Electrical characterization of Graphene and nano-devices

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Keysight role in Graphene/Nano technology science

Characterisation of Graphene and Nano Devices
Keysight role in Graphene/Nano technology science
Keysight instruments for Graphene/Nano technology

- **Parametric Analyzer**
- **Network Analyzer**
- **Oscilloscope**
- **Digital Multimeter**
- **Source/Measure Unit**
- **Pico-ammeter/Electrometer**
- **Impedance / Material Analyzer**
- **LCR Bridge**
- **Power Supply**
- **Pulse Generator**

**Measurements**

- Voltage/Current
- I/V curves
- Impedance
- Capacitance
- Resistance
- Conductance
- S-parameters
- Dielectric characteristics
- Frequency Response
- Time Response
- Pulse Stimulus
- DC power

...
Graphene Material Validation & Measurement

Applications
- DC Characterization of Graphene structure
- Mw & THz Graphene Characterization
- Absorbing Materials

Instruments
- Parametric Analyzer
- Network Analyzer
- Source/Measure Unit

Measurements
- Sheet Resistance
- S-parameters
- Dielectric characteristics
- Frequency Response
- Time Response
- Pulse Stimulus
- DC power
Sheet resistance measurement

Source/Measure Unit

V +/-

Source/Measure Unit

I +/-

Source/Measure Unit

Source/Measure Unit

V_{\text{substrate}} +/-
Graphene Transistor Devices

Graphene Transistor Instruments

Graphene Transistor Measurements

DC Characterization
• I/V measurement
• C/V measurement
• Transconductance

RF & Mw Characterization
• S-parameters
• Ft
• Impedance measurement
• Frequency response

Characterisation of Graphene and Nano Devices
Carbon Nanotube/Graphene FET / SET

Complete characterization of CNT FET’s or SET’s

**B1500A**
Semiconductor Device Analyzer

![Diagram of a semiconductor device analyzer](image)

**Measurement details**

**Keysight B1500A Semiconductor Device Analyzer**

Developed I-V curves using the built-in application software for CNT FET characterization

**Paper details**

Measuring CNT FET’s and CNT SET’s using the Keysight B1500A

Web site: [www.keysight.com/find/nano](http://www.keysight.com/find/nano)

Application Note 5989-2842EN
Keysight Parametric Test Solutions

Wide variety of SMU solutions for your semiconductor business

Analyzer series
- B1500A Semiconductor Device Analyzer
- B1505A (10kV/ 1500A) Power Device Analyzer / Curve Tracer

Bench top series
- B290xA/B291xA Series SMU’s
- B2960A Series low noise sources
- B2980A Series pico-ammeter/electrometer

Modular
- E5260/70 Modular SMU Products

Switch
- E5250, B220x Switching Matrix

Tester
- 4080 Parametric Tester

Characterisation of Graphene and Nano Devices
Keysight B1500A
Semiconductor Device Analyzer

Parametric measurement solutions spanning the range from DC to fast pulsed measurement.
Overview of the Keysight B1500A

Complete capacitance measurement solution
- QSCV using SMUs
- CV module for 1 kHz to 5 MHz measurement
- Built-in CV compensation
- Automatic CV/IV switching
- Agilent 4294A driver (for up to 110 MHz CV or Cf)

Versatile design
- Flexible: 10 module slots
- Large touch screen display
- Windows XP-based for easy workplace integration

Integrated fast pulsed measurement
- Voltage pulsing and fast IV measurement in one module
- Fast: 1 μs spot and 100 μs 10-pt sweep measurement
- Test up to 10 channels in parallel

Advanced measurement functions
- Linear/binary search
- Multi-channel sweep
- List Sweep
- Parallel test
- Direct control mode
- Range management

EasyEXPERT software
- Intuitive interface
- >330 furnished application tests
- Built-in test sequencing & wafer prober control
- Easy data export

Leading edge non-volatile memory test
- ±40 V pulsing capability
- 0.4 mV force voltage resolution
- 10 ns pulse widths
- Arbitrary waveform creation
- Up to 10 independent pulse channels

