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Test methods for the characterization of organic transistor-based ring oscillators

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Contents

TEST METHODS FOR THE CHARACTERIZATION OF ORGANIC TRANSISTOR-BASED RING OSCILLATORS

FOREWORD

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International Standard IEC 62860-1/IEEE Std 1620.1™-2006 has been processed through IEC technical committee 113: Nanotechnology standardization for electrical and electronic products and systems, under the IEC/IEEE Dual Logo Agreement.

The text of this standard is based on the following documents:

IEEE Std	FDIS	Report on voting
IEEE Std 1620.1™-2006	113/185/FDIS	113/195/RVD

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

The IEC Technical Committee and IEEE Technical Committee have decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

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- withdrawn,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

A bilingual version of this standard may be issued at a later date.

IEEE Standard for Test Methods for the Characterization of Organic Transistor-Based Ring Oscillators

Sponsor
Microprocessor Standards Committee
of the
IEEE Computer Society

Approved 8 June 2006

IEEE-SA Standards Board

Abstract: Recommended methods and standardized reporting practices for electrical characterization of printed and organic ring oscillators are covered. Due to the nature of printed and organic circuits, significant measurement errors can be introduced if the electrical characterization design-of-experiment is not properly addressed. This standard describes the most common sources of measurement error, particularly for high-impedance electrical measurements commonly required for printed and organic ring oscillators. This standard also gives recommended practices in order to minimize and/or characterize the effect of measurement artifacts and other sources of error encountered while measuring printed and organic ring oscillators.
Keywords: electrical characterization, high-impedance printing, organic transistor, printed electronics, ring oscillator

IEEE Introduction

This introduction is not part of IEEE Std 1620.1-2006, IEEE Standard for Test Methods for the Characterization of Organic Transistor-Based Ring Oscillators.

This standard covers recommended methods and standardized reporting practices for electrical characterization of organic transistor-based ring oscillators. Due to the nature of organic transistors and circuitry, significant measurement errors can be introduced if not properly addressed. This standard describes the most common sources of measurement error and gives recommended practices in order to minimize and/or characterize the effect of each.

Standard reporting practices are included in order to minimize confusion in analyzing reported data. Disclosure of environmental conditions and design-of-experiment are included so that results can be appropriately assessed by the research community. These reporting practices also support repeatability of results, so that new discoveries may be confirmed more efficiently.

The practices in this standard were compiled from research and industry organizations developing organic transistor devices, materials, circuitry, and manufacturing techniques. These practices are based on standard operating procedures utilized in laboratories worldwide.

The development of this standard was initiated in 2004 to facilitate the evolution of organic transistor circuitry from the laboratory into a sustainable industry. Standardized characterization methods and reporting practices create a means of effective comparison of information and a foundation for manufacturing readiness.

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Test Methods for the Characterization of Organic Transistor-Based Ring Oscillators

1. Overview

1.1 Scope

This standard describes a method for characterizing organic electronic transistor-based ring oscillators, including measurement techniques, methods of reporting data, and the testing conditions during characterization.

1.2 Purpose

The purpose of this standard is to provide a method for systematically characterizing organic transistor-based ring oscillators. This standard is intended to maximize reproducibility of published results by providing a framework for testing organic ring oscillators, whose unique properties cause measurement issues not typically encountered with inorganic-based circuitry. This standard stresses disclosure of the procedures used to measure data and extract parameters so that data quality may be easily assessed. This standard also sets guidelines for reporting data, so that information is clear and consistent throughout the research community and industry.

