IEC 62047-28

Edition 1.0 2017-01

# INTERNATIONAL STANDARD



colour inside

## Semiconductor devices – Micro-electromechanical devices – Part 28: Performance testing method of vibration-driven MEMS electret energy harvesting devices

IEC 62047-28:2017-01(en)

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

Tel.: +41 22 919 02 11
Fax: +41 22 919 03 00
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 corrigenda or an amendment might have been published.

**IEC Catalogue - webstore.iec.ch/catalogue**
The stand-alone application for consulting the entire bibliographical information on IEC International Standards, Technical Specifications, Technical Reports and other documents. Available for PC, Mac OS, Android Tablets and iPad.

**IEC publications search - www.iec.ch/searchpub**
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 It also gives information on projects, replaced and withdrawn publications.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 also once a month by email.

**Electropedia - www.electropedia.org**
The world's leading online dictionary of electronic and electrical terms containing 20 000 terms and definitions in English and French, with equivalent terms in 16 additional languages. Also known as the International Electrotechnical Vocabulary (IEV) online.

**IEC Glossary - std.iec.ch/glossary**
65 000 electrotechnical terminology entries in English and French extracted from the Terms and Definitions clause of IEC publications issued since 2002. Some entries have been collected from earlier publications of IEC TC 37, 77, 86 and CISPR.

**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: csc@iec.ch.

IEC 62047-28

Edition 1.0 2017-01

# INTERNATIONAL STANDARD



colour inside

## Semiconductor devices – Micro-electromechanical devices – Part 28: Performance testing method of vibration-driven MEMS electret energy harvesting devices

INTERNATIONAL ELECTROTECHNICAL COMMISSION

ICS 31.080.99

ISBN 978-2-8322-3819-6

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

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

____________

**SEMICONDUCTOR DEVICES –**
**MICRO-ELECTROMECHANICAL DEVICES –**

**Part 28: Performance testing method of vibration-driven MEMS electret energy harvesting 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) Attention is drawn to the possibility that some of the elements of this IEC Publication may be the subject of patent rights. IEC shall not be held responsible for identifying any or all such patent rights.

International Standard IEC 62047-28 has been prepared by subcommittee 47F: Micro-electromechanical systems, of IEC technical committee 47: Semiconductor devices.

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

| FDIS | Report on voting |
|---|---|
| 47F/266/FDIS | 47F/271/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 62047 series, published under the general title *Semiconductor devices – Micro-electromechanical 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

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

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

**IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.**

# SEMICONDUCTOR DEVICES – MICRO-ELECTROMECHANICAL DEVICES –

# Part 28: Performance testing method of vibration-driven MEMS electret energy harvesting devices

## 1 Scope

This part of IEC 62047 specifies terms and definitions, and a performance testing method of vibration driven MEMS electret energy harvesting devices to determine the characteristic parameters for consumer, industry or any application.

This document applies to vibration driven electret energy harvesting devices whose electrodes with a gap below 1 000 µm are covered by dielectric material with trapped charges and are fabricated by MEMS processes such as etching, photolithography or deposition.



## 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.

**3.1**
**vibration frequency**
frequency of the periodic motion of vibration-driven MEMS electret energy harvesting devices

