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Semiconductor devices – Flexible and strechable semiconductor devices – Part 3: Evaluation of thin film transistor characteristics on flexible substrates under bulging

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SEMICONDUCTOR DEVICES –
FLEXIBLE AND STRECHABLE SEMICONDUCTOR DEVICES –

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The text of this International Standard is based on the following documents:

FDIS	Report on voting
47/2492/FDIS	47/2511/RVD

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 62951 series, published under the general title *Semiconductor devices – Flexible and stretchable semiconductor devices*, 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 "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

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INTRODUCTION

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SEMICONDUCTOR DEVICES – FLEXIBLE AND STRECHABLE SEMICONDUCTOR DEVICES –

Part 3: Evaluation of thin film transistor characteristics on flexible substrates under bulging

1 Scope

This part of IEC 62951 specifies the method for evaluating thin film transistor characteristics on flexible substrates under bulging. The thin film transistor is fabricated on flexible substrates, including polyethylene terephthalate (PET), polyimide (PI), elastomer and others. The stress is applied by applying a uniformly-distributed pressure to the flexible substrate using the equipment.

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 62047-17, *Semiconductor devices – Micro-electromechanical devices – Part 17: Bulge test method for measuring mechanical properties of thin films*

IEC 60747-8, *Semiconductor devices – Discrete devices – Part 8: Field-effect transistors*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 62047-17, in IEC 60747-8 and the following 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
flexible substrate
substrate with flexibility onto which a thin film transistor is fabricated

4 Test piece

4.1 General

The test piece shall be prepared using the thin film transistor fabrication process on flexible substrates. The mechanical and electrical properties of thin film transistors may depend on the fabrication processes. Thin film transistors shall be prepared to prevent formation of cracks or flaws and delamination from the substrate.

4.2 Size of a test piece

As long as the size of a test piece is larger than that of the chamber open area, any test piece will suffice. Since the change in electrical characteristics is related to strain or stress, it is recommended that the thin film transistors be fabricated in a central region, where the strain is uniform. To measure the electrical characteristics, attach lead wires to the source, drain and gate pads of thin film transistors of the test piece.

4.3 Measurement of dimensions

The thickness and dimension of the thin film transistors and flexible substrate shall be accurately measured respectively, because they are used to determine the mechanical and electrical properties of thin film transistors. It is recommended that the thickness of thin film transistors be smaller than that of the substrate in order to keep the deformation of the thin film transistors uniform. The substrate material should be in-plane isotropic in order to keep the stress and strain applied on the thin film transistor equibiaxial. There can be some combinations of thin film transistor and substrate where it is difficult to fulfil the tolerance of thickness measurement. In this case the average and the standard deviation of the thickness measurement should be reported.

4.4 Storage prior to testing

In the case of thin film transistors, the storage environment may affect the electromechanical properties of the thin film transistors. For example, oxidation on the test piece surface will deteriorate the electrical and mechanical properties of the test piece. If there is an interval between final preparation and testing, particular care should be taken in storing the test pieces, and the specimens should be examined by appropriate means to ensure that the surface has not deteriorated during the storage period. If any deterioration is observed that was not present after the specimens were prepared, testing shall not be performed. However, if the damage was introduced during the preparation processes, the test shall be performed.

5 Test apparatus and procedure

5.1 General

The test is performed by bulging a test piece at a specified temperature. To measure the change in electrical characteristics along with the change in mechanical strain, carefully select the measuring section. The section for measuring mechanical strain shall be coincident with or scalable to that for measuring electrical characteristics. There are several types of bulging equipment by which to measure the electromechanical property of thin film transistors. It is not necessary that a certain type of bulging test method be preferred. As examples, absorption-type electrical and mechanical test equipment with a heating system and bulging-type electrical and mechanical test equipment with a halogen lamp heating system are described in Annex A.

5.2 Test apparatus

5.2.1 General

By applying pressure to the specimen, the deformation response, i.e. the change in bulge height as well as the electrical response of the thin film transistor on flexible substrate, shall be measured. In general, test apparatus can be composed of pressuring device, pressure chamber, pressure chamber open window, heating device (optional), bulging height measurement unit and electrical measurement units as shown in Figure 2. Exemplary schematics of pressure chamber, pressure chamber open window and wire bonding are given in Figure 3 and Figure 4.

5.2.2 Apparatus

5.2.2.1 Pressuring device

The pressuring device should be equipped to apply a specified continuous pressure with a controlled rate or a certain level of pressure to the pressure chamber open window to be stressed. Pressure media can be oil, gas and distilled water. In general, the device can be composed of a pressure sensor and pressure controller. The controller should show an accuracy of 1 % in the full test scale.