1.3 Electrical characterization overview

1.3.1 Testing apparatus

Testing shall be performed using an electronic device test system with an accuracy and resolution of at least ±0.1% of the measurement values for both signal level and timing or frequency measurements. In order to maintain the necessary accuracy, this test method requires that the instrumentation be calibrated against a known and appropriate set of standards [e.g., National Institute of Standards and Technology (NIST)]. These calibrations may be performed by the equipment user or as a service by the equipment vendor. Calibration is not performed against a known organic field-effect transistor (OFET), organic circuit, or other FET-type device; the basic instrument operations (e.g., voltage, current, and resistance) are calibrated against some method traceable to a NIST (or similar internationally recognized standards organization) physical standard. Recalibration is required according to the instrument manufacturer's recommendations or when the instrument is moved or when the testing conditions change significantly (temperature change greater than 10 °C, relative humidity change greater than 30%, etc.).

1.3.2 Measurement techniques

1.3.2.1 Required measurements

Characterization of the organic ring oscillator shall include at minimum the following primary set of measurements:

- A ring of an odd number (at least three) of inverter stages, operated at a single supply voltage, characterizing output voltage from a single node versus time in seconds. The number of inverter stages should be chosen to be as large as practically possible. Ideally the ring oscillator should comprise at least seven or more stages. Shorter ring oscillators can often oscillate with signal level not closely related to their saturation values. While this results in faster oscillation, the timing numbers so obtained are much less useful in understanding realistic digital circuit speeds. In addition, ring oscillators with few stages are more affected by the way in which the output voltage is measured, and, in particular, measurement results will depend more on the capacitance with which the node being measured is loaded by the measurement. For all ring oscillators particular care should be taken to report the conditions of the signal measurement at the output node. In all cases the value of the load capacitance in relation to the input capacitance of an inverter stage should be reported.

- Both output frequency and output signal level and swing shall be reported.

- Static measurements of inverter transfer characteristics. Preferably, the inverters for static measurements should have the same size and geometry as those used in the ring oscillator. Geometry information shall be provided for both ring oscillators and static inverters.

1.3.2.2 Recommended measurements

The following additional measurements are strongly recommended:

- Measurement of ring oscillator output using multiple supply voltages.

- Simultaneous measurement of ring oscillator output at two or more nodes, using buffer stages between the ring oscillator and measurement apparatus. This is in addition to, and should not be instead of, measurement of ring oscillator output at one node.

1.3.3 Repeatability and reporting sample size

Sample performance between different devices may vary due to variations in the fabrication process. Additionally, it is useful to determine the repeatability of the reported results. Therefore, sample size is to be reported thus:

- 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 (e.g., whether all devices were characterized, a randomly-chosen fraction of the total sample set).

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

1.3.4 Application of low-noise techniques

In order for comparability between different device structures and eventual compatibility to nanoelectronics, voltages and applicable geometries are given so that electrical fields (V/cm) may be determined. For example, film thickness is reported along with VGS values, and channel length is reported with VDS data. Preferably, electrical field values are specified.

Due to optical sensitivity of some organic 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, proximity of 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.

1.3.5 Characteristics and effects of instrument probing

The probe means used for characterizing ring oscillator output will affect the waveform due to loading of the ring oscillator nodes. Methods of measuring the oscillator wave include direct probing of the ring oscillator with an oscilloscope probe (passive or active), or indirect probing where the oscillator output is connected to a suitable buffer amplifier (for example, another inverter; this mimics the loading effects when the circuit is used in typical applications).

Effects of all types of measurements include:

— Introduction of capacitance, which may reduce ring oscillator speed

— Introduction of shunt resistances, which may reduce voltage swing and/or affect oscillator speed

It is recommended that a buffer stage or stages be added to the ring oscillator for frequency output measurement. This buffer is typically an additional inverter (often, but not necessarily, with the same physical design of the inverters used to construct the ring oscillator) with the input terminal connected to the output of one stage of the oscillator. The output of the buffer stage or stages is then measured. This method of measuring the operating frequency of a ring oscillator helps to minimize the effect of capacitive loading from the measurement on oscillator performance.

