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Printed electronics –
Part 503-1: Quality assessment – Test method of displacement current measurement for printed thin-film transistor

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FOREWORD

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

FDIS	Report on voting
119/303/FDIS	119/307/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 62899 series, published under the general title *Printed electronics*, 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

- reconfirmed,
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INTRODUCTION

There has been a need for a method to measure and evaluate performance and reliability that is appropriate for printed thin-film transistors (TFTs). In the case of printed TFTs, there is much larger parasitic capacitance than dielectric capacitance in the channel. Accordingly, there has been a need for a method to measure and evaluate the properties for printed TFTs. Carrier behavior is one such property, and mobility and threshold voltage (V_{th}) for TFTs are other properties. In the case of inorganic TFTs, for example complementary metal-oxide semiconductor (CMOS) TFTs, carriers are induced by the strong inversion at the semiconductor/dielectric interface. But in the case of organic or printed TFTs, carrier generation takes place in the accumulation mode. The total number of carriers in the organic semiconductor layer can often be insufficient to enrich the carrier concentration at the channel. There exists a carrier injection. The carrier injection occurs at the interface of the organic semiconductors' source/drain electrodes. There are three methods to investigate the carrier injection property, that is, Kelvin probe microscopy, four-terminal measurement, and displacement current measurement (DCM). Both Kelvin probe microscopy and four-terminal measurement are indirect methods, but DCM is a direct method to detect charge motion in semiconductors, molecular thin films, and nanoparticles. In this document, the DCM-based channel charge trapping and channel capacitance measurement method is proposed as a measuring method for the carrier properties of organic or printed TFTs.

PRINTED ELECTRONICS –

**Part 503-1: Quality assessment –
Test method of displacement current
measurement for printed thin-film transistor**

1 Scope

This part of IEC 62899 specifies a test method for displacement current measurement (DCM) for printed thin-film transistors (TFTs) or organic thin-film transistors (OTFTs).

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 291, *Plastics – Standard atmospheres for conditioning and testing*

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
printed thin-film transistor
printed TFT
device of a field effect transistor whose components, that is, source-drain electrodes, semiconductor, gate electrode, and insulator, are formed by any kind of printing technologies

3.2
saturation region
operating region of a TFT in which, when the drain voltage with a magnitude greater than the difference in the applied drain-to-source voltages is applied, the drain current stays constant despite the increase in drain voltage

3.3
displacement current measurement
DCM
measurement method to measure carrier motion between the source/channel/drain and gate electrodes

3.4
charge trapping
phenomenon where the charge is trapped within (active layer and insulator layer) due to external and internal causes, when passing from the printed TFT's gate voltage through the forward scan (injection) and reverse scan (ejection)

3.5
channel capacitance
total capacitance generated in the boundary between the active and insulator layers due to the injection of electrons (or electron holes) into the active layer

3.6
turn-on voltage
magnitude of the gate voltage that needs to be applied to a printed transistor to cause the drain current to rise above the background (off) current

4 Abbreviated terms

For the purposes of this document, the following abbreviated terms apply.

DCM displacement current measurement
FET field effect transistor
OTFT organic thin-film transistor
TFT thin-film transistor

5 Symbols and units

The information that is reported with all the symbols is shown in Table 1.

Table 1 – List of symbols

No	Name of quantity	Symbol	Unit	Remarks
1	Gate electrode	G	-	Refer to Figure 1
2	Drain electrode	D	-	Refer to Figure 1
3	Source electrode	S	-	Refer to Figure 1
4	Drain current	I_D	A	Refer to Figure 1 Refer to Figure 2
5	Source current	I_S	A	Refer to Figure 1 Refer to Figure 2
6	Voltage measured between the gate electrode and the source electrode	U_{GS}	V	Refer to Figure 1 Refer to Figure 2 Refer to Figure 3
7	Voltage measured between the drain electrode and the source electrode	U_{DS}	V	Refer to Figure 1
8	Current flow calculated as the sum of each measured value of I_S versus U_{GS} and I_D versus U_{GS}	I_{dis}	A	Refer to Figure 3
9	Ammeter		A	Refer to Figure 1
10	Oscilloscope		V	Refer to Figure 1
11	Trapped charge	Q_{trap}	C	Refer to Table 3
12	Value difference between the first and second trap charge	ΔQ_{trap}	C	Refer to Table 3
13	Injected carrier charge	$Q_{injected}$	C	Refer to Table 3
14	Ejected carrier charge	$Q_{ejected}$	C	Refer to Table 3