NOTE At the pressures encountered in the tests, gas is over a million times more compressible than typical liquids such as oil and distilled water.

5.2.2.2 Pressure chamber

The pressure chamber should be as compact as possible, to reduce the compliance of the test system. The volume, which has to be pressurized and which potentially contributes to the compliance, would be minimized.

In case liquid is used to pressurize the test system, the system shall contain as little air as possible because even a small air bubble trapped inside the test system can dominate the system's compliance. It is recommended that the system including the chamber be designed so that there are no places where air bubbles can hide and that the liquid can be refilled easily. It is necessary that special care be taken not to introduce air bubbles when the test piece is mounted and removed.

The material of the chamber should be chosen considering the pressure media for the test, testing pressure range, measurement temperature range and interference with the electrical measurements.

In case liquid is used to pressurize the test system, it is recommended that the testing apparatus be made out of transparent plexiglass (polymethyl methacrylate) in order to see air bubbles and then to minimize them trapped within the chamber.

The pressure chamber is connected to the pressuring device and thus allows a test piece to be deformed with fine control. The test piece is mounted on the pressure chamber by mechanical clamping or the epoxy gluing method, etc.

NOTE In the case of a capacitance measurement type, the pressure chamber has an electrode and a mechanical spacer. The electrode, which measures the height change of a test specimen due to deformation, is made of Cu-coated polychlorinated biphenyl (PCB). A mechanical spacer that is located between the specimen and the electrode controls a sensitivity of capacitance change by adjusting the thickness of the spacer.

The pressure inside the chamber shall be monitored and measured through a suitable pressure sensor, which can be installed directly in the chamber or connected though the tube transporting the pressure without loss of the pressure to be measured.

It is recommended that exposition of the area of the pressure sensor to the pressure media be minimized and that the area have no indentation or internal cavities trapping air.

It is recommended that the nonlinearity and hysteresis of the pressure sensor be less than 0,5 % and be calibrated according to the national standard.

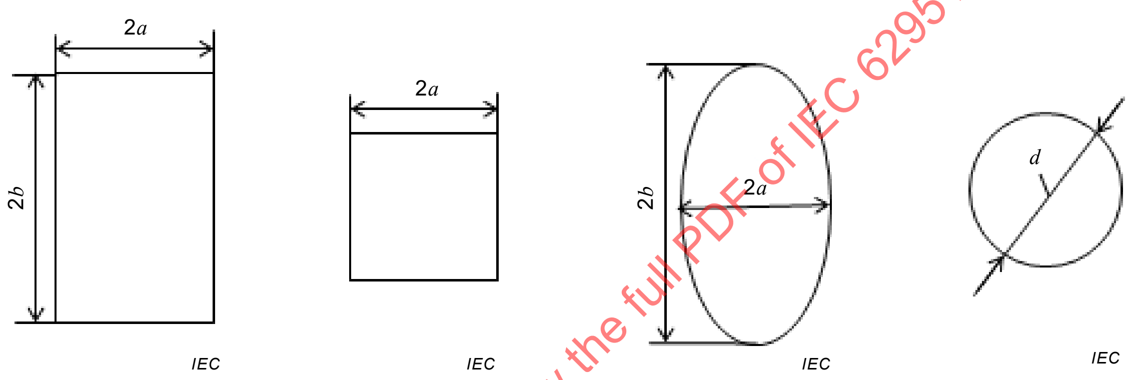
5.2.2.3 Heating device (optional)

When a very large pressure is needed to deform a flexible substrate, an optional heating device such as a hot plate or a halogen lamp can be added to increase the temperature of the device under testing. A heating device can be used when a large elastic or plastic deformation is needed through a reasonable pressuring device, since the elastic modulus of flexible substrates such as PET or PI becomes smaller at a higher temperature. When a plastic deformation is effected, the flexible substrate is deformed permanently and cannot be recovered to its initial non-stressed state. When a heating device is used, the pressure chamber should be designed with materials that conduct heat easily from the heating device to the flexible substrate under testing. The materials used for the pressure chamber should be able to withstand the supplied heat.

5.2.2.4 Pressure chamber open window

5.2.2.4.1 Pressure chamber open window shapes

Pressure chamber open windows can be in the shape of a rectangle, square, circle or ellipse, as shown in Figure 1. In case of a square or circle shape, the stress state of the sample is biaxial, while in case of a rectangle or ellipse, the stress state may be uniaxial. In case of measuring transistor characteristics, a square or circle shape is recommended, since the alignment of the thin film transistor under test is not necessary with biaxial stress. The pressure chamber open window is surrounded with a thick substrate frame or frame jig, which is not deformed by pressure. It is recommended that the half width, a, of the rectangular, square and elliptic chamber open window and the diameter, d, of the circular window be in the range of 1 mm to 50 mm.



a) rectangular **b) square** **c) ellipse** **d) circle**

Figure 1 – Pressure chamber open window shapes

5.2.2.4.2 Measurement of pressure chamber open window dimension

To analyze the test results, the accurate measurement of the pressure chamber open window dimension and pressure is required since the dimensions are used to extract mechanical properties of the test piece. The dimension of the window (width and length or diameter) should be measured with very high accuracy within less than ±1 %. Special care should be taken to measure the window size with clear division of the window boundary.