**3.2**
**vibration acceleration**
acceleration applied to the vibration-driven MEMS electret energy harvesting devices

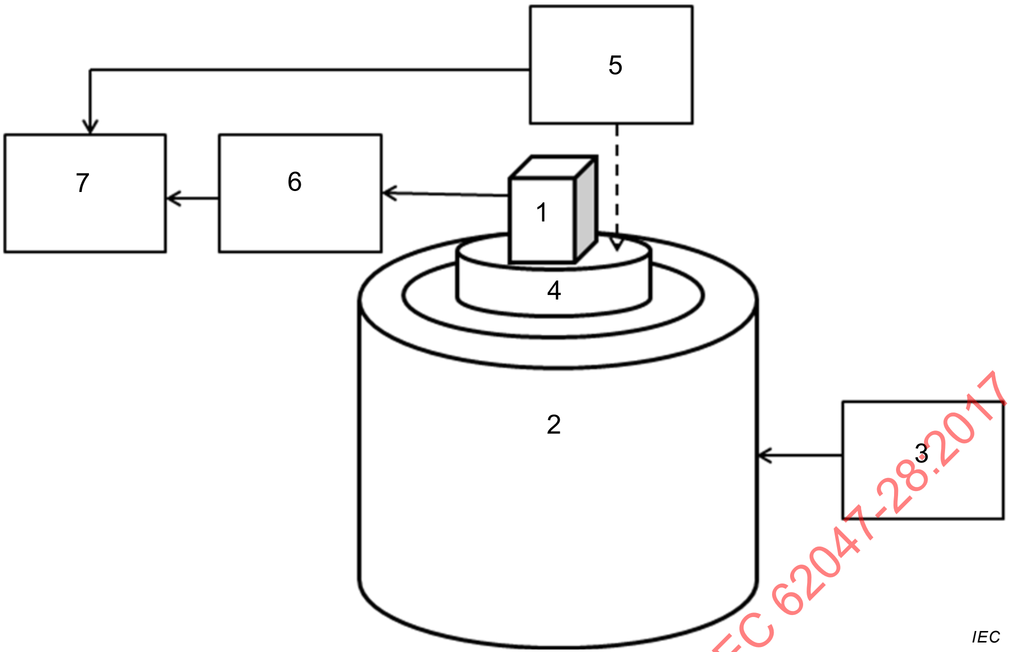
**3.3**
**amplitude**
maximum displacement in movement of the vibration-driven MEMS electret energy harvesting devices

**3.4**
**vibration direction**
direction of vibration applied to the vibration-driven MEMS electret energy harvesting device

## 4 Vibration testing equipment

### 4.1 General

Figure 1 provides fundamental configurations consisted of functional blocks or components for vibration testing equipment for MEMS electrets energy harvesting devices at a specified constant frequency and constant acceleration. Details of the functional blocks or components named as the keys are provided in the following 4.2 to 4.5.




**Key**

| | | | |
|---|---|---|---|
| 1 | DUT: Device under test | 2 | Vibration exciter |
| 3 | Vibration controller | 4 | Mounting bracket |
| 5 | Vibration detector | 6 | External load/output detector |
| 7 | Data recorder | | |

**Figure 1 – Testing equipment for vibration driven MEMS electret energy harvesting devices**



### 4.2 Vibration exciter

The vibration exciter shall generate vibration acceleration of necessary frequency along with necessary direction. Also the amplitude of the vibration perpendicular to the driving direction should be small enough.

The vibration acceleration control can be performed by either of the following methods:

a) Constant amplitude control: To maintain the vibration acceleration, by detecting and controlling the amplitude of the vibration for given vibration frequency;

b) Constant acceleration control: To maintain the vibration acceleration, by detecting and controlling vibration acceleration directly for given vibration frequency.

### 4.3 Mounting bracket

The mounting bracket shall fix the MEMS electret energy harvesting device under testing to the vibration exciter so that the generated vibration can drive the test device correctly. In addition, the direction of the vibration generated by the vibration exciter shall be within 2 degrees from the determined direction of vibration of the tested device.

### 4.4 Vibration or acceleration detector

The vibration or acceleration detector shall measure the vibration amplitude or vibration acceleration of the bracket or the DUT.

### 4.5 Output detector

The output detector and relevant equipment shall measure the voltage across the external load and the output power of the MEMS electret energy harvesting device within 3 % measurement error. The sampling frequency of the output detector shall be high enough to capture the wave form of the output voltage. In addition, the wiring between the electrical output and the DUT shall be short enough to minimize unwanted effect of parasitic capacitance.

### 4.6 Data recorder

The test system of vibration driven MEMS electret energy harvesting devices shall include data recorder to collect recording data as shown in 7.4.

## 5 Vibration-driven MEMS energy harvesting devices for testing

### 5.1 General

The vibration-driven MEMS energy harvesting devices for testing shall indicate way of mounting and direction of vibration. Furthermore the device for testing shall be mounted on the vibration exciter with the mounting bracket, and driven with determined vibration frequency and acceleration.

### 5.2 Electrical output

The device for testing shall comprise an electrical output.



## 6 Test conditions

### 6.1 Vibration frequency

Vibration frequency shall be constant during testing. When changing frequency, vibration shall be stopped before adjusting frequency. In case of sweeping frequency, sweep rate shall be low enough to minimize unintentional influence to characteristics of power generation. Data for sweeping in both directions (low to high or vice versa) shall be recorded. Also the testing vibration frequency range shall include the resonant frequency.