Depending on circuit and measurement details, measured buffer stage output voltage level and swing may not correspond well to internal circuit values. Direct probing of internal nodes using a low-capacitance, high-impedance active probe can provide additional information about ring oscillator signal level and, for ring oscillators with buffered output, the change in operation frequency with internal node probing provides additional circuit operation information and should be reported. Direct probing of ring oscillator output with a low-capacitance, high-impedance active probe is also an acceptable alternative to the use of a buffer stage or stages. For such measurements the capacitance and resistance or current burden of the probe should be reported.

2. Definitions, abbreviations and acronyms

For the purposes of this standard, the following terms and definitions apply. *The Authoritative Dictionary of IEEE Standards* [B1][1] should be referenced for terms not defined in this clause.

2.1 Definitions

2.1.1 characteristic: I_{DS} vs. V_{DS} for a fixed V_{GS}. *See also*: **output curve**.

2.1.2 dwell time: Duration starting at the point in time when the measurement voltage is applied to the time when the measurement is recorded. Used to minimize measurement errors due to transient noise. Alternatively, sweep speed can be adjusted.

2.1.3 earth ground: Safety grounding directly to earth ground connection or instrument frame, typically separate of system/signal ground. Intended for shielding operator from high voltages and provides additional noise shielding.

2.1.4 EMI/RFI: Electromagnetic and radio-frequency interference; potential contributor to noise in measurements.

2.1.5 environmental condition: Real or artificial atmospheric conditions immediately surrounding the device under test. These values are to be measured as close to the device under test as possible, and performed in a manner that introduces minimal effect on the test environment.

2.1.6 force voltage: Voltage source that is supplied by the instrument in order to bias a particular electrode.

2.1.7 ground chuck: Conductive platform on which the device under test is placed. The ground chuck is electrically referenced to system ground.

2.1.8 output curve: I_{DS} vs. V_{DS} for a fixed V_{GS}. *See also*: **characteristic**.

2.1.9 stray capacitance: Any undesirable interlayer or interfacial capacitance within the device. These typically impede device performance and are a likely source of measurement errors.

2.1.10 system ground: Zero voltage reference or “LO” connection to instrument. Typically isolated from earth ground.

2.2 Acronyms

EMI electromagnetic interference
FET field effect transistor
NIST National Institute of Standards and Technology
OET organic electronic technology
OFET organic field-effect transistor
OST organic semiconductor technology
PFET polymer field-effect transistor
RFI radiofrequency interference
RH relative humidity
UV ultraviolet

[1] The numbers in brackets correspond to those of the bibliography in Annex A.

3. Standard ring oscillator characterization procedures

3.1 Circuit layout

The device structure used for characterization is to be reported, including general device geometry, electrode placement, etc. At minimum the following geometrical information shall be reported:

- Relation of gate electrode to substrate (e.g., bottom- or top-gate)
- Relation of source/drain electrode to semiconductor and dielectric (e.g., top-contact or bottom-contact)
- Gate length, gate width, and overlap between gate and source/drain electrodes for all devices (in µm, mm, cm, or mil)
- Dielectric thickness (in Å, nm, or µm)
- Estimated or measured semiconductor average thickness (in Å, nm, or µm)
- Microscope image of the top view of the fabricated oscillator with scale bar
- Distance between adjacent inverters
- Details of stage interconnections, including level-shifting if used
- Details of additional stage loading, for example fan-out or simulated wiring, if used
- Type of all devices used (e.g., *n*-channel, *p*-channel, or *n*- and *p*-channel, or ambipolar)
- Structure and dimensions of buffer stage (if used)

The following information for device fabrication should be reported:

- Description of the applicable fabrication process flow, including cleaning, deposition, patterning, passivation/encapsulation, and annealing/curing methods. Any surface treatment(s) between deposition steps, including chemical, interfacial agents to promote ordering (such as octadecyltrichlorosilane between dielectric and semiconductor, mechanical (e.g., brushing to promote ordering), or any other enhancements used should also be described).
- Description of applicable materials used for the semiconductor, dielectric, gate electrode, source/drain electrode, patterning-etch mask, and passivation/encapsulation.