Special care should also be taken to avoid damage to the test piece during the measurement.

5.2.2.5 Height measurement unit

The height measurement unit should be installed in a position suitable to measure the deformation of the flexible substrate and perform the function of continuous measurement, which is needed to determine the maximum deformation of the flexible substrate bulged with applying pressure. The maximum deformation of the flexible substrate can be determined from the measurement in full-field or on top of the bulged area using the laser interferometric system or capacitance type measurement system, which is described in detail in Annex B of IEC 62047-17:2015.

The resolution of the measurement device for the deflection measuring a bulged flexible substrate by pressure should be in units of micrometers. A fine resolution of less than 0,1 % in full scale is very important for an accurate measurement.

5.2.2.6 Electrical measurement unit

For DC characteristics of thin film transistors, testing is performed using an electronic device test system with measurement sensitivity sufficient to give an accuracy of at least ± 0,1 % (minimum sensitivity at or better than three orders of magnitude below expected signal level). For example, the smallest current through a thin film transistor is often the gate leakage current. If gate leakage is approximately 1 pA, the instrument shall have a resolution of 1 fA or smaller. Additionally, due to the large (> 1 GΩ) impedances often encountered in thin film transistors, the input impedance of all elements of the test system shall be at least three orders of magnitude greater than the highest impedance in the device. Commercial semiconductor systems with the capability to characterize thin film devices typically have input impedance values of 10^{16} Ω, which is a recommended minimum value.

This test method requires that the instrumentation be calibrated against a known and appropriate set of standards (such as those of the National Institute of Standards and Technology (NIST)). These calibrations may be performed by the equipment user or as a service by the equipment vendor. The basic instrument operations (e.g., voltage, current and resistance) are calibrated against some method traceable to a physical standard of the NIST (or similar internationally recognized standards organization). Re-calibration is required according to the instrument manufacturer's recommendations or when the instrument is moved or when the testing conditions change significantly (e.g., temperature change greater than 10 °C, relative humidity change greater than 30 %).

5.2.2.7 Wire bonding

Wire bonding is needed to measure the in-situ electrical characteristics of thin film transistors under bulging. Wire bonding is typically done between the contact pads outside the chamber open area and the pads on flexible substrates. It is recommended that ohmic contact be formed during wire bonding and that the wire bonding be kept intact during testing. The electrical measurement unit is connected through the contact pads onto a device under test.

5.2.2.8 Test environment

It is recommended to perform a test under constant humidity after temperature is stabilized. Temperature change can induce thermal drift during deflection measurement. Temperature change during the test should be less than 2 °C.

