IEC TS 62607-6-5

Edition 1.0 2022-12

TECHNICAL SPECIFICATION

colour inside

**Nanomanufacturing – Key control characteristics –
Part 6-5: Graphene-based materials – Contact resistance and sheet resistance: transmission line measurement**

IEC TS 62607-6-5:2022-12(en)

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Nanomanufacturing – Key control characteristics – Part 6-5: Graphene-based materials – Contact resistance and sheet resistance: transmission line measurement

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 07.120 ISBN 978-2-8322-6224-5

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NANOMANUFACTURING – KEY CONTROL CHARACTERISTICS –

Part 6-5: Graphene-based materials – Contact resistance and sheet resistance: transmission line measurement

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

Draft	Report on voting
113/677/DTS	113/709/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.

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.

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

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

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

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INTRODUCTION

Technical Specifications for contact resistance and sheet resistance of two-dimensional materials provide a proper definition of contact resistance and sheet resistance measurement and an electrical characterization of two-dimensional materials. This document includes recommended conditions for a sample preparation and recommended method to measure contact resistance and sheet resistance of two-dimensional materials under test in the referenced background research results. Here, the transmission line measurement (TLM) is used which had been used to measure both contact resistance and sheet resistance for conventional bulk semiconductor devices including silicon devices. TLM devices are formed with various spacings between contacts from which contact resistance and sheet resistance are determined from voltage measured. Thickness of the atomic thin 2D materials cannot be defined clearly when the layers are ultrathin near monolayer, and therefore it is difficult to express the thickness-dependent electronic resistivities of the devices fabricated by using 2D materials. TLM is used conveniently to determine contact resistance and sheet resistance of 2D materials since it does not require thickness of tested materials to be included in the calculation procedure.

The objectives of this document are to

a) define the contact resistance and sheet resistance of two-dimensional materials;
b) specify the methodology for contact resistance and sheet resistance measurements of two-dimensional materials using transmission line measurement (TLM);
c) provide a contact formation method for two-dimensional materials with ohmic contact property which is an essential prerequisite;
d) establish units for the quantitative characteristics of contact resistance and sheet resistance for two-dimensional materials;
e) provide relevant case studies;
f) provide relevant references.

This document is meant to be a general document that can be applied to two-dimensional materials and their applications. It is the intent of this document to be compatible with and work in conjunction with the performance standards defined in the IEC TS 62607 series.

NANOMANUFACTURING – KEY CONTROL CHARACTERISTICS –

Part 6-5: Graphene-based materials – Contact resistance and sheet resistance: transmission line measurement

1 Scope

This part of IEC TS 62607 establishes a standardized method to determine the key control characteristics

- contact resistance, and
- sheet resistance

for graphene-based materials and other two-dimensional materials by a

- transmission line measurement.

The method uses test structures applied to the 2D material by photolithographic methods consisting of several metal electrodes with increasing spacing between the electrodes. By a measurement of the voltage drop between different pairs of electrodes, sheet resistance and contact resistance can be calculated.

- The method can be applied to any other two-dimensional materials which are subject to electrical metal contact on top of the materials.
- The method provides accurate and reproducible results, if the electrical contact formed between the two-dimensional material and the metal electrodes provides ohmic contact property.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for 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 General terms

3.1.1
detail specification
DS
specification based on a blank detail specification with assigned values and attributes

Note 1 to entry: The properties listed in the detail specification are usually a subset of the key control characteristics listed in the relevant blank detail specification. The industrial partners define only those properties which are required for the intended application.

Note 2 to entry: Detail specifications are defined by the industrial partners. Standards development organizations will be involved only if there is a general need for a detail specification in an industrial sector.

Note 3 to entry: The industrial partners can define additional key control characteristics if they are not listed in the blank detail specification.

3.1.2
graphene
graphene layer
single-layer graphene
monolayer graphene
single layer of carbon atoms with each atom bound to three neighbours in a honeycomb structure

Note 1 to entry: It is an important building block of many carbon nano-objects.

Note 2 to entry: As graphene is a single layer, it is also sometimes called monolayer graphene or single-layer graphene and abbreviated as 1LG to distinguish it from bilayer graphene (2LG) and few-layer graphene (FLG).

Note 3 to entry: Graphene has edges and can have defects and grain boundaries where the bonding is disrupted.

[SOURCE: ISO/TS 80004-13:2017, 3.1.2.1]

3.1.3
bilayer graphene
2LG
two-dimensional material consisting of two well-defined stacked graphene layers

Note 1 to entry: If the stacking registry is known, it can be specified separately, for example, as "Bernal stacked bilayer graphene".

[SOURCE: ISO/TS 80004-13:2017, 3.1.2.6]

3.1.4
few-layer graphene
FLG
two-dimensional material consisting of three to ten well-defined stacked graphene layers

[SOURCE: ISO/TS 80004-13:2017, 3.1.2.10]

3.1.5
two-dimensional material
2D material
material, consisting of one or several layers with the atoms in each layer strongly bonded to neighbouring atoms in the same layer, which has one dimension, its thickness, in the nanoscale or smaller and the other two dimensions generally at larger scales.

Note 1 to entry: The number of layers when a two-dimensional material becomes a bulk material varies depending on both the material being measured and its properties. In the case of graphene layers, it is a two-dimensional material up to 10 layers thick for electrical measurements, beyond which the electrical properties of the material are not distinct from those for the bulk (also known as graphite).

