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Edition 1.0 2023-10

TECHNICAL SPECIFICATION

colour inside

Nanomanufacturing – Key Control Characteristics –
Part 8-3: Nano-enabled metal-oxide interfacial devices – Analogue resistance change and resistance fluctuation: Electrical resistance measurement

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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FOREWORD

IEC TS 62607-8-3 has been prepared by IEC technical committee 113: Nanotechnology standardization for electrical and electronic products and systems. It is a Technical Specification.

The text of this Technical Specification is based on the following documents:

Draft	Report on voting
113/743/DTS	113/767/RVDTS

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Specification is English.

A list of all parts in the IEC 62607 series, published under the general title *Nanomanufacturing – Key control characteristics*, can be found on the IEC website.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- transformed into an International standard,
- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

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INTRODUCTION

Nano-enabled metal-oxide interfaces, such as an oxide nanolayer sandwiched by metal electrodes, are the essential components of IoT devices for computing. Nano-enabled functions derived from the nanoscale metal-oxide interface and the oxide nanolayer appear, such as a significant change in electrical resistance. The analogue resistance change is the typical characteristic which possesses the large potential for non-von Neumann information processing. More concretely, the metal-oxide interfacial device is an indispensable element in the product-sum circuit that records the learning process as the analogue resistance change. In the research community, however, the analogue change and the fluctuation of the resistance have not yet been systematically investigated. The reason why systematic research and development is not progressing is that the measurement protocol of these characteristics is not quantitative. The bottleneck impedes not only the electrotechnical evaluation of the device but also developments for various applications.

This document offers a measurement protocol of the analogue resistance change and the quantitative index to evaluate the linearity of the analogue resistance change in nano-enabled metal-oxide interfacial devices.

NANOMANUFACTURING – KEY CONTROL CHARACTERISTICS –

Part 8-3: Nano-enabled metal-oxide interfacial devices – Analogue resistance change and resistance fluctuation: Electrical resistance measurement

1 Scope

This part of IEC 62607, which is a Technical Specification, specifies a measurement protocol to determine the key control characteristics

– analogue resistance change, and
– resistance fluctuation

for nano-enabled metal-oxide interfacial devices by

– electrical resistance measurement.

Analogue resistance change as a function of applied voltage pulse is measured in metal-oxide interfacial devices. The linearity in the relationship of the variation of conductance and the pulse number is evaluated using the parameter fitting. The parameter of the resistance fluctuation is simultaneously computed in the fitting process.

– This method is applicable for evaluating computing devices composed of the metal-oxide interfacial device, for example, product-sum circuits, which record the learning process as the analogue resistance change.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 80004-1, *Nanotechnologies – Vocabulary – Part 1: Core vocabulary*

3 Terms, definitions, acronyms, and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 80004-1 and the following apply.

ISO and IEC maintain terminological databases for the use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1.1
device under test
DUT
sample attached to an apparatus for evaluation of a specific physical property such as electrical resistance or I-V behaviour

3.1.2
DC, qualifier
pertaining to time-independent electric quantities such as voltage or current, to devices operated with direct voltage and current, or to quantities associated with these devices

Note 1 to entry: The notation "DC" is preferred in English to the notation "d.c." which is an abbreviation of "direct current".

[SOURCE: IEC 60050-151:2001, 151-15-02, modified – Notes 2, 3 and 4 to entry have been deleted.]

3.2 Terms specific to this document

3.2.1
analogue resistance change
continuous variation of resistance as a function of applied voltage pulse

Note 1 to entry: When a voltage is applied to a metal-oxide interfacial device, for example, a resistive memory device, the resistance increases or decreases in an analogue manner based on the sign of the voltage [1].

Note 2 to entry: This kind of resistive device can be used to mimic a neural synapse wherein the resistance acts like a weight that modulates the voltage applied to it [1].

3.2.2
resistance fluctuation
least-squares error obtained during parameter fitting of analogue resistance changes

3.3 Abbreviated terms

SMU source measure unit

4 Measurement of resistance

4.1 General

The reliable test protocol of analogue resistance measurement is standardized. A schematic diagram of the typical resistance measurement is shown in Figure 1. Figure 2 is a set of example photos showing how the DUT is set onto a sample stage.