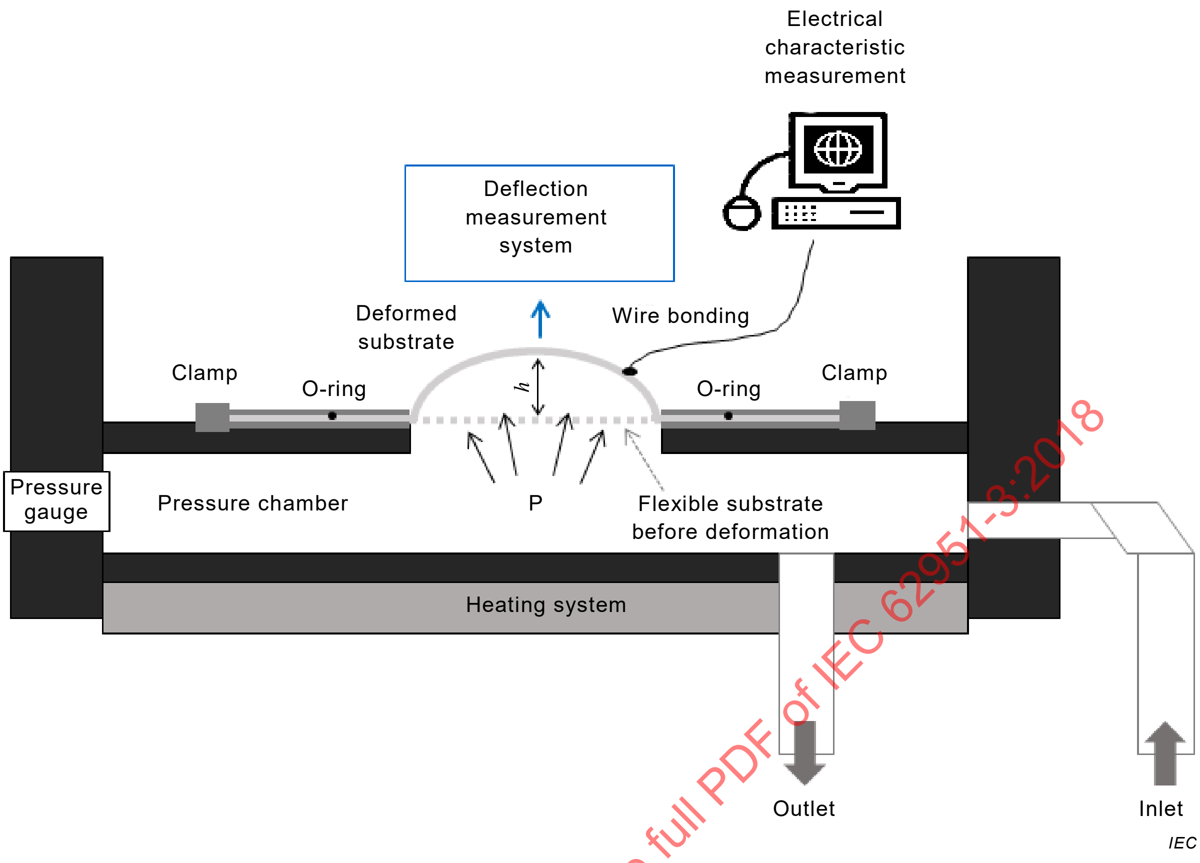


Figure 2 – Typical example of bulging-type mechanical and electrical measurement test apparatus with heating system

Dimensions in millimetres

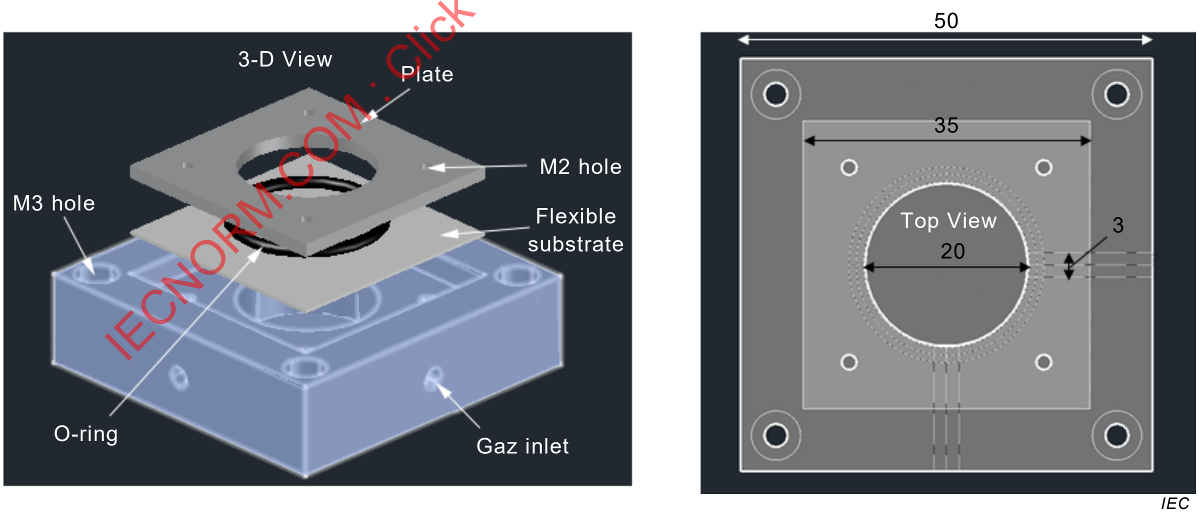


Figure 3 – Exemplary schematics of pressure chamber, pressure chamber open window