Note 2 to entry: Interlayer bonding is distinct from and weaker than intralayer bonding.

Note 3 to entry: Each layer can contain more than one element.

Note 4 to entry: A two-dimensional material can be a nanoplate.

[SOURCE: ISO/TS 80004-13:2017, 3.1.1.1]

3.2 Key control characteristics

3.2.1
key control characteristic
KCC
material property or intermediate product characteristic which can affect safety or compliance with regulations, fit, function, performance, quality, reliability or subsequent processing of the final product

Note 1 to entry: The measurement of a key control characteristic is described in a standardized measurement procedure with known accuracy and precision.

Note 2 to entry: It is possible to define more than one measurement method for a key control characteristic if the correlation of the results is well-defined and known.

3.2.2
sheet resistance
measure of the resistance of a thin film that is nominally uniform in thickness

Note 1 to entry: Sheet resistance can be measured together with contact resistance by TLM for 2D materials, as shown in Figure 2.

Note 2 to entry: Sheet resistance is one of a material's properties. The SI unit of measure of sheet resistance is the ohm per square (Ω/sq.).

3.2.3
contact resistance
measure of the contribution of the contacting interfaces to the total resistance of thin films that are nominally uniform in thickness

Note 1 to entry: Contact resistance can be measured together with sheet resistance by TLM for 2D materials, as shown in Figure 2.

Note 2 to entry: Contact resistance is a property that exists between a metal and a semiconducting (or conducting) material. Contacts need to supply necessary electrical current.

[SOURCE: Schroder [1], Pages 127, 131]

3.3 Terms related to the measurement method

3.3.1
transfer length
L_T
measuring distance over which most of the current flows from a semiconductor (or conducting material) into a metal or from a metal into a semiconductor (or conducting material)

[SOURCE: Schroder [1], Page 140]

3.3.2
transmission line measurement
TLM
measuring method to determine sheet resistance of a layer and contact resistance between a layer and an applied electrode by the formation of a set of electrodes and a measurement of the voltage drop between the electrodes

Note 1 to entry: In some cases, TLM is used as abbreviation for transfer length measurement, but this represents the same technique as the transmission line measurement.

[SOURCE: Schroder [1], Pages 139-141]

4 General

4.1 Measurement principle

TLM involves making a series of contacts separated by various distances. See Figure 1 for TLM pattern structure. Probes are applied to pairs of contacts, and the resistance between them is measured by applying a voltage across the contacts and measuring the resulting current. The current flows from the first probe, into the metal contact, across the metal–semiconductor junction, through the sheet of semiconductor, across the metal–semiconductor junction again into the second contact, and from there into the second probe and into the external circuit to be measured by an ammeter. The resistance measured is a linear combination (sum) of the contact resistance of the first contact, the contact resistance of the second contact, and the sheet resistance of the semiconductor between the contacts.

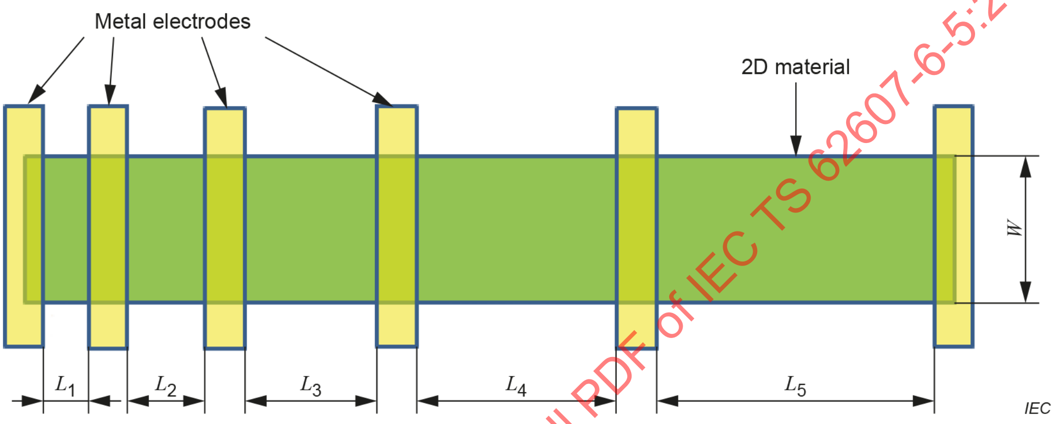

Figure 1 – TLM pattern structure

If several such measurements are made between pairs of contacts that are placed at different distances, a plot of resistance against contact separation can be obtained. If the contact separation is expressed in terms of the ratio L/W – where L and W are the length and width of the area between the contacts – such a plot should be linear, with the slope of the line being the sheet resistance. See Figure 2 for determination of contact resistance (R_C) and sheet resistance (R_{sh}).