No	Name of quantity	Symbol	Unit	Remarks
15	First swing trapped charge	$Q_{\mathrm{trap},1}$	C	Refer to Table 3
16	Second swing trapped charge	$Q_{\mathrm{trap},2}$	C	Refer to Table 3
17	Channel capacitance	C	F	Refer to Table 3

6 Measuring method of DCM

6.1 Guidelines on measurements of printed TFT channel properties

The standard atmosphere for evaluation (test and measurement) and storage of the specimen shall be a temperature of (23 ± 2) °C and relative humidity of (50 ± 10) %, conforming to standard atmosphere class 2 specified in ISO 291. For a test piece which is a plastic substrate with printed patterns, the standard atmosphere for evaluation (test and measurement) and storage of the specimen shall be a temperature of (23 ± 1) °C and relative humidity of (50 ± 5) %, conforming to standard atmosphere class 1 specified in ISO 291.

6.2 Procedure for DCM

6.2.1 Measuring apparatus

A function generator, an amplifier, an oscilloscope, and a battery shall be prepared as shown in Figure 1.

6.2.2 Measuring procedure

1) Set a printed TFT as a specimen according to Figure 1.
2) Apply a triangle wave with constant frequency and amplitude to a gate terminal of the specimen, using the function generator and the amplifier.
3) Measure I_S versus U_{GS} (current flowing in the source electrode in accordance with changes in the signal applied to the gate) and I_D versus U_{GS} (current flowing in the drain in accordance with changes in the signal applied to the gate) using the oscilloscope.
4) Calculate I_{dis}. (refer to Formula (A.1) and Formula (A.2) in Clause A.1).
5) Calculate Q_{trap} and ΔQ_{trap}. (refer to Formula (A.3) and Formula (A.4) in Clause A.1).

As a triangular wave with constant frequency and amplitude is applied to the gate voltage, I_S versus U_{GS} (current flowing in the source electrode in accordance with changes in the signal applied to the gate) and I_D versus U_{GS} (current flowing in the drain in accordance with changes in the signal applied to the gate) are measured.

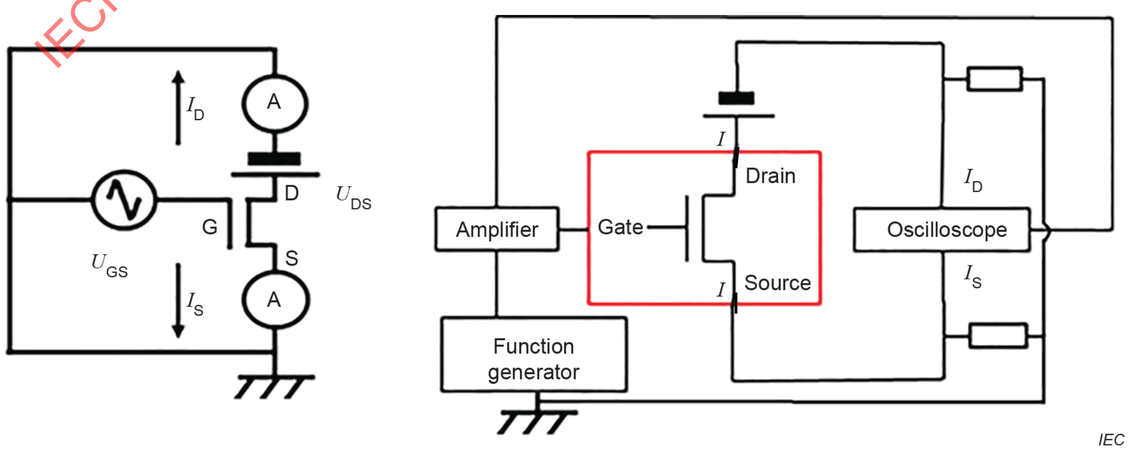


Figure 1 – Example of structure (left) and schema (right) of a measuring device

Because the probe station, passive probe, and measuring cable can cause distortion (delay) in the signal due to its internal capacitor, the electronic kit for measurement should be used in this document for the connection of the printed TFT and to minimize the effect of external capacitance. In DCM, the current flowing in the transistor cannot be measured directly, so commercial resistors should be connected.