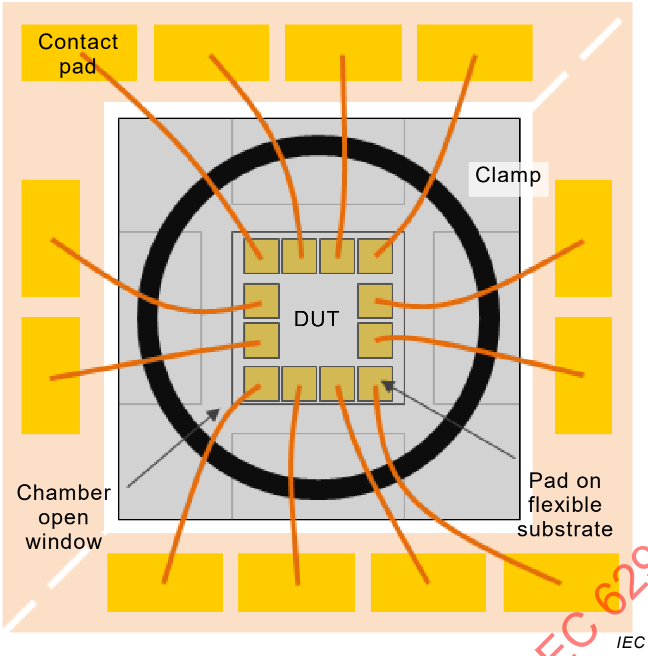


Figure 4 – Exemplary schematic of wire bonding

5.3 Test procedure and analysis

5.3.1 Test procedure

5.3.1.1 Test piece loading, application of pressure and height measurement

a) The flexible substrate should be loaded to the pressure chamber by covering the chamber open window through an appropriate method, such as the mechanical clamping or epoxy gluing method etc., so as not to cause unwanted stress, such as bending, shear or combined stress, or in-plane distortion on the flexible substrate.

The alignment of the thin film transistor with respect to the test apparatus is typically not necessary since the stress applied by bulging is typically biaxial, which is irrespective of the direction.

The clamping effect on the change in the bulge height should be considered when carrying out the test. Hard clamping on the specimen often causes residual stress on a flexible substrate. However, to avoid pressure leakage in the bulge chamber, a proper sealing method is required for the test.

The test piece can be mechanically clamped to the chamber with screws. In general, a test piece holder to which the flexible substrate would be attached is screwed tightly on to the chamber. To prevent any leakages, an O ring between the test piece holder (or test piece) and the chamber can be used as shown in Figure 3. Special care should be taken in positioning the O ring on the chamber to avoid offset of bulge height.

The test piece or test piece holder can be attached to the chamber using epoxy with sufficient adhesive strength.

b) Initial DC characteristics of the thin film transistor may be measured before loading the test piece.

c) To obtain quasi-static deformation of the flexible substrate, pressure should be carefully controlled to increase or decrease monotonically. The strain rate imposed on the test should be ranged from 10^{-9}/s to 10^{-4}/s.

d) The test should be performed within the appropriate deformation of the flexible substrate. It is recommended that the failure pressure of the flexible substrate under testing be estimated prior to the determination of the applying pressure in order to prevent over-pressuring the device under test, an example of which is given in Annex B.

e) Within the elastic or elastic-plastic regime of the flexible substrate, pressurizing and depressurizing steps can be repeated. Special care should be taken to avoid cyclic effect on the mechanical property of the flexible substrate by excessively repeating the depressurizing steps.

f) During test, the pressure and deformation in the window should be precisely measured simultaneously. Changes in the DC characteristics of the thin film transistor can be measured either in-situ or ex-situ at different bulging heights.

g) Unload the test piece when electrical failure occurs in the test piece or a fracture of the film caused by initiation of the cracks or delamination occurs. Optical microscopy or scanning electron microscopy examination of the failure sites is recommended.

5.3.1.2 Electrical measurement of thin film transistor under bulging

Although various types of field-effect transistors described in IEC 60747-8 can be tested under bulging, thin film transistors on flexible substrate may be most appropriate for testing under bulging. Many of the field-effect transistor characteristics described in IEC 60747-8 may be tested under bulging in addition to the characteristics described in the following.

Measure DC characteristics of thin film transistors under bulging. Measurement items may be selected from items described in IEC 60747-8 and/or 5.3.2 (Data analysis). It is recommended to select one of V_{th}(ci) or V_{th}(ext), and select one of I_d(sat) or I_d(lin).

Characterization of the thin film transistor requires at a minimum the following sets of measurements:

– the transfer (I_{ds} vs. V_{gs}) curves, which allow for preliminary determination of field-effect mobility, μ, and threshold voltage, V_{th};

– the I versus V output (I_{ds} vs. V_{ds}) curves that provide saturation and general electrical performance information. This curve is used to determine whether the device exhibits FET-like behavior;

– the gate leakage (I_{gs} vs. V_{gs}) curves that characterize the gate dielectric quality and quantify leakage current from the gate to the channel. Leakage measurements are carried out prior to transfer or I versus V measurements to ensure gate dielectric integrity before subsequent measurements are performed. Gate leakage characterization is necessary to ensure that its magnitude is negligible to the magnitude of the drain current, so that reliable and useful device characteristics may be measured and key parameters extracted.