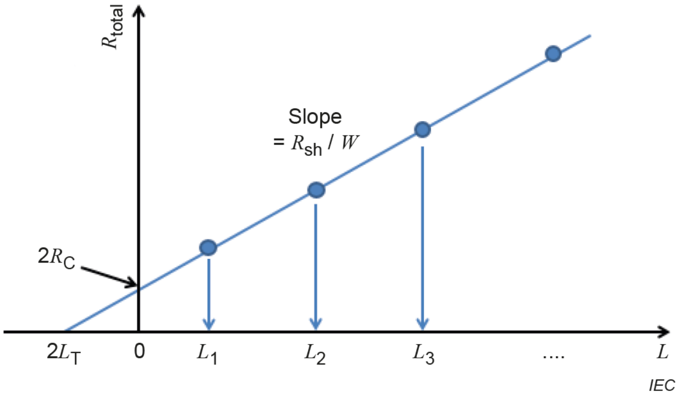

Figure 2 – Determination of contact resistance and sheet resistance

NOTE 1 Transfer length (L_T) is defined as the distance over which voltage drops to "1/e" compared to the voltage at the edge of the metal contact. That is, electron flow between metal and channel preferentially occurs at the edge of the metal contact and is reduced exponentially inside the metal in a way to minimize total resistance (R_{total}). [2], [3][1] Particularly, L_T can be very small for 2D-material-based devices due to its ultra-thinness. L_T is approximately characterized by

$$L_T = \sqrt{\frac{R_C L W}{R_{ch}}} \quad (1)$$

where R_C is the contact resistance and R_{ch} is the channel resistance.

NOTE 2 Channel lengths, L_1, L_2, ..., can be determined by availability of device dimension and capability of lithography technology.

NOTE 3 The edge roughness and inhomogeneity of the 2D material can give rise to error of the data.

4.2 Recommended sample preparation method

The TLM pattern shall be designed and implemented by lithography for device fabrication. For example, a graphene channel width (W) of 30 µm and a channel length (L) in the range from 10 µm to 50 µm, in increments of 10 µm, can be fabricated. For comparison, other patterns with L = 5 µm, 10 µm, 15 µm, 20 µm and 25 µm can be fabricated at the same time. These dimensions need to be determined by trial and error to ensure reliability of data, depending on the parasitic resistances of a tested device and the thickness uniformity of the 2D material sample. For example, if L is too small, the error range is large. In contrast, if L is too large, the non-uniformity of the sample can cause deviations from linearity.

For the fabrication of 2D material TLM pattern, 2D materials formed by mechanical exfoliation or chemical vapour deposition (CVD) are used. To fabricate TLM patterns, the use of degenerately doped Si wafer covered with thermally grown SiO_2 layer which serves as the global back gate electrode, the gate insulator, and the substrate is recommended. The wafer is ultrasonically cleaned in acetone and rinsed in isopropyl alcohol to remove chemical residues before using. The TLM pattern was defined by the general photolithography process as in the field effect transistor (FET) device fabrication. However, in the case where 2D material samples are too small for patterning by the general photolithography, electron-beam lithography (EBL) is commonly conducted using spin-coating of an electron-beam resist layer onto the 2D material sample. The TLM patterns are formed as rectangular shape by lithography to define the electronic transport channels in the pattern. This is often referred to as the channel definition patterning process. Figure 3 a) and Figure 3 b) show optical microscopy images of a graphene and a MoS_2 TLM pattern, respectively. The metal electrodes are deposited via electron beam evaporation to form TLM structures.

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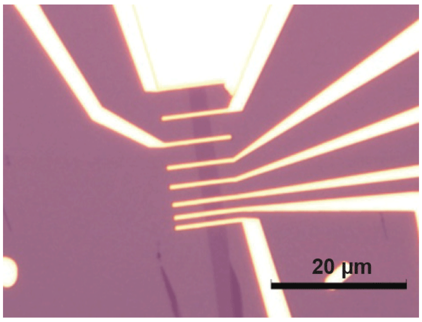
[1] Numbers in square brackets refer to the Bibliography.

It is recommended to check if the 2D material has been degraded before measurements. One possible way of checking the degradation of 2D material of the TLM pattern is to find out the significantly deviating measured points in Figure 2 where the slope line consists of measured points resulting a linear behaviour. When there is a significantly deviating measured point from the linear slope line, this indicates that in some parts the 2D material underneath the metal electrode has been degraded.



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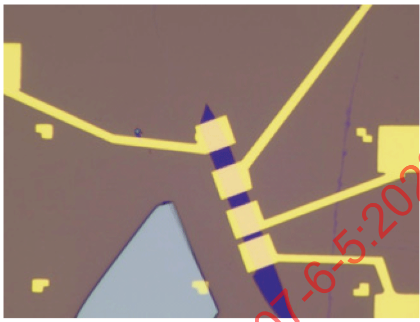
a) TLM patterns on graphene