Characteristic of Graphene and Nano Devices

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B1500A and EasyEXPERT Software form a Complete Parametric Analysis Solution

- **Microsoft Windows-based EasyEXPERT software**
- **Over 300 furnished application tests**
- **Innovative task-based approach to parametric test**
- **Measure, append and repeat functions**
- **Built-in semi-auto wafer prober drivers**
- **Integrated switching matrix control for the B2200A, B2201A and E5250A**
- **Standby mode for circuit debug**
- **“My Favorite Setup” feature allows users to customize application tests**
- **Intuitive GUI-based application test setup windows**
- **Can automatically export measurement data to external drives**

**Supported Functions:**
1. Sweep
2. Multi-channel sweep
3. List sweep
4. Time sampling
5. 1 kHz to 5 MHz CV
6. Quasi-static CV
7. Direct control
8. HV-SPGU Control

**“Quick Test” utility supports test sequencing without programming**

**Data and setup information can be automatically saved or selectively saved after each measurement**
B1500A’s Hardware allows both DC and Fast Pulsed Measurements

- Medium Current SMU (50 µs Pulse MCSMU)
- Multi-frequency capacitance measurement unit (MFCMU)
- Medium power SMU (New MPSMU)
- High resolution SMU (HRSMU)
- High power SMU (HPSMU)
- Waveform Generator/ Fast Measurement Unit (WGFMU)
- High-Voltage Semiconductor Pulse Generator Unit (HVSPGU)
- 4.2 Amp ground unit (GNDU)

All SMU types are Kelvin (separate force and sense inputs)

Ten slot modular mainframe
Complete Capacitance Measurement Solution
B1500A Capacitance Measurement Coverage

EasyEXPERT 5.50

QSCV
B1500A
(SMU)

HFCV
B1500A
(MFCMU)

Ultra-HFCV
4294A / E4990A(?)

- Standard (>2nm) dielectrics
- Thin-gate (<2nm) dielectrics

1 kHz 5 MHz 110 MHz
B1500A Step Voltage QSCV Measurement Technique (Using SMUs):

The step voltage technique is very similar to a standard voltage sweep. The difference is that at each point on the sweep the voltage is “bumped” and the resultant current (charge) is measured. The charge and voltage can then be used to determine capacitance at that point.

\[ C = \frac{\Delta Q}{\Delta V} \]
B1500A QSCV Measurement Results

A classic quasi-static CV curve.
B1500A Multi-frequency Capacitance Measurement Unit (MFCMU)

- Single slot module
- EasyEXPERT provides a PC-based GUI (including open/short/load calibration)
- 1 kHz to 5 MHz measurement range
- Can supply up to ±100 V of DC bias (when used with the SMUs)
- Easy to superimpose HFCV and QSCV measurements

QSCV response

HFCV response
You Can Easily Perform Automated Parameter Extraction on CV Curves Using EasyEXPERT

All important device parameters calculated in a matter of seconds.
SMU CMU Unify Unit (SCUU) Provides CV-IV Switching and Supports IV Measurements to 1 fA

Note: When using the SCUU with the SCUU cable capacitance compensation is automatic. The cable length is detected at boot-up and built-in compensation routines compensate to the output of the SCUU.
The B1500A Offers Complete Measurement Coverage – From DC to Ultra-fast Pulsed IV

Measurement Range

1 A

0.1 fA

SMU/MCSMU:
- Technology development
- Process integration
- Incoming inspection
- Failure analysis
- Reliability test
- Device modeling
- NVM cell test
- Nano device and material research
- Quasi-static CV
- Timing on-the-fly NBTI

WGFMU:
- Ultra-fast NBTI
- General pulsed IV
- RTS measurement
- Advanced NVM (PRAM, ReRAM)
- MEMS capacitor characterization
- All fast time-domain measurement

B1542A pulsed IV:
- SOI transistor test
- High-k gate transistor test

Minimum Pulsing capability

1ms 100us 10us 1us 100ns 10ns
What is Driving the Need for Fast Pulsed Measurement?