NOTE Resonant frequency is the frequency given in specification, or the frequency that generates peak output power in case of frequency sweeping.

### 6.2 Vibration acceleration

Vibration acceleration shall be constant during testing.

### 6.3 Waveform

Waveform of vibration shall be sinusoidal wave.

### 6.4 External load

External load shall be pure resistor of known value. Also parasitic capacitance of the external load and the output detector shall be measured.

### 6.5 Testing time

Testing time shall be long enough to stabilize electrical output of power generator for testing in comparison with vibration frequency and acceleration.

### 6.6 Test environment

The temperature and relative humidity should be constant during the test.

## 7 Measuring procedures

### 7.1 General

The following measuring procedures and measuring conditions are to be applied to the vibration testing equipment for MEMS energy harvesting devices as provided in Figure 1.

### 7.2 Vibration frequency response

The following steps are measuring procedures of the vibration frequency response.

a) Set an ambient temperature and relative humidity;
b) Fix the DUT on the vibration exciter with the mounting bracket;
c) Set an external load to the output of the DUT;
d) Apply input voltage to the vibration exciter to generate sinusoidal vibration and vibrate the DUT;
e) Measure vibration frequency and amplitude of the DUT;
f) Measure output voltage and power output of the DUT.

### 7.3 Vibration acceleration response

The following steps are measuring procedures of the vibration acceleration response.

a) Set an ambient temperature and relative humidity;
b) Fix the DUT on the vibration exciter with the mounting bracket;
c) Set an external load to the output of the DUT;
d) Apply appropriate input voltage to the vibration exciter to generate sinusoidal vibration and vibrate the DUT with a given frequency;
e) Measure acceleration of the DUT;
f) Measure output voltage and power output of the DUT.

### 7.4 Measuring conditions and electric characteristics of the external load

The measuring conditions and electric characteristics of the external load as provided in Figure 1 are as follows.

a) Set an ambient temperature and relative humidity.
b) Measure values of a specified resistance and parasitic capacitance of the external load and the output detector provided in Figure 1.

The resistor as the external load should be specified by considering resistance value, parasitic capacitance value and applied equipments or systems of the DUT.

## 8 Test report

Test report shall include at least the following information.

a) Mandatory:
   1) reference to this document;
   2) shape, weight and dimensions of tested energy harvesting device;
   3) test equipment;

4) detail of output detector and data recorder;
5) method for fixation of the energy harvesting device on the vibration exciter;
6) test conditions;
   – vibration frequency;
   – vibration acceleration;
   – external load;
   – parasitic capacitance;
   – testing time;
   – test environment (temperature and relative humidity);
7) test results;
   – output voltage;
   – output power.

b) Optional:
   1) purpose of testing;
   2) structure of tested device;
   3) principle of power generation.

# Annex A
(informative)

# Example of measurement for electret energy harvester

## A.1 General

Annex A describes an example of measurement for electret energy harvester. Clauses A.2 to A.5 summarize the principles of MEMS electret energy harvesting and the methods of measurement.

## A.2 Numerical model of electret energy harvester

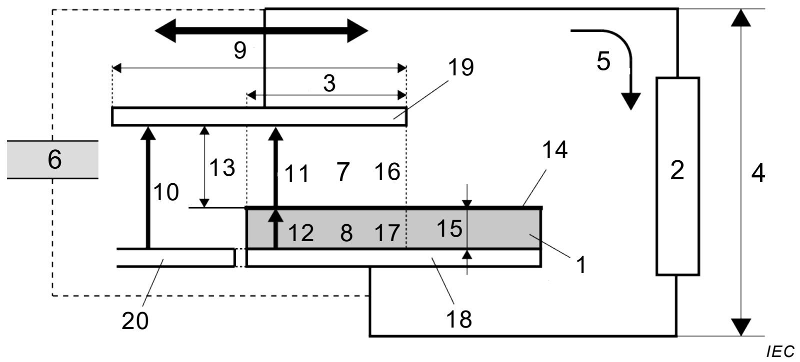
Figure A.1 shows a basic configuration of in-plane electret energy harvester [1][1], [2].