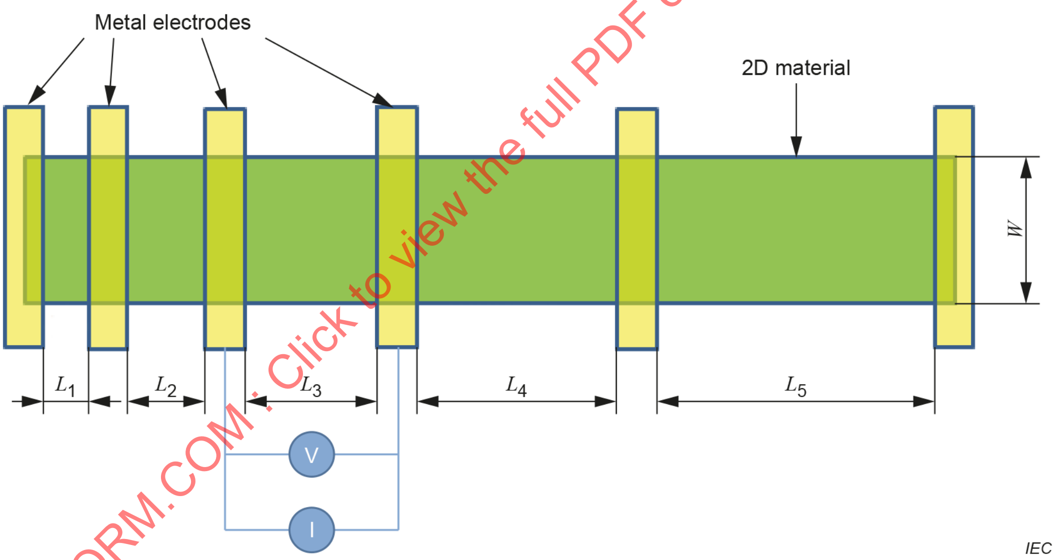


IEC

b) TLM patterns on MoS_2

Figure 3 – Optical microscopy pictures of rectangular TLM channels and differently spaced TLM electrodes defined by electron beam lithography

4.3 Recommended measurement equipment and apparatus



Key

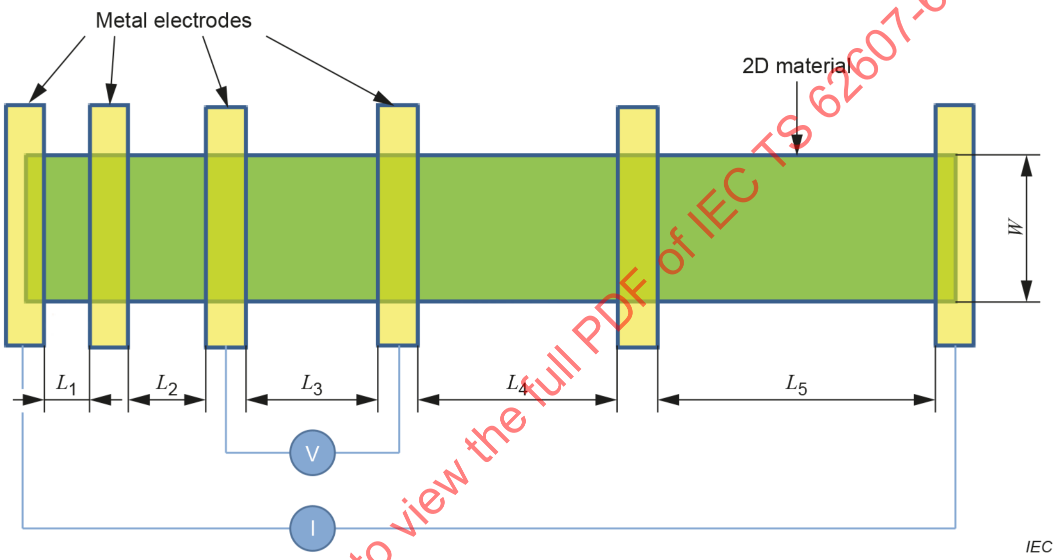
V voltmeter

I ammeter

Figure 4 – TLM structure and its equivalent circuit of two-point probe (2PP) TLM for contact resistance and sheet resistance

Figure 4 shows TLM pattern and its equivalent circuit of two-point probe (2PP) measurement for contact resistance and sheet resistance. The electrical measurements setup typically includes a probe station combined with a temperature controller, as shown in Figure 4. The device under test shall be placed and probed inside the chamber. Since 2D materials are air and moisture sensitive, it is recommended to measure KCC in a vacuum chamber. For more general measurement of contact resistance and sheet resistance, a temperature-dependent test can be performed. In this case, the temperature inside the probe station is controlled by a heater for heating and liquid N_2 source for cooling. This setup shall be connected with the two-point probe system. Before electrical measurements, the equipment, device under test, device handling equipment such as tweezer and human being should be properly grounded to avoid burning of sample due to electrostatic charges. Note that metal leads resistance also contributes to total resistance in addition to the contact resistance, but it is usually much smaller than contact resistance since conducting lead metals are thicker than 2D materials and interface resistance at the contact is much larger. In the case where leads resistance is large, it needs to be separated from contact resistance.

It is worthy to note here that the TLM result of contact resistance and sheet resistance measured using four-point probe setup (see Figure 5) is the same as that of the two-point probe setup. This is demonstrated by the simulation results comparing the two-point probe measurement result and the four-point probe (4PP) measurement result shown in Annex A (simulation of various TLM setups). However, in the case of four-point probe measurement, nonuniform current conduction can take place due to inner electrodes present between two outermost TLM electrodes. That is, current flowing through the TLM channel can be diverted under the inner electrodes which are used for measuring voltage drop, and this can cause measurement error.