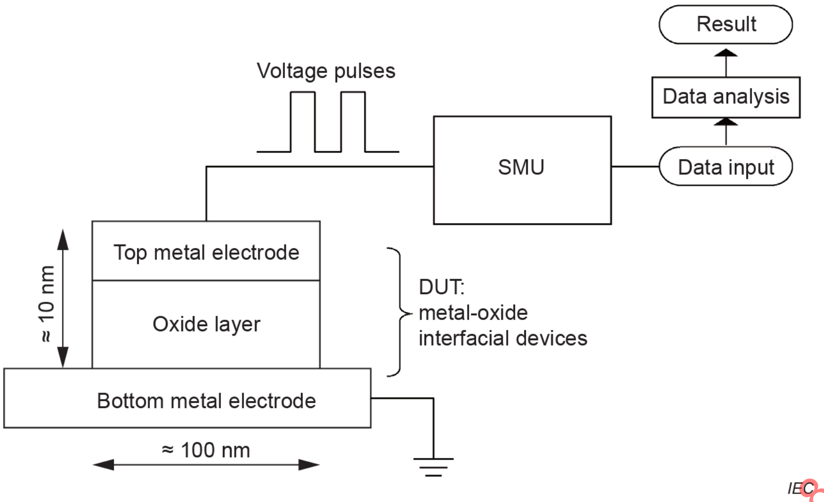
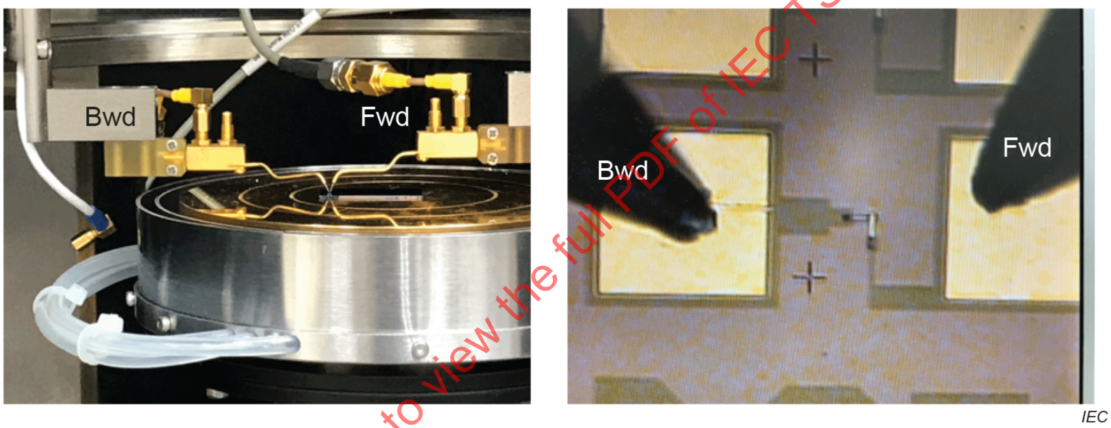


Figure 1 – Example of the experimental schematic diagram for the resistance measurement



Forward (Fwd) and backward (Bwd) contacts are shown.

Figure 2 – Photos of the sample stage

4.2 Method for processing and fabrication of DUT

Report the stacking structure of DUT, such as the material and the thickness of the metal-oxide interfacial device. In addition, the fabrication process information is important to be reported, such as the method of deposition, the shape of the DUT, and the electronic contact to SMU.

In order to avoid resistance measurement artifacts, the electric resistance of the substrate (R_{sub}) should be higher than that of the DUT (R_{dut}). The parallel current path in the substrate becomes smaller with the ratio of R_{dut}/R_{sub}. This value should be smaller than the error bar of the data. The electronic contact resistance, for example between the contact pad and the probe, should be minimized.

4.3 Experimental procedures

- Step 1. Recording of measurement conditions: temperature, humidity, and measurement setup, such as the probe specifications.
- Step 2. Sample setting: the DUT is mounted on the stage to connect to SMU electrically.
- Step 3. DC I-V measurement: from the result of DC I-V measurement, the ranges of current and voltage sweeps are decided.

