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Nanomanufacturing - Key control characteristics -
Part 12-3: 2D material-related products - Schottky barrier heights of 2D material-based field-effect transistors: temperature-dependent current-voltage measurements

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

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

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Nanomanufacturing - Key control characteristics - Part 12-3: 2D material-related products - Schottky barrier heights of 2D material-based field-effect transistors: temperature-dependent current–voltage measurements

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

Draft	Report on voting
113/967/DTS	113/976/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 62607 series, published under the general title *Nanomanufacturing - Key control characteristics*, can be found on the IEC website.

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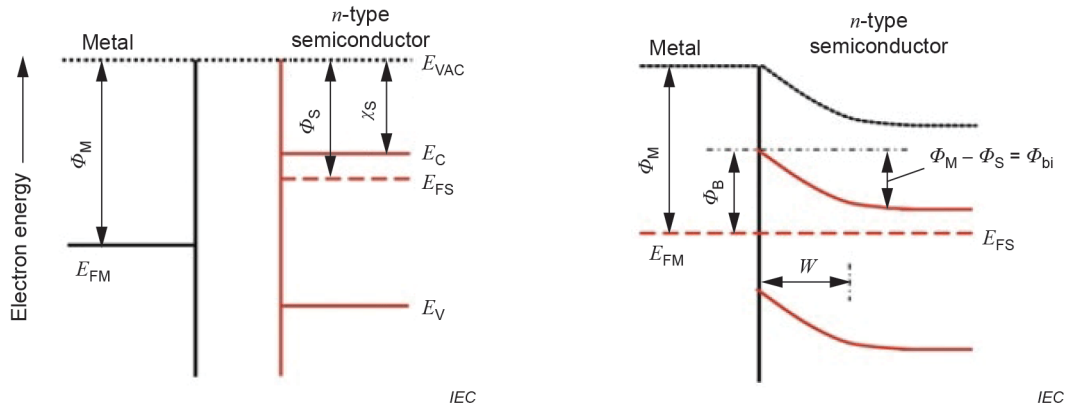
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INTRODUCTION

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

The Schottky barrier refers to a potential energy barrier that forms at the interface between a metal and a semiconductor or other material. See Figure 1.



a) Electron energy before contact **b) Electron energy after contact**

Key

Φ_M	work function of a metal
Φ_S	work function of a semiconductor
Φ_B	Schottky barrier height formed at the metal-semiconductor junction
W	depletion width in a semiconductor
Φ_{bi}	built-in potential induced in the depletion region of a semiconductor
E_{VAC}	energy level of vacuum
E_{FM} and E_{FS}	Fermi energy levels of a metal and a semiconductor, respectively
E_C and E_V	energy levels of conduction band minimum and valence band maximum, respectively
χ_S	electron affinity of a semiconductor

Figure 1 – Energy band diagram of a metal–semiconductor junction

In electronic devices, this barrier can influence the flow of current across the interface, as it can prevent or allow the movement of electrons depending on the direction of the voltage applied. The Schottky barrier height (SBH) is expressed in unit of Joule (J) or electron volt (eV); however, electron volt is more widely used in the electronic device community.

Specifically, when a metal is placed in contact with a semiconductor, the difference in work function between the two materials can lead to the formation of depletion of free carriers near the interface. The depletion region as shown in Figure 1 is dependent on SBH and doping concentration, and it affects the flow of electrons.

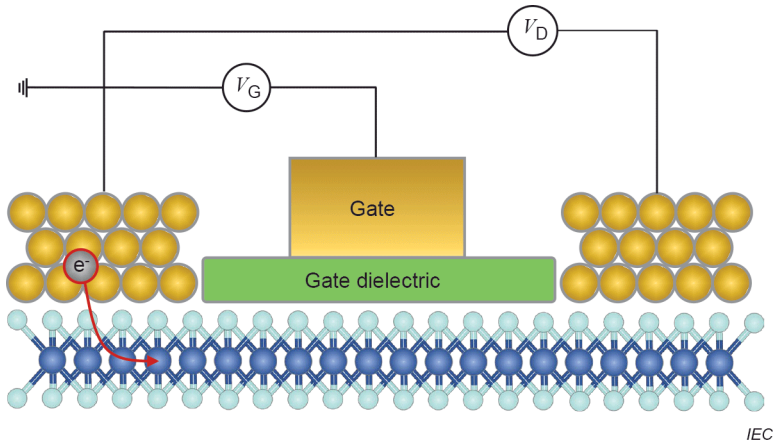
The magnitude of the SBH depends on a number of factors, including the choice of materials, the doping concentration of the semiconductor, and the voltages applied to the device. In some cases, the Schottky barrier can be deliberately engineered to control the flow of current in electronic devices, such as in Schottky diodes, which are commonly used in a range of electronic applications, including power supplies, radio frequency (RF) circuits, and digital logic circuits. Examples of Schottky devices include Schottky diodes, Schottky transistors, and Schottky barrier photodiodes.