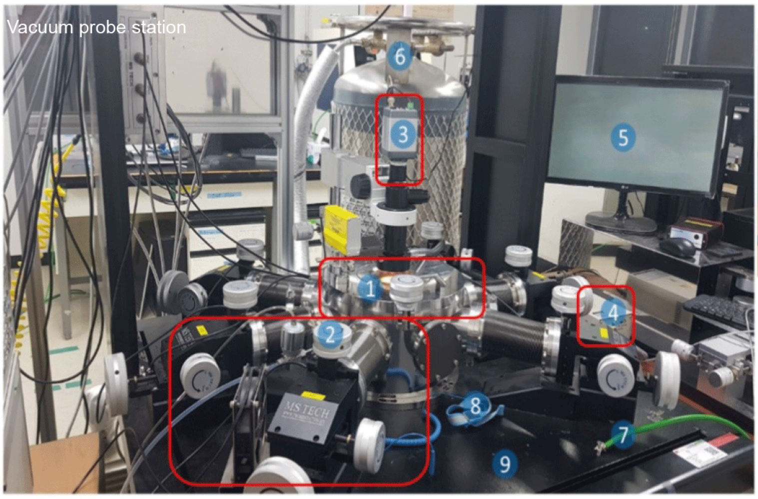


Key

V voltmeter

I ammeter

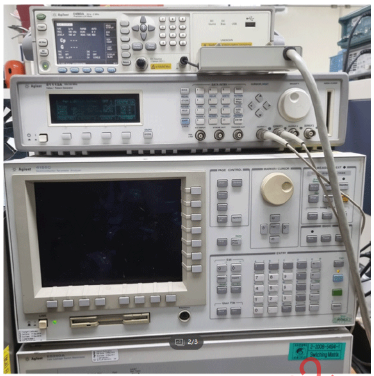
Figure 5 – Schematic view of four-point probe (4PP) TLM pattern for measuring contact resistance and sheet resistance



Key

1 vacuum chamber
2 probe position manipulator
3 CCD camera
4 light bank of CCD
5 computer
6 liquid N_2 cylinder
7 machine grounding
8 human grounding bracelet
9 anti-vibration table

a) Vacuum probe station



b) Semiconductor analyser

c) Temperature controller

Figure 6 – Experimental setup for contact resistance and sheet resistance measurements

All the electrical measurements are conducted using a semiconductor parameter analyser and a probe station, as shown in Figure 6. It is recommended to maintain gate leakage current measured from tested devices at less than 10^{-10} A.

5 Measurement of sheet resistance and contact resistance

5.1 Recommended measurement procedure

In order to apply the TLM method, L should be much larger than the carrier mean free path. As shown in Figure 2, the contact resistance is extracted from the y-intercept point, and the sheet resistance is derived from the slope of the curve.

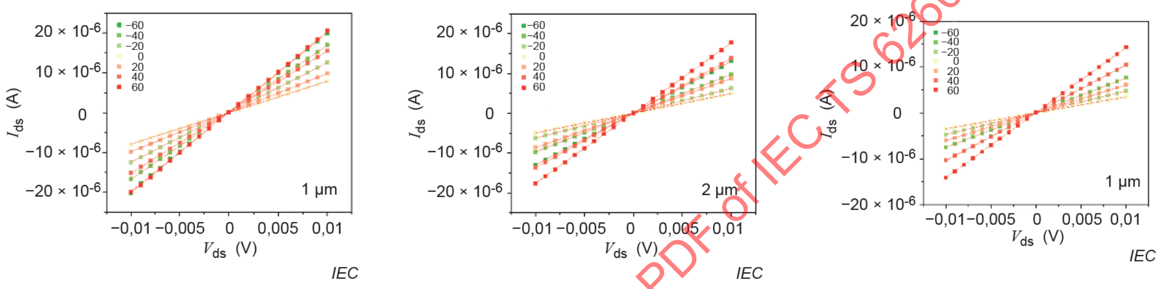
$$R_{\text{total}} = R_{\text{sh}} \frac{L}{W} + 2R_{\text{C}} \quad (2)$$

Designed TLM patterns are formed on a 2D material sample as shown in Figure 1, by conducting electrode metal deposition, etching, and lithography processes. Two-probe electrical measurements are performed between any two metal electrodes as shown in Figure 4. If several such measurements are made between pairs of contacts that are separated by different distances, a plot of resistance against contact separation can be obtained. When the total resistance is expressed as a function of separation between two electrodes, a linear line is expected to result from connecting the data points, with the slope of the line being the sheet resistance time with width of the channel. See Figure 2 for determination of contact resistance and sheet resistance.

During contact resistance measurements, very low probe voltages – for example 1 V between two probes – are recommended, because the extracted contact resistance value is highly sensitive to applied voltage conditions. If too high a voltage is applied between two probes, Joule heating and impact excitation in 2D materials can be induced and faulty resistance values are extracted. Therefore, low probe voltages usually below several volts shall be applied for accurate measurements. In addition, if substrate voltage (gate voltage equivalently in transistors which is used for modulating carrier concentration) is applied, carrier density in the channel changes due to doping effect and resistance is changed correspondingly. That is, substrate voltage shall be applied if doping-concentration-dependent resistance values need to be measured.

5.2 Suggested I-V measurement to ensure ohmic contact

Since the TLM method proposed here is applied mainly to ohmic contact devices, linear output curves drawn for total current as a function of voltage applied across the spacing between TLM electrodes need to be obtained to ensure the ohmic contact property of the tested devices as shown in Figure 7.