- Step 4. Pulse measurement: the resistance change as a function of the pulse height is evaluated with the different pulse width.
- Step 5. Initial measurement: with the targeted pulse height and width, the analogue resistance change as a function of the pulse number is measured.
- Step 6. Repeated measurement: step 5 is repeated.
- Step 7. Post-measurement characterization: the DC I-V curve is measured to make sure there are no electrical changes in the sample.
- Step 8. Recording of measurement conditions to confirm the stable measurement environment.

NOTE For Step 3, in some resistive switching devices, the DC I-V measurement can cause excess current and damage the device. One possible way to avoid damage in the DC I-V measurement is to gradually increase the voltage applied to the pristine device. By this protocol, the voltage at which the resistance change occurs can be determined. Normally, a slightly higher voltage pulse would be used in Step 4.

Table 1 summarizes the measurement sequence and the parameters to be recorded in each step.

Table 1 – Measurement sequence of analogue resistance change and its parameters

Step		Parameter 1	Parameter 2	Parameter 3
1	Recording of measurement conditions	Temperature	Humidity	
2	Sample setting	DUT is mounted on the stage to connect to SMU electrically.		
3	DC I-V measurement	Ranges of current	Voltage sweeps	
4	Pulse measurement	Voltage sweeps	Voltage step	Pulse width
5	Initial measurement	Voltage sweeps	Voltage step	Pulse width
6	Repeated measurement	Number of repetitions		
7	Post-measurement characterization	Ranges of current	Voltage sweeps	
8	Recording of measurement conditions	Temperature	Humidity	

5 Reporting data

- Sample description.
- Measurement conditions shown in 4.3.
- I-V measurement configuration.
- Resistance or conductance as a function of pulse number.

6 Data analysis and interpretation of results

6.1 General

From the measured raw current and voltage, the conductance G is calculated as follows:

$$G = I/V,$$

where I is the current and V is the voltage obtained by SMU.

NOTE Conductance G is the reciprocal of electrical resistance.

6.2 Parameter fitting

The variation of the conductance (ΔG) as a function of the normalized pulse number p is given by Formula (1) [1][1], [2], [3]:

$$\Delta G(p) = \Delta G_{\text{max}} \frac{1 - e^{-Ap}}{1 - e^{-A}} \tag{1}$$

where $\Delta G(p) = G(p) - G_{\text{min}}$ and $\Delta G_{\text{max}} = G_{\text{max}} - G_{\text{min}}$. G_{max} and G_{min} represent maximum and minimum values of G in the range of the measurement, respectively. A least-squares method is utilized for the fitting with the parameters of A and ΔG_{max}.

After performing the fitting on the graph, ΔG, plotted as y-axis, is normalized as $\Delta G/\Delta G_{\text{max}}$ against the x-axis of normalized pulse number (p). The least-squares method shows the same value of A. The least-squares error (or chi-square value) should be recorded to quantitatively estimate the fitting error.

NOTE When metal-oxide interfacial devices are used in memory and AI devices, the stochastic fluctuation also has a large impact on device characteristics, so it is important to standardize indices for evaluating this stochastic fluctuation. However, the stochastic behaviour that appears as noise, for example, is subject to academic research because it varies with its origin [4], [5]. Therefore, the evaluation method is standardized when those studies are mature.

6.3 Interpretation of results

Parameter A obtained by the fitting is utilized to evaluate the linearity of the relationship of G and p in the analogue resistance change behaviour. As the absolute value of A becomes closer to zero, the more linear dependence on p is shown regarding the value of G. ΔG_{max} is expressed as Parameter B and applied as the range of normalization of ΔG during curve fitting. The least-squares error obtained as the chi-square value in the fitting process is denoted by Parameter C, which shows the degree of resistance fluctuation. A typical example of the analysis of measurement results is described in Annex A.

[1] Numbers in square brackets refer to the Bibliography.

Annex A
(informative)

Case study

A.1 Measurement of the analogue change and the fluctuation of the resistance

A.1.1 General

Analogue resistance change and the resistance fluctuation are evaluated in the sample with a structure of TiN/Ta-oxide/TiN.