An amplifier should be used for the application of gate voltage in the form of a triangular wave, for the saturation region of the printed TFT. The ability of the amplifier to distinguish signals depends on its type. When using a general-purpose, high-voltage amplifier, the increase in noise reduces the distinguishing capability, so a single-supply amplifier should be used, which has an amplification factor of 5. For a precise DCM, a unijunction transistor shall be used to measure separation, and for the connection of drain and source electrodes, an Ag paste ink, which does not require additional heat treatment processes or have parasitic capacitance, is recommended.

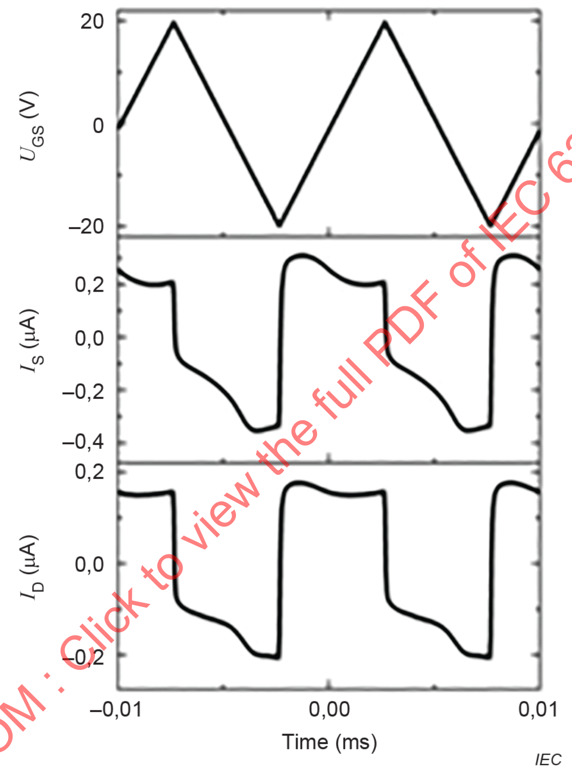


Figure 2 – Plots of the printed TFT's U_{GS}, I_s, I_D at U_{DS} = −20V with respect to time

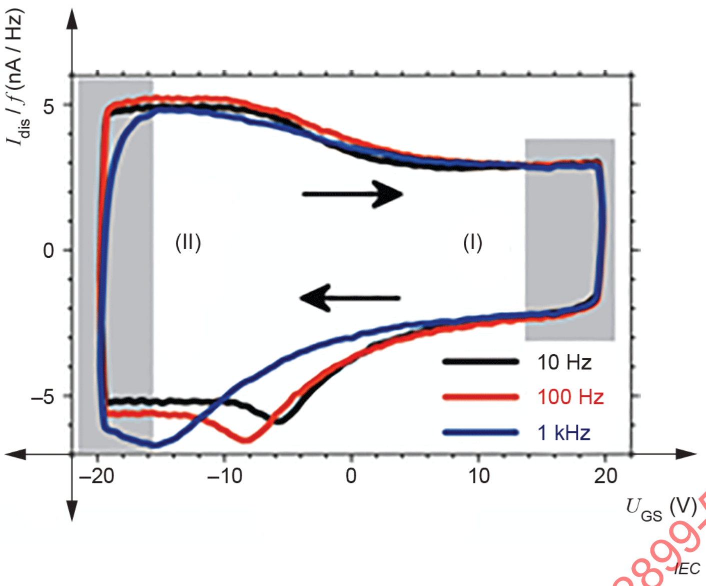


Figure 3 – Frequency dependence of DCM

The I_S and I_D values in accordance with the gate voltage (U_{GS}) applied to the unijunction transistor can be obtained by dividing the voltage measured at the resistance by the resistance values (Figure 2). I_{dis} is calculated as the sum of I_S and I_D values for the corresponding U_{GS} cycle (Figure 3).

7 Report

7.1 Experimental conditions

The printed TFT shall be measured in a standard room temperature where external light is blocked out. The equipment shall be sufficiently grounded. The following items shall be reported:

a) device temperature

b) relative humidity

c) environmental atmosphere

d) blocked external light

e) transistor terminal (gate, drain, source)

7.2 Appropriate data format

The printed TFT's DCM shall be reported as shown in Table 2 and Table 3.