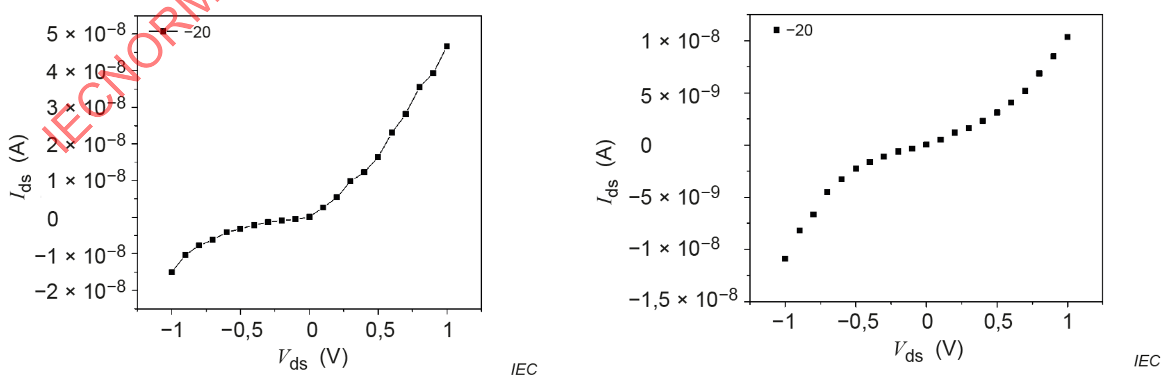


a) TLM electrodes spacing of 1 µm **b) TLM electrodes spacing of 2 µm** **c) TLM electrodes spacing of 3 µm**

The different colours in the panels show various back gate biases (V_{gs}) applied across 285-nm-thick SiO_2. The numbers in the legends indicate the different gate bias voltages applied to the FETs in volts (V).

Figure 7 – Output curves drawn for total current (I_{ds}) as a function of voltage applied (V_{ds}) for different spacings between electrodes from a bilayer graphene TLM pattern

On the other hand, the linear output characteristics are not obtained for Schottky contact devices as the contact resistance at the metal–semiconductor interface changes as a function of voltage applied, as shown in Figure 8.



a) Spacing between TLM electrodes of 2,5 µm **b) Spacing between TLM electrodes of 4,0 µm**

A back gate bias of −20 V is applied across 285-nm-thick SiO_2. The legend shown as −20 indicates −20 V of gate bias voltage.

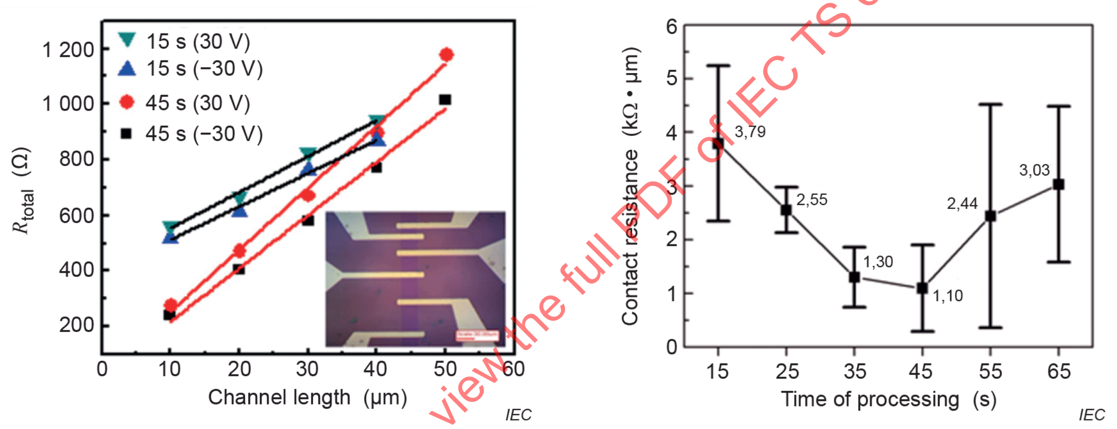
Figure 8 – Output curves drawn for total current (I_{ds}) as a function of voltage applied (V_{ds}) for different spacings between TLM electrodes from a MoS_2 TLM pattern

5.3 Constraint in using TLM for Schottky contact devices

Although the TLM method in this document is intended to be used for ohmic contact devices, it can still be used for Schottky contact devices, if constant-current TLM (technique to apply constant current between two probes) is employed. Constant-current TLM is free of errors caused by the non-linearity of I-V curves since voltage drop at the contact is consistent regardless of channel lengths. Therefore, constant-current TLM can be used for both ohmic and Schottky contacts of TLM pattern electrodes. However, constant-voltage TLM (technique to apply constant voltage between two probes) gives rise to erroneous results from non-linear I-V curves. In the case of ohmic contact such as graphene FETs, constant-voltage TLM is commonly used in which constant current is obtained from the voltage drop between the two metal electrodes divided by sheet resistance. However, in the case of Schottky contact such as MoS_2 devices, introduction of only constant current gives rise to correct results, for which a constant-current source is required.