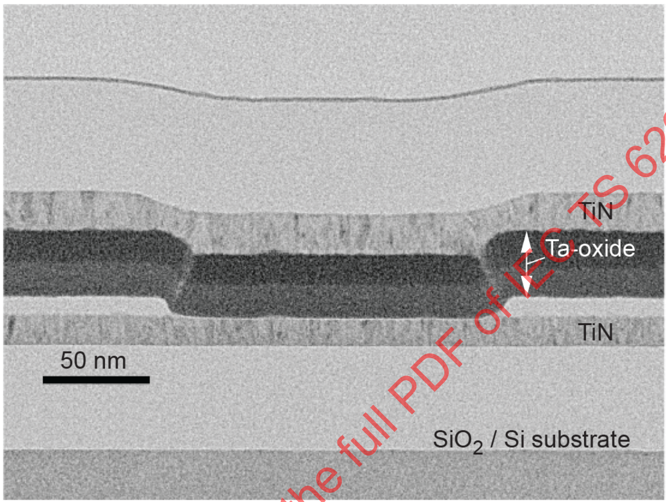


Figure A.1 – Transmission electron microscopy image of TiN/Ta-oxide/TiN

A.1.2 *I-V* measurement of TiN/Ta-oxide/TiN

The measurement sequence is summarized in steps as described below. Recorded parameters of each step are shown in Table A.1. For clarity, the graphs in The red line is a guide to the eye showing the increase of the pulse height. The blue arrows are also guides to the eye showing how to decide the pulse height.

Figure A.3 to Figure A.5 are shown using the conductance, because conductance is the reciprocal of electrical resistance and the positive-negative behaviour is the same as that of current.

- Step 1: Recording of measurement conditions

  Temperature, humidity, and measurement setup such as the probe specifications were recorded before conducting measurement. In this case study, the Kelvin probe arm and the tungsten probe with the tip radius of 5 µm were utilized for the precise measurement.

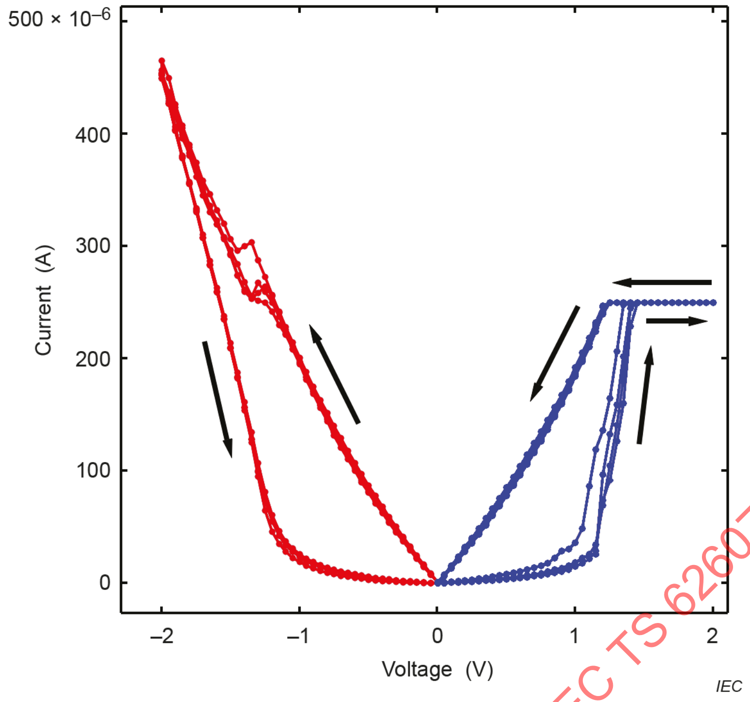
- Step 2: Sample setting

  DUT, a sample to be measured, was mounted on the stage. The sample structure is TiN/Ta-oxide/TiN as shown in Figure A.1.

- Step 3: DC *I-V* measurement

  The arrows in the figure show the directions of the voltage sweeps. The blue and red lines indicate the current behaviour which corresponds to the conductance increase and decrease processes, respectively.

  Figure A.2 shows DC *I-V* curves. The *I-V* curves were measured to investigate the range of the pulse voltage height applied to the following measurement step.