5.3.1.3 Repeatability and reporting sample size

Sample performance between different devices may vary due to variations in the fabrication process. Additionally, it is critical to determine how repeatable the reported results are. Therefore, sample size is to be reported as follows:

– if no sample size is reported, it is assumed that the data represents a sample size of a single device (i.e., may not represent repeatable results);

– for sample sizes larger than one, the sample size is reported with the method of sampling (whether all devices were characterized, a randomly-chosen fraction of the total sample set, etc.).

A description of what the reported data demonstrates (average values, worst-case, etc.) is also required.

5.3.1.4 Application of low-noise techniques

Generally, lower absolute gate bias voltages cause smaller stress effects, such as shifts in the threshold voltage, than higher absolute gate biases. Depending on the device structure, this shifting may be reduced by ensuring that the device under test is properly grounded. This issue may be further improved if this grounding is through a low-impedance path to system ground. In order for comparability between different device structures, voltages should be referenced to the corresponding film thickness (V_{GS}) and channel length (V_{DS}). Sufficient information is to be given so that electrical fields (V/m) may be determined. Preferably, electrical field values are specified.

Due to optical sensitivity of some thin film semiconducting materials, all measurements should be conducted inside a light-insulating enclosure that is preferably earth (safety) grounded. Optical isolation is recommended if exposure to ambient light causes a change of more than 1 % from values obtained in the dark. Due to the high impedances and extremely low current values being measured, personnel, heavy machinery or other potential electromagnetic/radiofrequency interference (EMI/RFI) sources should be maintained as far away from the measurement system while in operation. This is of particular concern when measured voltages are below 1 mV or when current values are less than 1 µA.

5.3.2 Data analysis

The following electrical (items a) to i)) and mechanical (item j)) characteristics of thin film transistor on flexible substrates under bulging can be analysed based on the measured I-V and pressure-deflection data (see Figure 5 and Figure 6).

a) $V_{th}(ci)$: constant current threshold voltage

The constant current threshold voltage is defined as:

$$V_{th}(ci) = V_{gs}(\text{if } I_d = 0{,}1\ \mu\text{A} \times W) \tag{1}$$

for linear region (V_{ds} = 0,05 V to 0,1 V approximately) or typical supply voltage of recommended operating condition. V_{th}(ci) is the gate voltage at which Id is equal to 0,1 µA times gate width (W).

b) $V_{th}(ext)$: extrapolated threshold voltage

The extrapolated threshold voltage is defined as:

$$V_{th}(ext) = V_{gs}(\text{gm}_{(max)}) - \frac{I_d(\text{gm}_{(max)})}{\text{gm}_{(max)}} \tag{2}$$

for linear region (V_{ds} = 0,05 V to 0,1 V approximately). V_{th}(ext) is the gate voltage at which the slope of I_d-V_{gs} curve becomes maximum. $V_{gs}(\text{gm}_{(max)})$ is the gate voltage at which gm becomes maximum and $I_d(\text{gm}_{(max)})$ is the drain current measured when V_{gs} is equal to $V_{gs}(\text{gm}_{(max)})$; $\text{gm}_{(max)}$ is the maximum trans-conductance.

c) $I_{d(sat)}$: saturated drain current

$I_{d(sat)}$ is the drain current measured when both V_{ds} and V_{gs} are equal to the typical supply voltage of the recommended operating condition.

d) $I_{d(lin)}$: linear drain current

I_d(lin) is the drain current measured when V_{ds} is from 0,05 V to 0,1 V and V_{gs} is equal to the typical supply voltage of the recommended operating condition.

e) $I_{d(leak)}$: drain leakage current

$I_{d(leak)}$ is the drain current measured when V_{ds} is equal to the typical supply voltage of the recommended operating condition and V_{gs} is zero.

f) $gm_{(max)}$: maximum trans-conductance

gm is the slope of I_d-V_{gs} curve. $gm_{(max)}$ is the maximum trans-conductance measured when V_{gs} is equal to V_{th}(ext). V_{ds} is linear region or V_{ds} = 0,05 V to 0,1 V(recommended).

g) $\mu_{(lin)}$: linear mobility

The linear mobility can be extracted from the slope of I_d-V_{gs} curve using the following equation:

$$\mu(lin) = \frac{L}{C_g W V_{ds}} \left(\frac{\partial I_d(lin)}{\partial V_{gs}} \right) \quad (3)$$

for linear region (V_{ds} = 0,05~0,1V approximately) given the gate oxide capacitance (C_g), gate width (W) and gate length (L).