6 Results to be reported (case studies)

6.1 Measured results of the contact resistance and sheet resistance of graphene

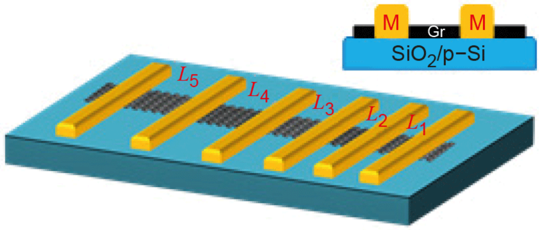


a) total resistance measured **b) contact resistance measured**

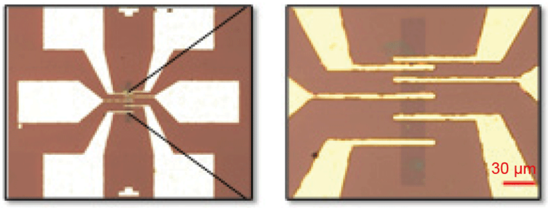
SOURCE: Reproduced from D.W. Yue et al. (2014) [2], with the permission of the Royal Society of Chemistry.

Figure 9 – Resistances of graphene measured by TLM

To obtain TLM results for graphene, two-probe electrical measurements are performed. The obtained current is plotted as a function of channel length. Total resistance (R_{total}) increases as L increases, as shown in Figure 9 a). Contact resistance (R_C) is extracted directly from the y-intercept of the R_{total} plotted against L curve, in accordance with Formula (2). A recommended contact formation process is as follows: after TLM patterning photolithography process, an additional plasma pre-treatment is conducted for forming a cleaner edge contact to graphene or 2D materials. And the metal electrodes of TLM pattern are formed after plasma pre-treatment. Change in contact resistance as a function of plasma treatment time are shown in Figure 9 b): a large reduction in contact resistance value as the plasma treatment time increases as much as 45 s. At a plasma treatment time of 55 s or longer, the contact resistance value increases because of reduced contact area due to over-etching during the plasma treatment. The cross-sectional schematic view of edge-contacted graphene and the optical microscopy images of TLM patterns are shown in Figure 10 a) and b). Table 1 shows the data of contact resistance and sheet resistance with different pre-treatment processing times.



a) schematic views of the graphene TLM pattern



b) optical microscopy images of the TLM pattern

Key

M metal electrode

Gr graphene

The channel lengths from L_1 to L_5 are 10 µm, 20 µm, 30 µm, 40 µm and 50 µm, respectively. The channel width is 5 µm. As the metal electrode, Cr–Pd–Au (each layer thickness of 1 nm–15 nm–50 nm) was deposited.

SOURCE: Reproduced from D.W. Yue et al. (2014) [2], with the permission of the Royal Society of Chemistry.

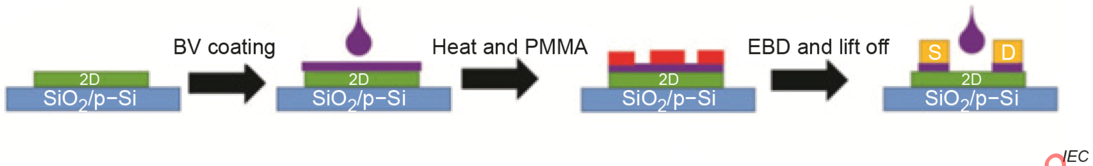
Figure 10 – Schematic views of the graphene TLM pattern where $L_5 > L_4 > L_3 > L_2 > L_1$ and optical microscopy images of the TLM pattern

Table 1 – Contact resistance and sheet resistance of graphene, obtained from different plasma etching conditions

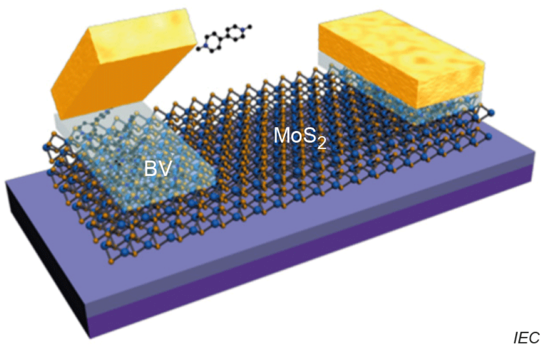
Plasma processing time (s)	Contact resistance (Ω·µm)	Sheet resistance (kΩ/sq.)
15	3,79	7,58
25	2,55	4,59
35	1,3	2,21
45	1,1	2,31
55	2,44	5,61
65	3,03	6,96
SOURCE: Reproduced from D.W. Yue et al. (2014) [2], with the permission of the Royal Society of Chemistry.		

6.2 Measured results of the contact resistance of MoS_2

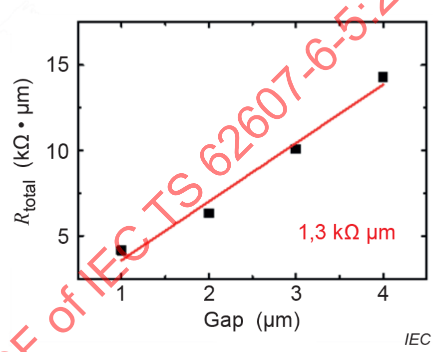
For a 2D material of MoS_2, see Figure 11 on fabricating TLM patterns and the measured total resistance from the TLM patterns.