3.2 Guidelines for the ring oscillator characterization process

Settings are to be chosen so that:

- Ring oscillator operation frequency or average stage delay versus operating voltage and current should be provided. Data should be given for a minimum of three operating points with five or more points recommended.
- For ring oscillators operating from two or more power supplies, the voltages and currents for each supply should be provided.
- Information about ring oscillator operational stability should be provided. When stability limits operation duration, this information should be provided.
- Because organic electronic device stability sometimes limits device and circuit performance, consideration of device operational degradation should be given when testing organic transistor ring oscillators. For example, beginning testing a low-power supply voltage and continuing testing

with increasing voltage may allow a wider range of operating voltage to be tested. However, beginning testing at higher power supply voltage may demonstrate shorter gate delay. In general, multiple ring oscillators should be tested with varying approach and relevant observations reported.

— Although device and circuit testing in the dark is generally recommended, testing under illumination can sometimes provide clues to changes in device operation (for example, illumination-induced trap filling). When illumination is used, device and circuit changes from dark operation should be reported.

— Ring oscillator output waveforms may be of interest, especially when such waveforms provide stage rise and fall time information.

— Inverter single-stage or delay chain time-domain measurements can provide useful additional information to ring oscillator measurements.

— Because OFET impedances often require operation far from coaxial cable-characteristic impedance, due consideration should be given to cable loading in addition to instrument loading effects. Low-capacitance, high-impedance or low-current active probes can reduce loading, but may limit measurement voltage.

Note that OFET response may not be stable over time. See 3.3 in IEEE Std 1620-2004™ [2, 3] for more information on device instability.

3.3 Other applicable standards

The measurement and hence characterization of an oscillator is corrupted by various forms of noise and uncertainty. IEEE Std 1139™-1999 [B2] recommends practices for the reporting of measurements and instabilities associated with oscillators. In addition, IEEE Std 1193™-1994 [B3] provides insight into possible systematic instabilities, however, this standard is targeted at oscillators whose frequency stability is better than one part in 10 000.

3.4 Reporting data

3.4.1 Reporting standards

The information that is reported with all electrical characterization data is shown in Table 1. The combinations are such that the other two parameters may be determined by calculation. Reporting these parameters shall follow the terminology, symbol use, and units as shown in Table 1. Environmental test and storage conditions (discussed in 3.4.8) shall also be reported.

The number of data points used for any curve fitting for parameter extraction shall be disclosed. Additionally, if available, information on the quality of the curve fitting (if any) shall also be reported (e.g., reliability factor *R*).

[2] The IEEE standards or products referred to in this clause are trademarks of the Institute of Electrical and Electronics Engineers, Inc.
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Table 1—List of parameters to be reported with all electrical data

Characteristic	Standard symbol	Units
Number of inverters	N	unitless
Oscillation frequency[a]	f_{OSC}	Hz
Time to oscillation[a]	t_I	s, ms
Time to steady state[a]	t_{SS}	s, ms
Oscillation amplitude[a]	V_{OSC}	V
Supply voltage(s)	V_{DD}, V_{SS}, *etc.*	V
Oscillator power consumption[a]	P_{Osc}	W
Gate delay (per stage)	t_{Stage}	s, ms
[a]Techniques used to calculate marked parameters shall be reported.		

3.4.2 Sample waveform

A graph of experimental data of at least one full oscillation period should be reported. As most critical parameters are extracted from the measured waveform, inclusion of this graph greatly assists in data evaluation. If multiple waveforms from the same oscillator are included, this graph should also include a schematic of the oscillator and corresponding identification of each node from which the waveforms are measured.

3.4.3 Determination and reporting of oscillation amplitude

The oscillation amplitude is the difference between the maximum and minimum in voltage of the output waveform. A graph showing a digitized sample waveform is the preferred method for reporting the oscillation amplitude. If the presented data represents a repetitive average of the waveform, the number of averages should be reported. If an accurate pictorial representation is not possible, the reported oscillation amplitude value should represent the underlying behavior of the waveform, rather than any noise that may be present.