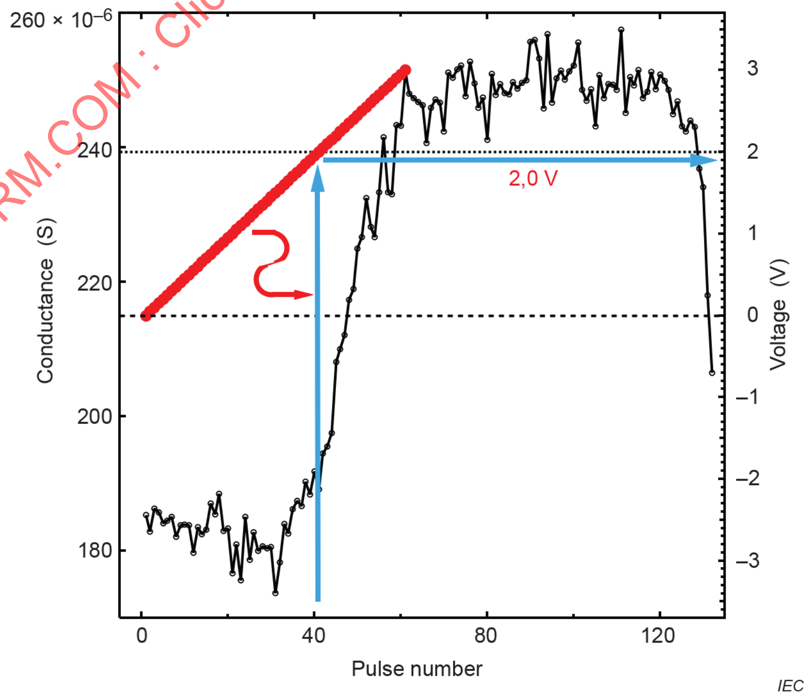
The arrows in the figure show the directions of the voltage sweeps. The blue and red lines indicate the current behaviour which corresponds to the conductance increase and decrease processes, respectively.

Figure A.2 – DC *I*-*V* measurement

- Step 4: Pulse measurement

  The resistance change as a function of the pulse height was evaluated as shown in The red line is a guide to the eye showing the increase of the pulse height. The blue arrows are also guides to the eye showing how to decide the pulse height.

  Figure A.3. For the conductance increasing process, the pulse height was determined as 2 V.



The red line is a guide to the eye showing the increase of the pulse height. The blue arrows are also guides to the eye showing how to decide the pulse height.

Figure A.3 – Pulse measurement

- Step 5: Initial measurement

  With the targeted pulse height and width, the analogue resistance change as a function of the pulse number was measured by switching cycles. Figure A.4 shows the result of the measurement of this case study.

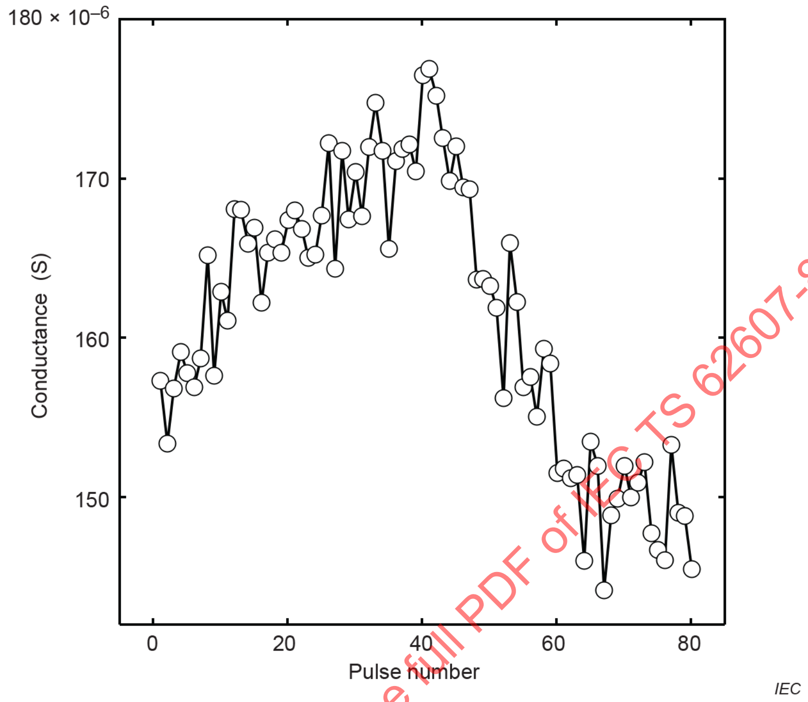


Figure A.4 – Initial measurement

- Step 6: Repeated measurement

  Repeat Step 5. In this study, the measurement cycle was repeated six times (Figure A.5).

