and sensors respectively, and it isnecessary to calculate the effective bandwidth of the entire instrument with your mainframe bandwidth using the following formula.

$$BW_{effective} = 1 \Big/ \sqrt{1/BW_{sensor}^2 + 1/BW_{mainframe}^2}$$

The effective bandwidth limits the narrowness of pulse that can be measured. It is known that the rise time performance of the instrument is limited by the instrument effective bandwidth (BW_{ef}) as calculated $Tr = 0.35/BW_{ef}$. For example, the instrument Tr (Tr_{inst}) is limited to 2.5 ns for 141 MHz BWef of 20 mA range and 39ns for 9 MHz BWef of 200 µA range in CX1103A. By using the Trinst and input pulse Tr (Tr_{pulse}), the actual measured Tr is calculated as the following formulate.

$$Tr_{meas} = \sqrt{Tr_{inst}^2 + Tr_{pulse}^2}$$

This formula indicates that the Trinst is not negligible unless the Tr_{inst} is much faster than the Tr_{pulse}. When you attempt to apply the narrow pulse with Tr_{pulse} close to Trinst, note that the measured Tr contains timing error calculated by the formula above. If Tr_{pulse} equals to Trinst, timing error is about 40%, and it can be reduced to 5% by setting Tr_{pulse} 3 times of Tr_{inst}.

Many of next generation NVM devices require you to measure the current in the pulse narrower than 1 µs, for example 100 ns. In this case, the pulse trailing time (Tr) can be down to tens of nano-second order, and take the limitation and errors into account.

- Sampling rate

In general, a sampling rate 5 times the bandwidth is required. The CX3300 supports a max 1 GSa/s sampling rate (1 ns timing resolution) for 200 MHz BW, and it is sufficient for the measurement discussed here. The sampling rate and number of data point is normally adjusted automatically, but it can also be set manually. Although the CX3300 supports the high resolution mode (16 bit ADC) in addition to standard (14 bit ADC), note that the sampling rate and bandwidth are limited to 75 MSa/s (13 ns timing resolution) and 14 MHz respectively. Waveform is visualized with interpolation between the measurement points, but the raw data is only measured at the specified sampling rate.

When you have a measurement problem

When the signal frequency gets higher and higher, various phenomena may be observed which have not been seen before in DC or low frequency measurements. It is not always the device behavior, it might be disturbance caused by various factors in the measurement environment. Therefore, it is better to measure known device characteristics (e.g. resistance), have the reference, then compare to the target device. Here are some steps to follow if you encounter any issues when making a measurement:

- The current waveform is not as expected

Check the input voltage as well as the current. Voltage monitoring capability with CX1151A is very helpful for debugging. If it is found that the voltage waveform is not as expected, check the connections including cables and connectors. When the applied pulse is fast, try to use the 50 Ω feed-thru for impedance matching.

- The voltage waveform is ok, but current waveform is not as expected

Check that the bandwidth and sampling rate is appropriate for the current measurement. If you use the auto ranging, the scaling can change the range up or down automatically, and the bandwidth may be changed unexpectedly. If needed, you can disable the auto range to fix the range. There is still a problem, the current response may be disturbed by the parasitic factors in the measurement path. In high frequency measurement, parasitic capacitance and inductance of cable and connector may not be negligible unlike DC measurement, so try to shorten the cable as much as possible. In addition, the device itself may have such parasitic factors. For example, constant current may be observed in addition to the resistive current at voltage switch such as pulse leading. The voltage is changed in the rate of dV/dt, and the current may be induced by the parallel capacitance C, as calculated as $I=dQ/dt=C(dV/dt)$.

- The current waveform is noisy

First, disconnect the DUT and cable, then check the noise. It is the reference of the noise floor of the instrument. If the noise gets higher after connecting the cables and DUT, it is introduced by the measurement setup. To reduce the noise, shorten the cable length as noted above. In addition, check the circuit common is as closely connected to the DUT as possible. If the conductive body is floating and is not connected to any potential, it can be a noise source. The circuit common is basically connected using a connector shield, try to connect the ground cable close to the DUT.

Summary

This application note explains how the CX3300 can be used for NVM characterization.

The CX3300 supports ultra wideband low current measurements across a wide frequency range with a 1 GSa/s sampling rate, 200 MHz bandwidth, low noise floor and advanced current sensors. It enables sub-μA/sub-μs current waveform measurement for NVM, which has been difficult to obtain using conventional methods.

The CX3300 enables you to easily and accurately visualize never before seen true transient current waveform of NVM materials and devices. It has a wide range of capabilities, from undertaking basic research on pulse transient characteristics, to performing more detailed evaluations of devices that support the latest breakthroughs in NVM technology.

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