IEC TS 62876-3-4

Edition 1.0 2025-12

TECHNICAL SPECIFICATION

**Nanomanufacturing - Reliability assessment -
Part 3-4: Linearity of output characteristics for metal contacted 2D semiconductor devices**

ICS 07.120

ISBN 978-2-8327-0928-3

IEC TS 62876-3-4:2025-12(en)

THIS PUBLICATION IS COPYRIGHT PROTECTED
Copyright © 2025 IEC, Geneva, Switzerland

All rights reserved. Unless otherwise specified, no part of this publication may be reproduced or utilized in any form or by any means, electronic or mechanical, including photocopying and microfilm, without permission in writing from either IEC or IEC's member National Committee in the country of the requester. If you have any questions about IEC copyright or have an enquiry about obtaining additional rights to this publication, please contact the address below or your local IEC member National Committee for further information.

IEC Secretariat
3, rue de Varembé
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
info@iec.ch
www.iec.ch

About the IEC
The International Electrotechnical Commission (IEC) is the leading global organization that prepares and publishes International Standards for all electrical, electronic and related technologies.

About IEC publications
The technical content of IEC publications is kept under constant review by the IEC. Please make sure that you have the latest edition, a corrigendum or an amendment might have been published.

IEC publications search - webstore.iec.ch/advsearchform
The advanced search enables to find IEC publications by a variety of criteria (reference number, text, technical committee, …). It also gives information on projects, replaced and withdrawn publications.

IEC Just Published - webstore.iec.ch/justpublished
Stay up to date on all new IEC publications. Just Published details all new publications released. Available online and once a month by email.

IEC Customer Service Centre - webstore.iec.ch/csc
If you wish to give us your feedback on this publication or need further assistance, please contact the Customer Service Centre: sales@iec.ch.

IEC Products & Services Portal - products.iec.ch
Discover our powerful search engine and read freely all the publications previews, graphical symbols and the glossary. With a subscription you will always have access to up to date content tailored to your needs.

Electropedia - www.electropedia.org
The world's leading online dictionary on electrotechnology, containing more than 22 500 terminological entries in English and French, with equivalent terms in 25 additional languages. Also known as the International Electrotechnical Vocabulary (IEV) online.

Warning! Make sure that you obtained this publication from an authorized distributor.

CONTENTS

FOREWORD 3
INTRODUCTION 5
1 Scope 7
2 Normative references 7
3 Terms and definitions 7
3.1 General terms regarding the sample 7
3.2 General terms regarding the sample test 8
4 Recommended sample preparation 9
4.1 Device structure of the sample under test 9
4.2 Sample preparation method 9
4.2.1 Sample preparation 9
4.2.2 Fabrication of FETs 9
4.2.3 Consideration on sample design 10
5 Measurement procedure 11
5.1 Measurement equipment 11
5.2 Calibration of measurement equipment 11
5.3 Measurement procedure 11
6 Data analysis / interpretation of results 12
Annex A (informative) Worked example – Linearity of I-V curves for bottom-contacted WSe_2 FETs 17
A.1 Background 17
A.2 Results to be reported 18
Annex B (informative) Worked example – Linearity of I-V curves for edge-contacted MoS_2 FETs 20
B.1 Background 20
B.2 Results to be reported 21
Annex C (informative) Worked example – Linearity of I-V curves for WS_2 FETs with current saturation 23
C.1 Background 23
C.2 Results to be reported 23
Bibliography 24

Figure 1 – Metal–semiconductor (SC) junctions and their respective band diagrams 6
Figure 2 – Schematic of a FET 8
Figure 3 – Schematic output curves obtained from ohmic and non-ohmic contact 12
Figure 4 – Schematic I-V conductance of output curves obtained from Ohmic contact without and with current saturation 13
Figure 5 – Schematic I-V conductance of output curves obtained from non-ohmic contact without and with current saturation 14
Figure 6 – Schematic I-V output curves and linearities obtained from ohmic contact 15
Figure 7 – Schematic I-V output curves and linearities obtained from non-ohmic contact 16
Figure A.1 – Device fabrication processing steps to induce ohmic-like transport by conducing O_2 plasma treatment [3] 17

Figure A.2 – (a), (b) Output curves and (c), (d) corresponding linearities collected from pristine and plasma-treated WSe_2 FET at various V_G 18

Figure A.3 – Time dependent output curves and corresponding linearities collected from pristine and plasma-treated WSe_2 FETs for various gate voltages applied 19

Figure B.1 – Cross-sectional view of edge-contact interface formed between MoS_2 and metal that was used to induce ohmic-like contact 20

Figure B.2 – (a, b) Output curves and (c, d) corresponding linearities collected from Pd and Sb edge-contacted MoS_2 FETs with various gate voltages applied 21

Figure B.3 – (a-c) Time dependent output curves and (d) corresponding linearities collected from pristine and aged Sb edge-contacted MoS_2 FETs for various V_g 22

Figure C.1 – (a, d) Output curve, (b, e) the first derivative curve (dI_D/dV_D) and (c, f) linearity for devices with channel thicknesses of 2,1 nm and 7 nm, respectively 23