$X(t)$ is the length of the overlapping area between vibrating counter electrode and the electret depending on a specified time interval of $t$. As specified in Figure A.1, the voltage difference between counter electrode and base electrode $V(t)$ can be observed with a specified external resistor connected with the electrodes of DUT. $V(t)$ arises by the induced current $I(t)$ by mechanical vibration of a part of DUT.

The relationship between $V(t)$ and $X(t)$ is obtained by using the relationship from Equations (A.1) to (A.5).



1 Numbers in square brackets refer to the Bibliography.




**Key**

| | | | | | |
|---|---|---|---|---|---|
| 1 | DUT: basic configuration of in-plane electrets energy harvester | 8 | $C_e$: capacitance between the electret surface and the base electrode | 15 | $d$: thickness of the electret film |
| 2 | R: specified external resistor | 9 | $w$: width of the counter electrode | 16 | $\varepsilon_1$: relative permittivity of the air gap |
| 3 | $X(t)$: length of the overlapping area between the electret and the counter electrode | 10 | $E_c$: electrostatic field between the counter electrode and the guard electrode | 17 | $\varepsilon_2$: relative permittivity of the electret |
| 4 | $V(t)$: voltage difference between the counter electrode and the base electrode | 11 | $E_a$: electrostatic field between the counter electrode and the electret surface | 18 | base electrode: electrode attached to the bottom of the electret |
| 5 | $I(t)$: induced current by the mechanical vibration of a part of DUT | 12 | $E_b$: electrostatic field between the electret surface and the base electrode | 19 | counter electrode: electrode with narrow air gap from the electret |
| 6 | $C_p$: parasitic capacitance of DUT | 13 | $g$: gap between the counter electrode and the air gap | 20 | guard electrode: additional electrode to minimize the unwanted effect of the fringe field |
| 7 | $C_g$: capacitance between the electret surface and the counter electrode | 14 | $\sigma$: surface charge density | | |

**Figure A.1 – Basic configuration of in-plane electret energy harvester**



A one-dimensional electrostatic field is assumed. $\sigma$, $d$, $g$, and $\varepsilon$ are respectively the surface charge density, thickness of the electret film, the gap between the electret and the counter electrode, and relative permittivity of the electret material. In Figure A.1, a guard electrode is employed to reduce the fringe field and thus the parasitic capacitance $C_p$. The external load is assumed to be a pure resistance R. The parasitic capacitance is assumed to be constant with time. Applying the Gauss's law at the electret surface, we get

$$-\varepsilon_2\varepsilon_0 E_b + \varepsilon_1\varepsilon_0 E_a = \sigma \tag{A.1}$$

where

$E_b$ is the electrostatic field between the electret surface and the base electrode;

$E_a$ is the electrostatic field between the counter electrode and the electret surface;

$\sigma$ is the surface charge density;

$\varepsilon_1$ is the permittivity of the air gap;

$\varepsilon_2$ is the relative permittivity of the electret material;

$\varepsilon_0$ is the permittivity of vacuum.

By using the Kirchhoff's law, the following equations are obtained.

$$V(t) + dE_b + gE_a = 0 \tag{A.2}$$

$$V(t)+(d+g)E_c = 0 \tag{A.3}$$

where

$E_c$ is the electrostatic field between the counter electrode and the guard electrode.

The induced current $I(t)$ is obtained with the conservation charges given by Equation (A.4):

$$\frac{d}{dt}[\sigma_{i1}bX(t)+\sigma_{i2}b\{w-X(t)\}]+I(t)=0 \tag{A.4}$$

where

$\sigma_{i1}$ is the induced charges on the counter electrode overlapped with the electret;

$\sigma_{i2}$ is the induced charges on the counter electrode overlapped with the guard electrode;

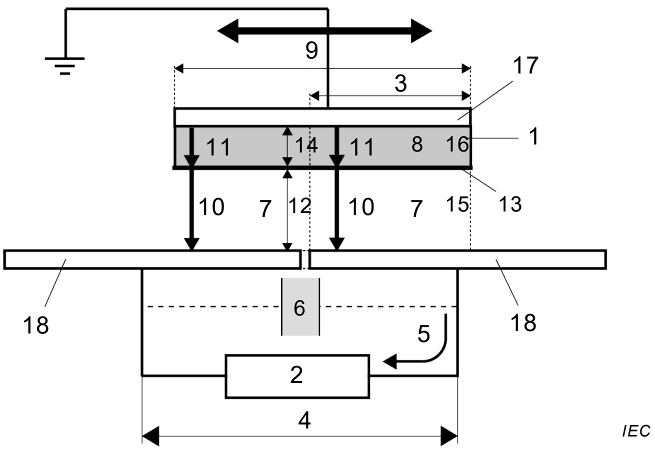
$b$ is the depth of the electrodes.