h) $\mu_{(sat)}$: saturated mobility

The saturated mobility can be extracted from the slope of I_d-V_{gs} curve using the following equation:

$$\mu(sat) = \frac{2L}{C_g W} \left(\frac{\partial^2 I_d(sat)}{\partial V_{gs}^2} \right) = \frac{2L}{C_g W} \left(\frac{\partial \sqrt{I_d(sat)}}{\partial V_{gs}} \right)^2 \quad (4)$$

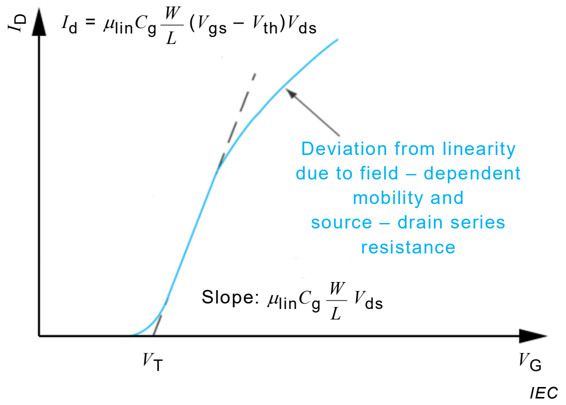
for saturation region ($V_{ds} \geq V_{gs}$-V_{th}) given the gate oxide capacitance (C_g), gate width (W) and gate length (L).

i) SS: sub-threshold slope

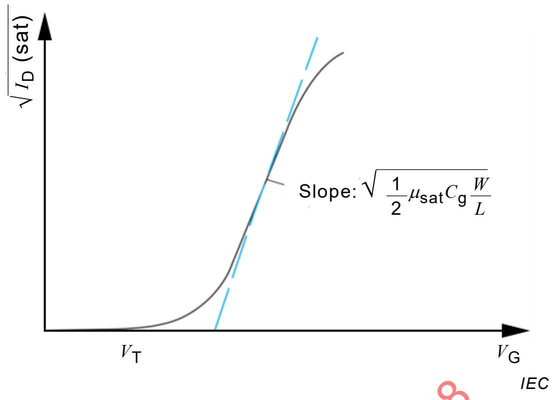
The sub-threshold slope is a measure of how efficiently a conductive channel is formed within the device and can be measured via the following equation:

$$SS = \frac{\partial V_{gs}}{\partial \left(\log_{10} I_d \right)} \quad (5)$$

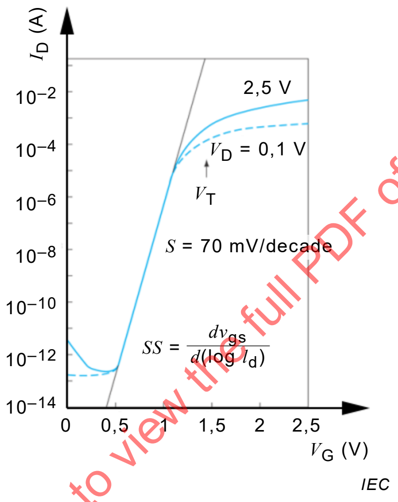
SS is the slope of V_{gs}-log10(I_d) curve. A plot of logarithmic drain current versus gate-source voltage with drain-source voltage fixed will exhibit approximately log linear behavior in thin film transistor operating regime.



a) **Exemplary DC characteristics for determining μ_{lin}**



b) **Exemplary DC characteristics for determining μ(sat)**



c) **Exemplary DC characteristics for determining SS**

Figure 5 – Exemplary DC characteristics for determining (a) μ_{lin} (b) μ_{sat} and (c) SS

j) Pressure- deflection relation

Figure 6 presents the representative bulge test data showing pressure-deflection relation for Ag-Pd/SiN_x. Residual stress and modulus can be extracted from the slope and intercept of p/h vs. h^2 curve.