Table 2 – Environmental factors

Item	Symbol	Unit	Value	Remarks
Frequency	W	Hz		
Gate voltage range	L	V		
Drain voltage		V		
Temperature, time, and atmosphere of subsequent heat treatment		°C, h, –		Choose whether to use the subsequent heat treatment process or not If this process is chosen, set temperature, time, and atmosphere For example: 150 °C, 1 h, vacuum
Measurement temperature	T	°C		
Measurement atmosphere		Torr		For example: atmosphere, vacuum
Relative humidity		%RH		
External light blockage		lx		For example: external light blocked out (darkroom: 0 lux)
Shielding of electromagnetic disruption				For example: shielding of electromagnetic disruption
Resistance value		Ω		Resistance value for measurements source/drain current

Table 3 – Measured properties of the TFT

Item	Standard symbol	Unit	Value (channel capacitance)	Remarks
Trapped charge	Q_{trap}	C		$Q_{trap} = \|Q_{injected}\| - \|Q_{ejected}\|$
	ΔQ_{trap}	C		$\Delta Q_{trap} = \|Q_{trap,1}\| - \|Q_{trap,2}\|$

Annex A
(informative)

Experimental results

A.1 Charge trapping measurement method

The charge trapping of the printed TFT is distributed between the active and insulator layers as the charge is injected during the forward scan from the gate voltage. During the reverse scan, the charge is ejected due to the operating frequency, the surrounding environment (humidity, temperature, light), and the active layer's structure. Another cause is the trapping of the charge after the initial scan of the printed TFT's gate voltage. The formulae to induce the trapped charge are as follows:

Injected charge:

$$\int I_{\text{dis}}\, dt = \int \frac{dQ}{dt} dt \rightarrow \int_{I_{\text{D}}}^{I_{\text{injected}}} I_{\text{dis}}\, dt = \int_{I_{\text{D}}}^{I_{\text{injected}}} dQ \tag{A.1}$$

Ejected charge:

$$\int I_{\text{dis}}\, dt = \int \frac{dQ}{dt} dt \rightarrow \int_{I_{\text{D}}}^{I_{\text{ejected}}} I_{\text{dis}}\, dt = \int_{I_{\text{D}}}^{I_{\text{ejected}}} dQ \tag{A.2}$$

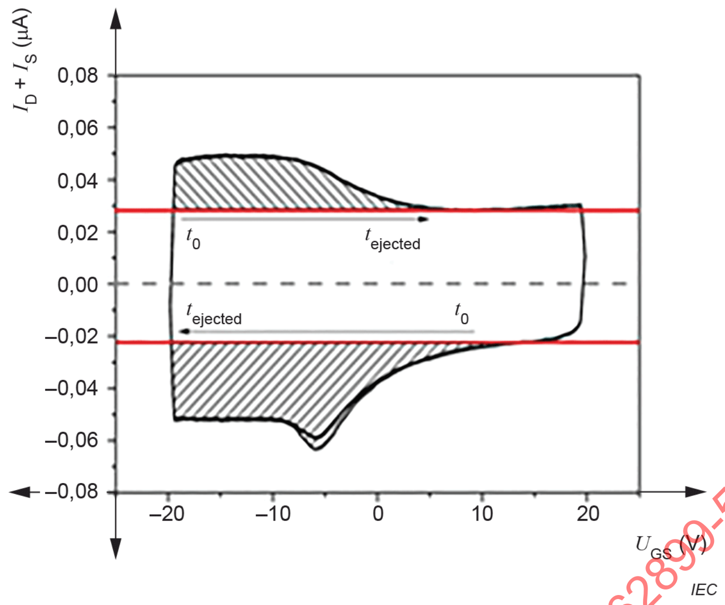
Trapped charge:

$$Q_{\text{trap}} = \left|Q_{\text{injected}}\right| - \left|Q_{\text{ejected}}\right| \tag{A.3}$$

The ΔQ_{trap} caused by a continuous voltage application can obtained by the following formula:

$$\Delta Q_{\text{trap}} = \left|Q_{\text{trap,1}}\right| - \left|Q_{\text{trap,2}}\right| \tag{A.4}$$

The trapped charge should be obtained from a DCM plot generated by the above formula (see Figure A.1):



NOTE The paunchy shape on both sides is an artificial measurement effect.