The induced charges are given by the following Equation (A.5):

$$\sigma_{i1}=-\varepsilon_1\varepsilon_0 E_a, \text{ and } \sigma_{i2}=-\varepsilon_1\varepsilon_0 E_c \tag{A.5}$$

Substituting Equations (A.1), (A.2), (A.3) and (A.5) into Equation (A.4), a differential equation with respect to the output voltage $V(t)$ is obtained, which can be solved numerically. When a sinusoidal vibration is applied to the counter electrode, the overlapping area $X(t)$ is also a sinusoidal function with given amplitude and frequency.

Figure A.2 shows an alternative configuration with patterned electret/electrodes, in which the electret is vibrating above a pair of electrodes. In this configuration, induced current flows in between two sets of the bottom electrodes. The main contribution to the parasitic capacitance is the capacitance between neighbouring electrodes [3].




**Key**

1 DUT: alternative configuration of in-plane electrets energy harvester

2 R: specified external resistor

3 $X(t)$: length of the overlapping area between the electret and the counter electrode

4 $V(t)$: voltage difference between the work electrodes

5 $I(t)$: induced current by the mechanical vibration of a part of DUT

6 $C_p$: parasitic capacitance of DUT

7 $C_g$: capacitance between the electret surface and the work electrodes

8 $C_e$: capacitance between the electret surface and the base electrode

9 $w$: width of the counter electrode

10 $E_a$: electrostatic field between the work electrode and the electret surface

11 $E_b$: electrostatic field between the electret surface and the base electrode

12 $g$: gap between the counter electrode and the air gap

13 $\sigma$: surface charge density

14 $d$: thickness of the electret film

15 $\varepsilon_1$: relative permittivity of the air gap

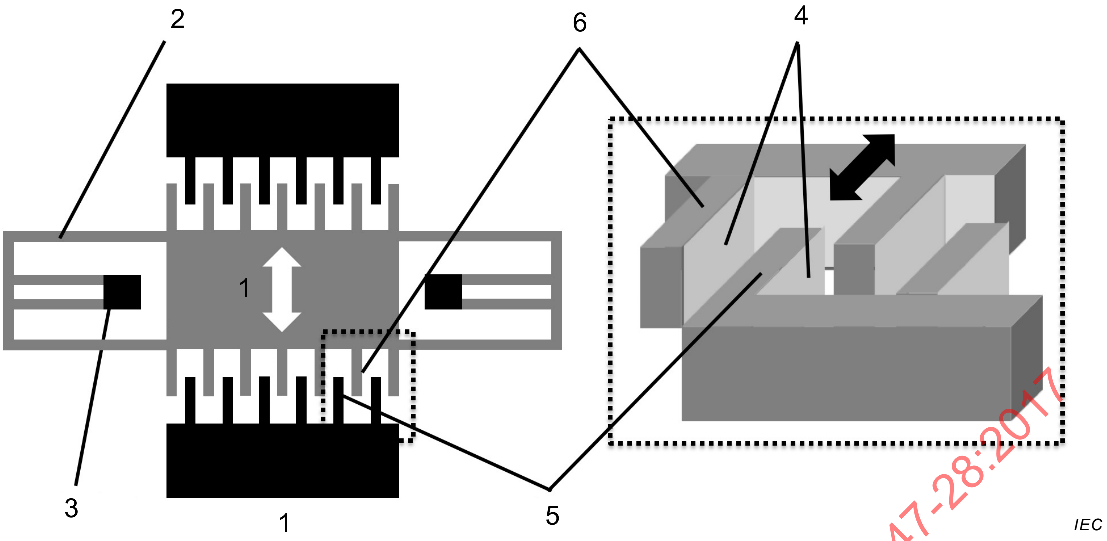
16 $\varepsilon_2$: relative permittivity of the electret

17 base electrode: electrode attached to the bottom of the electret

18 work electrode: electrode with narrow air gap from the electret

**Figure A.2 – Alternative configuration of in-plane electret energy harvester with patterned electrets and electrodes**

Figure A.3 shows an in-plane electret energy harvester with comb drives, where electret layers are formed on the vertical sidewalls of the comb electrodes. Depending on the vibration direction, the capacitance is changed due to the overlapping-area change or the air-gap change [4].