As for conventional semiconductor devices, several methods have been used to determine SBH, e.g. temperature-dependent current–voltage (I–V) measurement, capacitance–voltage (C–V) measurement, and photocurrent measurement. [1][1]

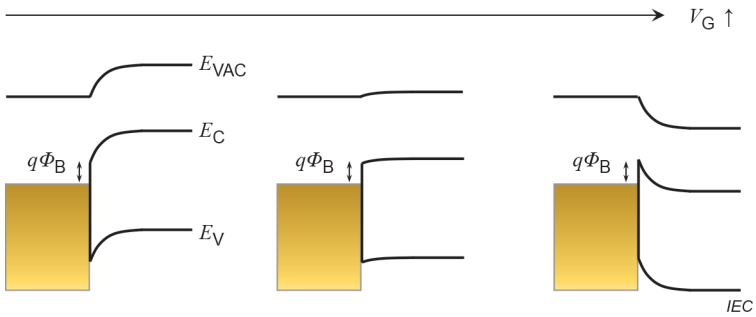
However, it is difficult to measure SBH of 2D materials by using C–V methods because their ultra-thinness and van der Waals (vdW) gap formed at the metal–2D semiconductor interfaces give rise to unreliable results arising from various parasitic capacitance components. It is also difficult to measure SBH of 2D materials by using photocurrent which is dependent on internal photo-emission because their ultra-thinness gives rise to weak optoelectronic intensity and vdW gap formed at the metal-semiconductor interfaces gives rise to noisy photocurrent signal.

Therefore, the current–voltage (I–V) measurement as the fundamental electrical characterization technique has been predominantly utilized to measure SBH in 2D materials-based electronic devices. Especially, I–V transfer curves obtained from 2D material-based field-effect transistors (FETs) at various temperatures have been used to extract SBH, as shown in Figure 2. That is, SBH can be determined by measuring only current arising from thermionic emission at elevated temperatures at the flat-band condition without current arising from field emission which is commonly described as tunnelling.

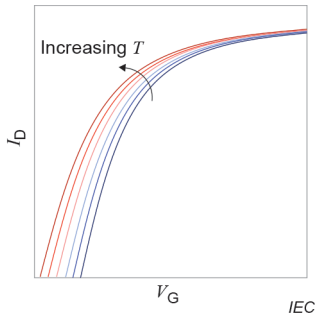
[1] Numbers in square brackets refer to the Bibliography.



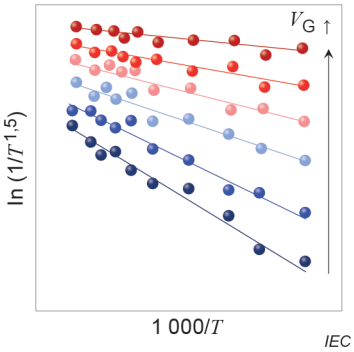
a) **Cross-sectional schematic of 2D FET**



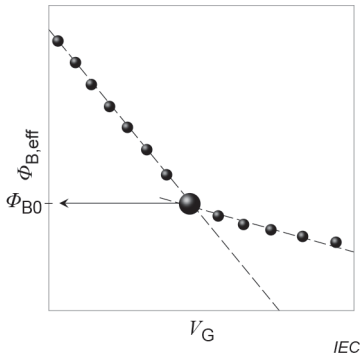
b) **Different transport regimes at the source contact as a function of gate voltage (V_G)**



c) **Temperature-dependent I–V transfer curves**



d) **Arrhenius plot (ln $1/T^{1,5}$ versus 1 000/T) of c)**



e) **Schottky barrier as a function of V_G**

Key

V_G gate voltage

V_D drain voltage

E_{VAC} energy level of vacuum

E_C and E_V energy levels of conduction band minimum and valence band maximum, respectively

NOTE Thermionic emission dominates in the OFF state ($V_G < V_{FB}$), and tunnelling current begins to dominate in the ON state. Here, $q\Phi_{B0}$ is equivalent to the n-type SBH ($q\Phi_{Bn}$) at flat-band condition.

Figure 2 – Extraction of SBH from a temperature-dependent transfer curve [1]

1 Scope

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

– Schottky barrier height (SBH)

from the temperature-dependent current–voltage characterization results obtained from two-dimensional (2D) material-based electronic devices.

This document

– defines the Schottky barrier formed from the interface between a 2D material and a metal;
– specifies a 2D device sample for the measurement of the Schottky barrier;
– specifies the measurement procedure for the Schottky barrier formed at the interface within 2D devices;
– provides proper mathematical formulas used to extract the Schottky barrier formed from 2D-materials-based devices;
– provides relevant case studies; and
– provides relevant references

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 terminology databases for use in standardization at the following addresses:

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

3.1 General terms regarding the sample

3.1.1
Schottky barrier
junction between a metal and a semiconductor in which a transition region, formed at the surface of the semiconductor, acts as a rectifying barrier

[SOURCE IEC 60050-521:2002 [2], 521-02-71]

3.1.2
Schottky barrier height
SBH
<n-type semiconductor> difference between the conduction band minimum of a semiconductor and the Fermi energy level of a metal

Note 1 to entry: Schottky barrier height refers to a potential energy barrier that forms at the interface between a metal and a semiconductor.