The following measurement conditions can affect the measurement and should be reported as well:

- Ring oscillator power supply voltages
- Input impedance
- Input capacitance
- Measurement bandwidth of the instrument used to determine the oscillation amplitude

3.4.4 Determination and reporting of oscillation frequency

The oscillation period is the time elapsed between two peaks when the oscillation has reached steady state. Alternatively, the oscillation period may be determined by the time it takes the waveform to cross the midpoint twice. This midpoint is the average of the minimum and maximum voltage output value. For example, if the oscillator output varies between –60 V and 0 V, the midpoint is –30 V.

Measured oscillation frequency may be adversely affected by the electrical properties of the probes used and the instrumentation. Details of the effects of probes on oscillator performance are found in 1.3.5.

Using a frequency counter or spectrum analyzer is an alternative to characterize ring oscillator frequency. These can be used to correlate with the results of oscilloscope or other measurement technique.

For accurate determination of the frequency of oscillation, care should be taken to ensure that the measurement equipment has sufficient absolute accuracy and stability. For example, frequency sources within oscilloscopes and spectrum analyzers are not always absolutely accurate and can posses moderate levels of noise. Locking these instruments to a standard frequency source is recommended.

3.4.4.1 Voltage-dependent oscillation frequency

The oscillation frequency is typically dependent on the oscillator supply voltage. Usually, an increased supply voltage improves the transfer characteristic of the inverters, resulting in a reduced phase delay and an increase operating frequency. In the simplest case, the change in frequency is linear with the change in supply voltage, and can be reported as a frequency shift in Hertz per volt change in supply voltage. The range of supply voltage over which the shift was observed should also be reported. If the behavior of the oscillator is more complicated, best practice would be to illustrate it with a graph.

3.4.4.2 Frequency stability/period jitter

The observed frequency/oscillation period is subject to fluctuation due to the following:

- Fluctuations in the power supply voltage
- Sources of noise, including RFI/EMI
- Variations in temperature and humidity during measurement period

Minimizing the effect of these sources of variation shall be done before measurement. In order to minimize overall effect, frequency measurement shall be done for a time period much greater than the oscillation period. Measurement for at least 100 oscillation periods is recommended.

3.4.5 Determination and reporting of delay time to oscillation

The delay time to oscillation is the time elapsed between power-up of the ring oscillator circuit to the time oscillation begins.

NOTE—Time to oscillation is heavily dependent on multiple factors, many of which may not be controllable by process. For example, time to oscillation can be dependent on the charge state of each node upon powering the oscillator, and upon the ramp rate of this applied power. Other factors include stiffness of the power sources, external noise, and recent test history. Due to these factors, determination and reporting of delay time to operation is not often reported. However, if there is a need for such reporting, the specific criteria for how delay time is characterized and what is considered "start of oscillation" should be explicitly defined.[4]

3.4.6 Determination and reporting of delay time to steady-state operation

The delay time to oscillation is the time elapsed between power-up of the ring oscillator circuit to the time oscillation reaches steady state. Steady state is determined when the oscillation ceases to increase in magnitude and does not deviate more than a specified amount from an average magnitude.

The criteria for steady state heavily depend on operating conditions, the stability of devices, application requirements, nature of test, etc. Therefore, the time to attain steady state shall be disclosed along with a definition of the steady-state criterion.

[4] Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

3.4.7 Determination and reporting of oscillator power consumption

The power consumption of an oscillator is the total power (in watts) consumed by an oscillator during operation. Total power consumption is measured by monitoring current drain from the oscillator power supply set at a known and constant dc voltage.

Power consumption can be affected by many factors; it is recommended that the following should be evaluated:

- Power consumption versus supply voltage
- Static versus dynamic power consumption
- Power consumption vs. environmental factors (see 3.4.8)
- Power consumption from each oscillator stage

3.4.8 Reporting of environmental conditions

The environmental conditions present during device storage and characterization shall be reported with all electrical characterization data. Guidelines for environmental monitoring are detailed in 3.5.