• New reliability tests (NBTI/PBTI) require spot and sweep measurements to be made in a few microseconds

• The transient current consumed by memory arrays can be quite large, and characterizing these current spikes requires current measurements to be made in one microsecond or less.

• Characterization of SOI MOSFETs requires pulsed measurement in the nanosecond range to prevent device self-heating effects from distorting the measurement results

• Characterization of high-k gate dielectric MOSFETs requires pulsed measurement in the nanosecond range to remove the effects of electron trapping in the gate oxide due to electron tunneling

• R&D for novel devices or materials (MEMS, Organic Transistor, etc.) and many other newly discovered phenomena (such as random telegraph signal noise) require very fast current and voltage
Issues in Advanced process devices

**#1: SOI**

- **Self-heating effect**
- **High thermal resistance**

**MOS-FET on SOI**

Drain current decrease

**#2: High-k**

- **MOS-FET with High-k Gate dielectrics**
- **Trapped electron & Gate leakage**

- Electrons trapped in the boundary defects influence the electronic field applied to the channel.

**#3: HEMT**

- **Self-heating effect & Current collapse**
- **Drain current decrease**

**GaN HEMT**

- Electrons trapped in the AlGaN surface states influence the electronic field applied to the channel

**#4: Nano**

- **Damage/Destroy DUT**
- **Joule heating effect**

**Joule heating effects damage small nanodevices**

**Characterisation of Graphene and Nano Devices**
Keysight has a complete line of Pulsed IV solutions

◆ B1542A Pulsed IV Parametric Test Solution
  ◆ *Ultra Narrow* Pulse IV solution for SOI/High-k devices
    ➢ +/- 4.5V pulses for the gate and +/-10V and 80mA for the drain
    ➢ **10ns** gate pulse width with **2ns** rise and fall times
    ➢ 1uA current measurement resolution

◆ B1530A WGFMU Pulsed IV Solution
  ◆ *High resolution* Pulse IV solution for advanced process devices
    ➢ +/-10V for gate/drain and drain current up to 10mA
    ➢ 100ns pulse width
    ➢ **2nA** current measurement resolution

◆ New B1514A MCSMU Module 50us, 30V to be discussed later

◆ B1525A SPGU Pulsed IV Solution
  ◆ *Higher Voltage/Current* Pulse IV solution for HEMT or Power device
    ➢ +/-40V for gate/drain and drain current up to **400mA**
    ➢ 5us pulse width
    ➢ 40uA current measurement resolution
B1542A Pulsed IV Parametric Test Solution

◆ Target Application

- Id-Vd and Id-Vg measurement with pulse “gate” bias for the SOI or high-k gate dielectrics MOSFET.

◆ Benefits

- Ultra narrow pulses reduces the self-heating effects and the incidence of electron trapping for SOI transistors and high-k gate dielectric transistors respectively
  - Capability to apply 10ns gate pulse width with 2ns rise and fall times

- Complete package contains all instruments, cables, connectors and software needed for PIV
  - System cabling to keep impedance matching for uncluttered pulse shape down to 10ns pulse width with 2ns rise/fall time
  - Specially designed Bias-T to make pulse top flat
  - Feedback loop enables accurate Id-Vd and Id-Vg measurement
B1542A Pulsed IV solution - System Configuration

Keysight 81110A Pulse Generator

Gate Pulse Output Ch

Keysight B1500A Semiconductor Device Analyzer

System configuration keeping impedance matching everywhere

Keysight DSO90254A 2.5 GHz Digital Storage Oscilloscope

Gate Pulse Monitor Ch

Pulse Splitting Tee

DC Bias Ch from SMU

Terminator

RF coaxial cable

DUT

Bias-T

RF coaxial cable

Triaxial cable

Characterisation of Graphene and Nano Devices
B1542A Pulsed IV solution - Effect of Pulsed IV for SOI/SSOI

Reference:
- "High Performance and New Structure CMOS Device Technology for the leading edge LSI" by Shinichi Takagi from MIRAI project, at Agilent AMF2006 in Japan
**Target Application**

- Nanoscale devices such as carbon nanotubes, semiconductor nanowires, graphene-based electronics, molecular organic-based electronics, single electron devices and advanced semiconductor devices
- NBTI & PBTI Reliability measurements plus Random Telegraph Signal Noise Measurements.