Table 1 – Allowed channel lengths to apply this document when contact resistance is limited up to 20 % and 50 % 11

INTERNATIONAL ELECTROTECHNICAL COMMISSION

_____

Nanomanufacturing - Reliability assessment - Part 3-4: Linearity of output characteristics for metal contacted 2D semiconductor devices

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as “IEC Publication(s)”). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
6) All users should ensure that they have the latest edition of this publication.
7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
9) IEC draws attention to the possibility that the implementation of this document may involve the use of (a) patent(s). IEC takes no position concerning the evidence, validity or applicability of any claimed patent rights in respect thereof. As of the date of publication of this document, IEC had not received notice of (a) patent(s), which may be required to implement this document. However, implementers are cautioned that this may not represent the latest information, which may be obtained from the patent database available at https://patents.iec.ch. IEC shall not be held responsible for identifying any or all such patent rights.

IEC TS 62876-3-4 has been prepared by IEC technical committee 113: Nanotechnology for electrotechnical products and systems. It is a Technical Specification.

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

Draft	Report on voting
113/920/DTS	113/938/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 62876 series, published under the general title *Nanomanufacturing - Reliability assessment*, 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, or

– revised.

INTRODUCTION

– Atomically thin two dimensional (2D) nano-materials are expected to be used for future electrical sub-systems or electronic device applications.

– I-V measurements are the fundamental electrical characterization technique for assessing reliability of field-effect transistors (FETs) as well as semiconductor device performance.

– The performance of the FET is mainly characterized by measuring the output (drain current as a function of drain voltage at different gate voltages) and transfer (drain current as a function of gate voltage at different drain voltages) characteristics.

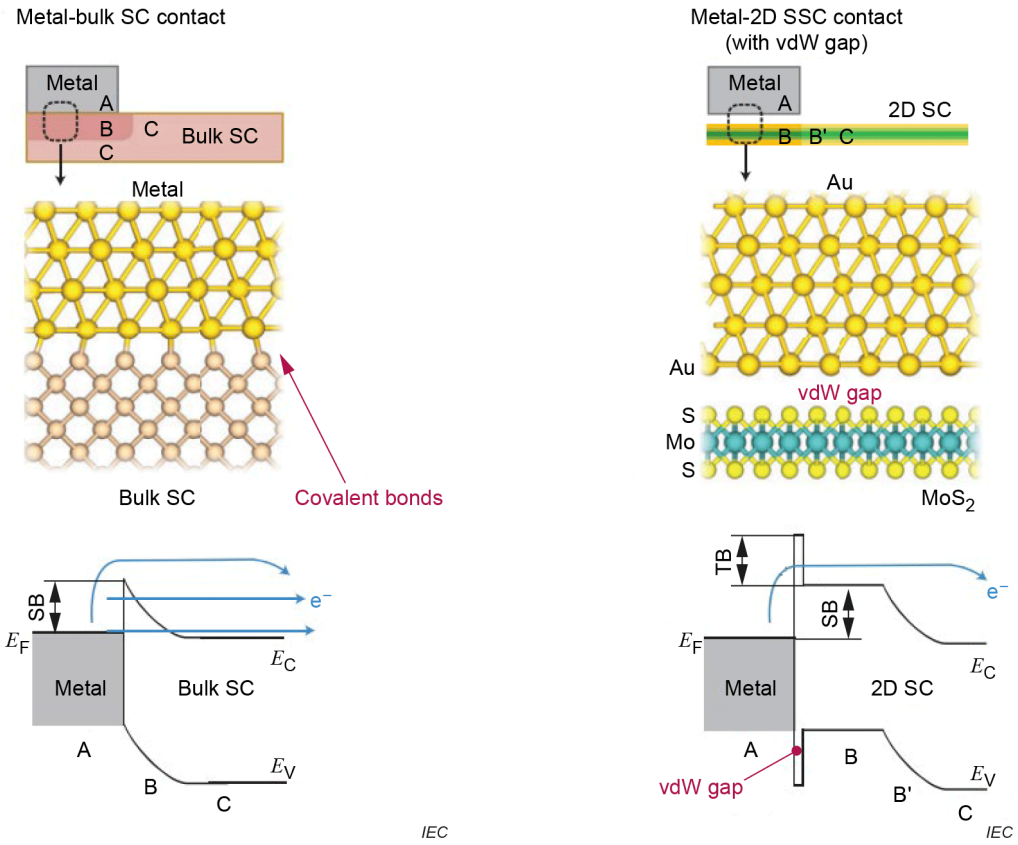
– If metallic electrical contacts have negligible effects on electronic transport, output characteristics show a linear behaviour according to the following formula: $I_{\mathrm{d}} = \frac{\mu_{\mathrm{n}} W C_{\mathrm{ox}}}{L}\left[\left(V_{\mathrm{g}} - V_{\mathrm{th}}\right)V_{\mathrm{d}}\right]$, where I_d is the drain current, μ_{n} is the electron mobility, W is the transport channel width, C_{ox} is the gate oxide capacitance, V_{g} is the gate voltage, V_{th} is the threshold voltage, and V_{d} is the drain voltage, which can indicate ohmic contact. In contrast, when metallic contact gives rise to high resistance to electronic transport, output characteristics do not show the linear behaviour, following the formula: $I_{\mathrm{D}} = \frac{\mu_{\mathrm{n}} W C_{\mathrm{ox}}}{L}\left[\left(V_{\mathrm{g}} - V_{\mathrm{th}}\right)\left(V_{\mathrm{d}} - I_{\mathrm{d}} \times 2R_{\mathrm{C}}\right)\right]$ [1] where R_{c} is the contact resistance, which is interpreted as Schottky contact which can bring about a reliability issue of ohmic-contact semiconductor transistor operation.