Figure A.1 – Plot of DCM at U_{DS} = 0 V

$Q_{injected}$ can be obtained by integrating the region (lower hatched area in Figure A.1) in the I_{dis} versus U_{GS} plot under the curve obtained from the reverse movement of U_{GS} (from + to −) where the derivative is 0 in the curve.

Table A.1 shows an example of implementation. For a more specific DCM, a trapped charge was obtained from four repeating cycles (continuous voltage application) (see Table A.1).

Table A.1 – Obtained trap charge from four cycles (accumulated)

Cycle	$Q_{injected}$	$Q_{ejected}$	$Q_{trap}(\lvert Q_{injected}\rvert - \lvert Q_{ejected}\rvert)$	ΔQ_{trap}
1st	$-8{,}18 \times 10^{-10}$ C	$3{,}75 \times 10^{-10}$ C	$4{,}43 \times 10^{-10}$ C	$8{,}7 \times 10^{-11}$ C
2nd	$-7{,}32 \times 10^{-10}$ C	$3{,}76 \times 10^{-10}$ C	$3{,}56 \times 10^{-10}$ C	$2{,}1 \times 10^{-11}$ C
3rd	$-7{,}54 \times 10^{-10}$ C	$3{,}76 \times 10^{-10}$ C	$3{,}77 \times 10^{-10}$ C	0
4th	$-7{,}45 \times 10^{-10}$ C	$3{,}70 \times 10^{-10}$ C	$3{,}75 \times 10^{-10}$ C	0

The printed TFT used in the above example has a trapped charge of $4{,}43 \times 10^{-10}$ C, and shows a change of $8{,}7 \times 10^{-11}$ C.

A.2 Channel capacitance measurement method

The printed TFT’s channel capacitance measurement method is as follows. The DCM plot can be divided into section (I) (no charge injection region) and section (II) (charge injection region) (see Figure A.2).

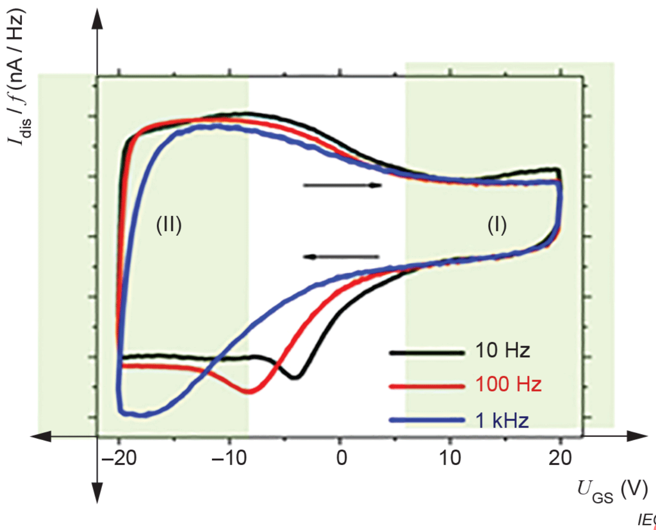


Figure A.2 – Division of regions according to carrier injection

Section (I) is the section in which the carrier is not injected, expressed as:

$$I_{dis} = \frac{\varepsilon(S_s + S_D)}{d}\frac{dV_g}{dt}$$

where S_s and S_d are the areas of the source and drain electrodes, and ε is the dielectric constants.

Section (II) is the section in which the carrier is injected, expressed as:

$$I_{dis} = (C_S + C_D + C_{ch})\frac{dV_g}{dt}$$

where C_S, C_D and S_{ch} are the capacitance of the source, drain and channel capacitance respectively.

These formulae can be used to derive the capacitance in the insulator layer and channel capacitance. The following is an example.

From section (I):

$$I_{dis} = \frac{\varepsilon(S_s + S_D)}{d}\frac{dV_g}{dt}$$

$dV_g/dt = 4050\,V/s \quad \varepsilon/d = 15{,}83$ nF/cm^2

$C_S + C_D = 1{,}235$ nF

From section (II):

$$I_{dis} = (C_S + C_D + C_{ch})\frac{dV_g}{dt}$$

$I_{dis} = 5{,}374$ μA $\quad C_{ch} = 0{,}092$ nF

Thus, the inducement of the printed TFT's channel capacitance from this document is recommended.