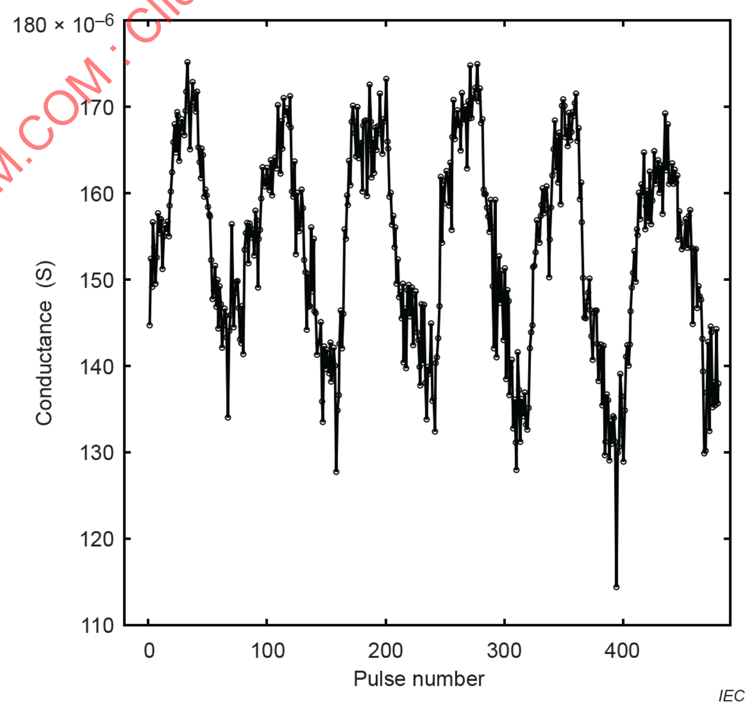
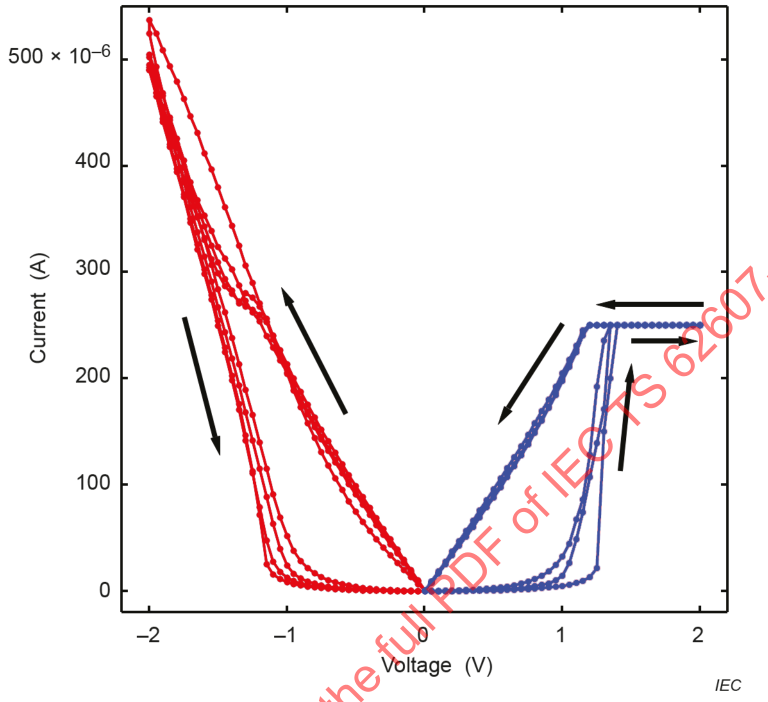


Figure A.5 – Repeated measurement

- Step 7: Post-measurement characterization

  DC I-V curve was measured again to make sure no electrical changes occurred in the sample in consequence of the measurement sequence. The arrows in the figure show the directions of the voltage sweeps. The blue and red lines indicate the current behaviour which corresponds to the conductance increase and decrease processes, respectively.