– Current transport at the metallic contact of 2D semiconductor material-based FETs mainly consists of two distinct components: thermal emission where charge injection occurs over the energy barrier and tunnelling (field emission) where the charge injection occurs through the barrier formed at the metal-semiconductor interface.

– Current transport at the metallic contact of 2D material-based FETs can be limited due to the van der Waals (vdW) gap that forms at the metal-2D semiconductor interface, creating a high contact resistance and suppressing current transport of the 2D FETs. However, being different from 2D material-based FETs, conventional FETs have good ohmic contact and usually have not had reliability issues in metallic contacts. But 2D materials involving vdW gap can give rise to uncontrollable Schottky contact leading to a serious reliability issue of metallic contact. See Figure 1.

– In addition, the lack of efficient doping techniques for 2D materials at the metal-semiconductor junction, also contributes to the high contact resistance and suppressed current transport, in contrast to 3D bulk semiconductors such as silicon. See Figure 1 for comparison.

– The issues arising from the vdW gap at the 2D material-metal interface and thus the resulted high contact resistance pose challenges to the reliability of metallic electrical contacts of 2D FETs. Therefore, we propose a standard method to quantify the reliability of the metallic electrical contacts by analyzing current-voltage (I-V) characteristics of 2D FETs.



a) Typical metal/bulk SC interface **b) Au-MoS_2 interface with vdW**

Key

E_F	Fermi level of metal
E_c	conduction band of 2D SC
E_v	valence band of 2D SC
TB	tunnel barrier height
SB	Schottky barrier height
A, B, B' and C	Different regions in the current path from the metal to the SC.

Blue arrows from top to bottom: Thermionic emission, thermionic field emission, and field emission (tunnelling).

Figure 1 – Metal–semiconductor (SC) junctions and their respective band diagrams

– Therefore, it is important to obtain accurate current-voltage (I-V) characteristics and to assess linearity of the I-V output curves, so that reliable 2D FET device operation can be ensured. The reliability of the devices also needs to be evaluated over an extended time period.

NOTE Both capital and small letters in subscripts of device parameters are used with no differences each other, dependent on users (typically device engineers): e.g. I_D is the same as I_d, V_D is the same as V_d, and V_G is the same as V_g.

1 Scope

This part of IEC 62876 establishes a standardized guideline to assess

– reliability of metallic interfaces

of ohmic-contacted field-effect transistors (FETs) using 2D nano-materials by quantifying

– linearity of current-voltage (I-V) output curves

for devices with various materials combinations of van der Waals (vdW) interfaces.

For metallic interfaces with 2D materials (eg. graphene, MoS_2, $MoTe_2$, WS_2, WSe_2, etc) and metals (eg. Ti, Cr, Au, Pd, In, Sb, etc), the reliability of ohmic contact is quantified.

For FETs consisting of 2D materials-based channels (eg. MoS_2, $MoTe_2$, WS_2, WSe_2, etc), the reliability of ohmic contact when varying contacting metal, channel length, channel thickness, applied voltage, and surface treatment condition is quantified.

The reliability of the metallic contacts is quantified from the linearity of I-V characteristics measured over extended time periods.

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.

IEC TS 62607-6-5, *Nanomanufacturing - Key control characteristics - Part 6-5: Graphene-based materials - Contact and sheet resistance: transmission line measurement*

Bibliography

[1] S B Mitta et al, *Electrical characterization of 2D materials-based field-effect transistors*, 2D Materials, 8, 012002 (2021)

[2] A Allain et al, Ele*ctrical contacts to two-dimensional semiconductors*, Nature Materials, 14, 1195-1205 (2015)

[3] K Lee et al. *Effects of Oxygen Plasma Treatment on Fermi-Level Pinning and Tunneling at the Metal–Semiconductor Interface of WSe_2 FETs*, Advanced Electronic Materials, 9, 2200955 (2023)

[4] S Lee et al. *Semi-Metal Edge Contact for Barrier-Free Carrier Transport in MoS_2 Field Effect Transistors*, ACS Applied Electronic Materials, 6, 4149−4158 (2024)

[5] C-S Pang, et al. *Thickness-Dependent Study of High-Performance WS2-FETs With Ultrascaled Channel Lengths*, IEEE Transactions on Electron Devices, 68, 4, (2021)

[6] ISO TS 80004-13, *Nanotechnologies - Vocabulary - Part 13: Graphene and other two-dimensional (2D) materials*

_____