a) MoS_2 FET fabrication process using benzyl viologen polymeric interlayer



b) schematic view of the MoS_2 FET



c) TLM result which was used to obtain the contact resistance of 1,3 kΩ·µm

Key

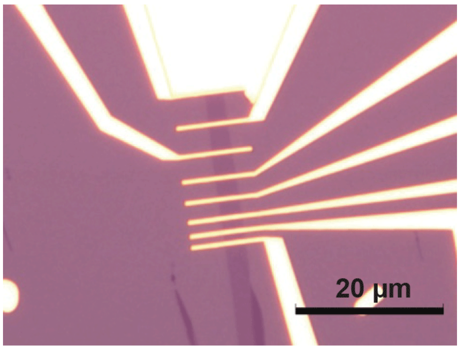
2D	two-dimensional material	S	source
PMMA	poly-methyl-methacrylate	D	drain
EBD	electron-beam deposition	p-Si	p-type Si

SOURCE: Reproduced from D. Yue et al. (2018) [3], with the permission of Wiley-VCH.

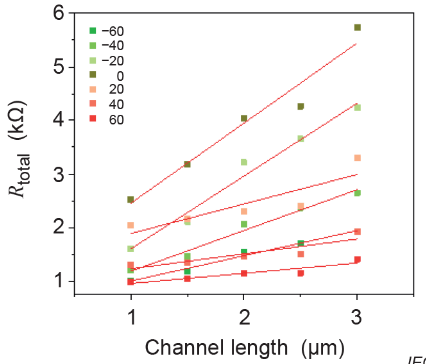
Figure 11 – Contact resistance of MoS_2 device fabricated by forming benzyl viologen (BV) polymeric interlayer

6.3 TLM patterns for the bilayer graphene and the results obtained by the four-point probe method

With the bilayer graphene, TLM patterns with the transistor structure of a global bottom gate were fabricated to measure the total resistance at different gate bias voltages from −60 V to 60 V, as shown in Figure 12 a) and b). The detailed application cases of TLM patterns to the two-point probe measurement setup and the four-point probe measurement setup are shown in Annex A.



a) bilayer graphene TLM pattern with the transistor structure of a global bottom gate



b) total resistance (R_{total}) measured by the four-point probe method at different gate bias voltages from −60 V to 60 V, obtained from TLM pattern in a)

285-nm-thick SiO_2 layer was used, where L = 1 µm, 1,5 µm, 2 µm, 2,5 µm, 3 µm, W = 3 µm. All transistors are measured at room temperature. Metal electrodes are Cr–Au (each layer thickness of 5 nm to 50 nm).

The results are obtained from the experimental measurements at Sungkyunkwan University, Nano Devices Processing Laboratory.

Figure 12 – TLM patterns for the bilayer graphene and the results obtained by the four-point probe method

Annex A
(informative)

Measurement results and the simulation results from various setups

Values of contact resistance and sheet resistance are obtained differently dependent on the various measurement setups of TLM and conventional four-point probe methods. The device shown in Figure 12 a) was used to demonstrate different results obtained from the various measurement setups. In addition, values of contact resistance and sheet resistance were obtained by the simulation of the various measurement setups. In this context, the following are added in this Annex A: Table A.1 on experimentally measured contact resistance results by using TLM and four-point probe methods, Table A.2 on experimentally measured contact resistance results by using TLM and four-point probe methods, Figure A.1 on schematic comparison of TLM two-point probe and four-point probe setups, and Table A.3 on simulation results of contact resistance and sheet resistance obtained from TLM two-point probe and four-point probe methods.

The results in Annex A tables are obtained from the experimental measurements at Sungkyunkwan University, Nano Devices Processing Laboratory.

Table A.1 – Contact resistance measurement by TLM and conventional four-point probe methods based upon the case study of Figure 12

		TLM two-point probe	**TLM two-point probe**	**TLM four-point probe**	**Conventional four-point probe**	**Conventional four-point probe**	**Conventional four-point probe**
Measurement methods and variables	I-V curves	Output curve	Transfer curve	Transfer curve			
	Channel length				1,5 µm	2,0 µm	2,5 µm
	Applied voltage	V_{ds} = 10 mV	V_{ds} = 10 mV				
	Applied current			I_{ds} = 20 µA	I_{ds} = 20 µA	I_{ds} = 20 µA	I_{ds} = 20 µA
	Measured value	I_{ds}	I_{ds}	ΔV	ΔV	ΔV	ΔV
Measured data at various back gate bias V_{bg} or (V_{bg} − V_{th})	−40 V	208 Ω·µm	268 Ω·µm	289 Ω·µm	169 Ω·µm	134 Ω·µm	180 Ω·µm
	−30 V		265 Ω·µm	295 Ω·µm	180 Ω·µm	122 Ω·µm	181 Ω·µm
	−20 V	118 Ω·µm	282 Ω·µm	377 Ω·µm	199 Ω·µm	119 Ω·µm	210 Ω·µm
	20 V	667 Ω·µm	323 Ω·µm	351 Ω·µm	167 Ω·µm	302 Ω·µm	128 Ω·µm
	30 V		323 Ω·µm	357 Ω·µm	178 Ω·µm	260 Ω·µm	153 Ω·µm
	40 V	474 Ω·µm	325 Ω·µm	364 Ω·µm	183 Ω·µm	236 Ω·µm	167 Ω·µm