**Benefits**

- Capability to measure small current/voltage due to the necessity of applying very small voltage pulses to reduce the Joule heating effects
  - Current measurement range: 10uA – 10mA
  - Effective resolution: 0.2% of range (Minimum 2nA)
- Easy to use
  - B1530A WGFMU Pulsed IV Solution does NOT require any external equipment and messy cablings because of the capabilities for both pulse generation and precise measurement on one channel
• Offer the combination of arbitrary linear waveform generation (ALWG) with synchronized fast and precise current or voltage (IV) measurement

• Optional module for B1500A

• Compact solution without any external equipment

• Multi-channel parallel testing for up to 9 devices

• Upgradable for existing B1500A mainframe

B1530A

• Minimum Pulse Width: 100ns
• Up to 10V/10mA output
• 200MHz samp/s
• 2nA current measurement resolution
• 2ch/Module

Up to 5 modules

Characterisation of Graphene and Nano Devices
The B1530A includes WGFMU module, two RSU and two cables between WGFMU and RSU.

* Doesn’t include the cables from RSU-output and RF-Probe.

-Some prober vendors can provide the cables between RSU/Probes and also Probes. Please contact prober vendor.
B1530A WGFMU Pulsed IV solution
- System Configuration (2) : For DC Probes

-The B1530A/B1530A-FG includes WGFMU module, two RSU and two cables between WGFMU and RSU.
* Doesn't include the cables from RSU-output and DC-Probe, and SSMC cable.

Some prober vendors can provide the cables between RSU/Probes and also Probes. Please contact prober vendor.
B1530A WGFMU PIV Solution - Example of Measurement Data

Note:
100us Step measurement was done by SMU
1us Step & 1us Pulse measurement was done by B1530A WGFMU
B1530A WGMFU Can Make Random Telegraph Signal Noise Measurements

Spectral Density Plot

Convert to Frequency Domain

RTS Noise

Characterisation of Graphene and Nano Devices
B1525A HV-SPGU Pulsed IV Solution for High Voltage/High Current applications

- **Target Application**
  - High Voltage/Current Pulsed IV, such as characterization for HEMTs

- **Benefits**
  - Evaluate High power devices by minimizing the self-heating effect
    - Able to apply gate/drain pulses up to 40V and drain current up to 400mA
    - Wide range of pulse width from 5 us to 10 s
  - Easy to use & economical solution
    - Require only one B1525A module for three terminal devices
    - No need any external equipment and complex cabling
    - GUI-based sample Application Tests run on EasyEXPERT
B1525A SPGU (Semiconductor Pulse Generator Unit)

- A fully integrated high-voltage pulse generator unit module
  - Two channels per module
  - Up to 5 modules (10 channels) per B1500A
- ± 40V pulse supply capability
- Superior pulse level accuracy
- Three-level pulse and open-state pulse capability on each channel
- Complex waveform generation
- Integrated into B1500A EasyEXPERT software
- Output SPGU voltage monitor function (*industry first function!*)

Characterisation of Graphene and Nano Devices
A One Million Cycle Write/Erase Endurance Test Can be Completed in Hours Rather Than Days!

% of Write/Erase Cycles Completed is Displayed

Written Vth

Erased Vth

Written/Erased Vth Separation Over Time
All the parameters for Pulsed IV parametric test can be easily set and changed.

- Tracer test mode/OSC view

User can optimize the timing parameters such as integration time and delay for the best measurement.

- Application test mode

✓ Oscilloscope view gives you more confidence for the pulse measurement of MCSMU by optimizing timing parameters with monitoring actual V/I waveform that has been impossible before.

✓ GUI-based dedicated Application test for pulsed Id-Vd or Id-Vg makes task-oriented approach also to fast pulsed IV measurement as easy as 1-2-3.

200+ pages of invaluable information on parametric test

You can request it online:
http://www.keysight.com/find/parametrichandbook
You can also request a copy by completing the evaluation form.
Thank you for your kind attention