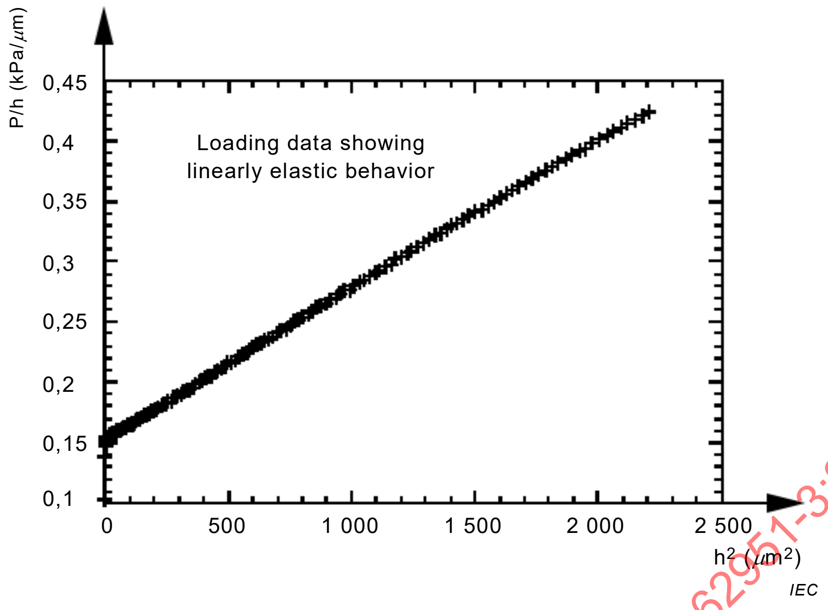


Figure 6 – Representative bulge test data showing pressure-deflection relation for Ag-Pd/SiN_x

6 Test report

The test report should contain at least the following information:

a) references to this International Standard;
b) identification number of the test piece;
c) fabrication procedures of the test piece;
d) test piece material and substrate material;
e) shape and dimension of the test piece and chamber open window;
f) environment (temperature, humidity, light, etc.);
g) description of testing apparatus;
h) pressure-deflection relationship;
i) pressure-electrical characteristics.

Annex A
(informative)

Other types of electrical and mechanical test equipments

A.1 Absorption type electrical and mechanical test equipment with heating system

Figure A.1 shows an exemplary schematic of absorption-type electrical and mechanical test equipment with a heating system.

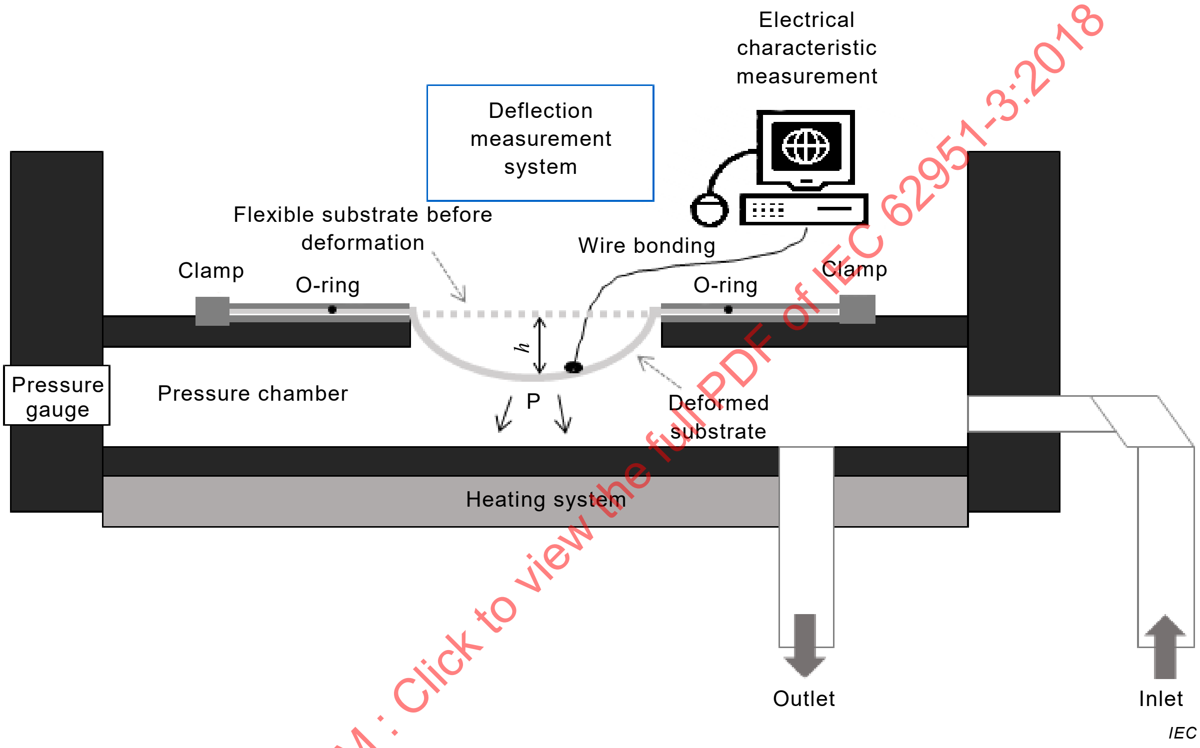


Figure A.1 – Exemplary schematic of absorption-type electrical and mechanical test equipment with heating system

A.2 Bulging-type electrical and mechanical test equipment with halogen lamp heating system

Figure A.2 shows an exemplary schematic of bulging-type electrical and mechanical test equipment with a halogen lamp heating system.