3.4.9 Reporting of non-sinusoidal waveforms

Typically, the waveform output from a ring oscillator is sinusoidal. Under certain conditions, the waveform may become distorted. In such instances, the waveform shape shall be described, and should include a graphic of at least one full waveform.

Table 2—Timing parameters for non-sinusoidal waveforms

Characteristic	Standard symbols	Units
Time in high state	t_H	s, ms
Time in low state	t_L	s, ms
Rise time	t_{LH}, t_r	s, ms
Fall time	t_{HL}, t_f	s, ms

In addition to a graphical representation of the waveform, four primary attributes of the waveform should also be given. If such timing description is used, all four parameters shall be given. These parameters are listed in Table 2.

Portions in a period of oscillation are the distribution of four regions in any oscillation cycle. They are high, low, transition from low to high, and transition from high to low. The high and low state can be defined in any way that is necessary for the application, but the definitions shall be given. Typically, the high state is the voltage at which is closest to the power supply voltage. The low state is usually the voltage that is closest to ground voltage.

The time in the high state is the time in a steady-state oscillation period that the output stays within 10% of the oscillation amplitude from the high output voltage in the period.

The time in the low state is the time in a steady-state oscillation period that the output stays within 10% of the oscillation amplitude from the low output voltage in the period.

The rise time is the time required for the waveform to move from 10% of the low state voltage to within 10% of the high state voltage.

The fall time is the time required for the waveform to move from 10% of the high state voltage to within 10% of the low state voltage.

3.5 Environmental control and standards

Circuit storage conditions from time of device fabrication to time of measurement are to be reported. Environmental conditions during circuit storage have been shown to significantly affect circuit performance. Changes in the storage and characterization environment will result in potentially significant variation in circuit performance. Therefore, diligent reporting of circuit storage and characterization environments is necessary for comparing or verifying data.

The environmental conditions driving the measurement shall be monitored and recorded for every measurement. Conditions are at a minimum to be recorded at the beginning and at the end of each experiment. However, real-time recording of the environmental conditions repeatedly and recorded with each data point is recommended.

The following environmental conditions must be monitored and recorded:

- Measurement atmosphere (e.g., ambient air, nitrogen environment, vacuum)
- Light illumination conditions and light exposure time (e.g., dark, UV protection, etc.). Also include change in lighting conditions, such as length of time sample was placed in dark after light exposure and before electrical measurement.
- Device temperature (measured to a resolution of at least 1 °C or 1 K, 0.1 °C or 0.1 K recommended).
- Relative humidity (RH) (to a resolution of 5% minimum, 1% recommended).
- Measurement duration, time of measurement (in order to assist in evaluating measurement artifacts due to very long lifetime effects).

Annex A
(informative)
Bibliography

[B1] IEEE 100™, *The Authoritative Dictionary of IEEE Standards Terms*, Seventh Edition.[5, 6]

[B2] IEEE Standard 1139-1999™, IEEE Standard Definitions of Physical Quantities for Fundamental Frequency and Time Metrology—Random Instabilities.

[B3] IEEE Standard 1193-1994™, IEEE Guide for Measurement of Environmental Sensitivities of Standard Frequency Generators

[B4] "Accurate and Efficient Frequency Evaluation of a Ring Oscillator," Agilent Application Note 4070-3, 2000.

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[6] IEEE publications are available from the Institute of Electrical and Electronics Engineers, Inc., 445 Hoes Lane, Piscataway, NJ 08854, USA (http://standards.ieee.org/).

Annex B
(informative)
IEEE List of Participants

At the time this standard was completed, the Working Group for Organic and Molecular Electronics had the following membership:

Daniel Gamota, *Chair*
Paul Brazis, Jr., *Vice Chair*

Hakeem Adewole
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