  Figure A.6 shows the result of the measurement of this case study.



The arrows in the figure show the directions of the voltage sweeps. The blue and red lines indicate the current behaviour which corresponds to the conductance increase and decrease processes, respectively.

Figure A.6 – Post-measurement characterization

- Step 8: Recording of measurement conditions

  At the end of the sequence, room temperature and humidity were recorded to confirm that the stable measurement environment was maintained.

Table A.1 – Measurement sequence of analogue resistance change and its parameters (case study)

Step		Parameter 1	Parameter 2	Parameter 3
1	Recording of measurement conditions	Temperature 24,1 °C	Humidity 63 %	
2	Sample setting	DUT was mounted on the stage to connect to SMU electrically.		
3	DC I-V measurement	Ranges of current Current compliance Reset: 1 mA Set: 250 µA	Voltage sweeps Reset: 0 V to −2 V Set: 0 V to 2 V	
4	Pulse measurement	Voltage sweeps First half: 0 V to 3 V Second half: 0 V to −3,5 V	Voltage Step: 0,05 V	Pulse width: 1 µs

Step		Parameter 1	Parameter 2	Parameter 3
5	Initial measurement	Voltage sweeps First half: 2 V Second half: −2,6 V	Voltage Step: 0 V	Pulse width: 1 µs
6	Repeated measurement	Number of repetitions: 6		
7	Post-measurement characterization	Ranges of current Current compliance Reset: 1 mA Set: 250 µA	Voltage sweeps Reset: 0 V to −2 V Set: 0 V to 2 V	
8	Recording of measurement conditions	Temperature 25,3 °C	Humidity 66 %	

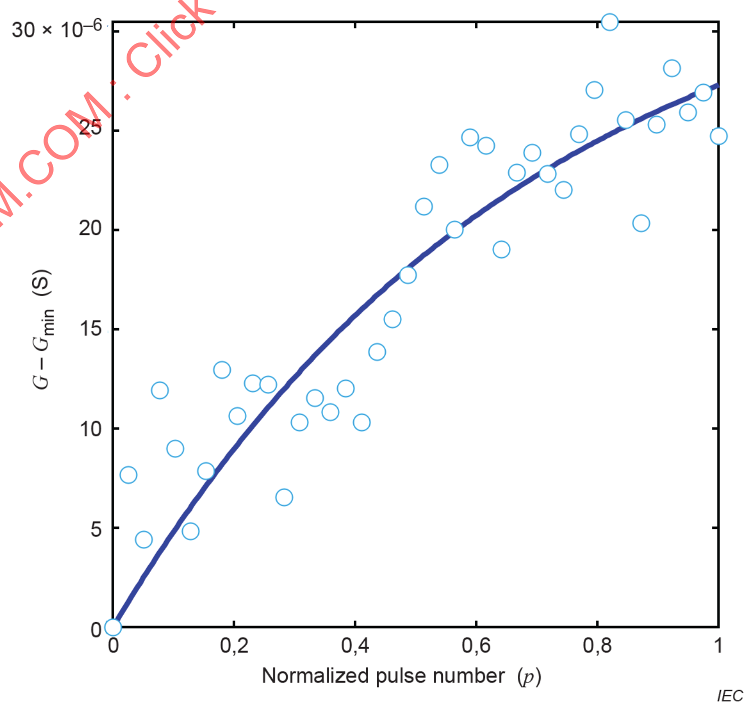
A.1.3 Data analysis

The ΔG and p were plotted and the results were fitted using following fitting function based on Formula (1):

$$f(x) = B \times (1 - \exp(-A \times x))/(1 - \exp(-A)),$$

where A is a fitting parameter, B is ΔG_{max} and also a fitting parameter, and x is an independent variable (namely p). The fitting results are shown in Figure A.7 and Figure A.9. The obtained values of the parameters are summarized in Table A.3.

ΔG was normalized in the range of the computed Parameter B. Curve fitting of the normalized ΔG was performed (Figure A.8 and Figure A.10) and the results are listed in Table A.3. Among the obtained values, the least-squares error (or chi-square value) is expressed as Parameter C showing the degree of resistance fluctuation and can be also used as a quantitative index comparable to other results to estimate the fitting error.



The result of the parameter fitting is shown in the solid line.