**Key**

1 DUT: in-plane electrets energy harvester with comb drives

2 spring: flexible member of the DUT supporting the mass

3 anchor: a part of the spring fixed on the substrate

4 electret: dielectric film with trapped charges for electrostatic induction

5 fixed electrodes: electrodes fixed on the substrate

6 movable electrodes: electrodes moving under vibration

**Figure A.3 – In-plane electret energy harvester with comb drives**

## A.3 An example of in-plane electret energy harvester with comb drives

Figure A.4 shows a prototype electret energy harvester with comb drives employed for an example test [4]. The energy harvester is microfabricated onto a 70 μm-thick Si device layer of a SOI wafer. Its dimensions are 10 mm x 10 mm and 0,6 mm in thickness. The Si chip is glued onto a print circuit board (32 mm x 32 mm) and the electrical connection is made with wire bonding. When external vibration is applied, the overlapping area between neighboring comb fingers with charged electret is changed and thus the external current is induced. The number of comb finger pairs is 1 035.

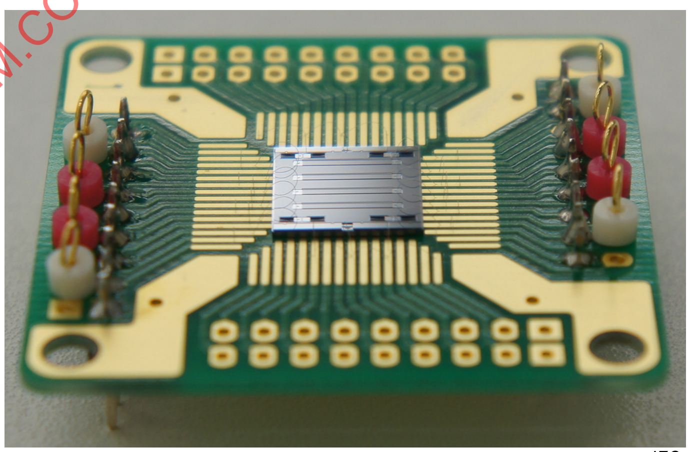
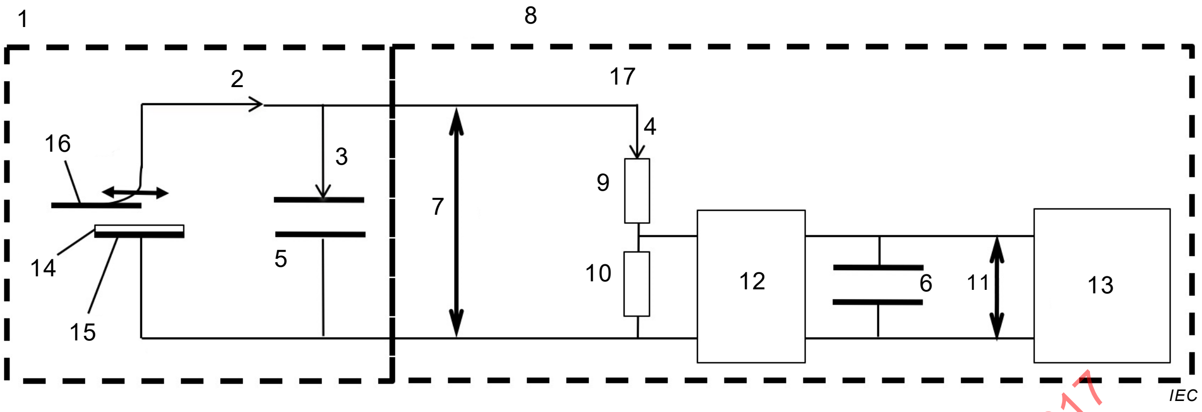



**Figure A.4 – In-plane electret energy harvester with comb drives mounted onto a PC board**

Figure A.5 shows an output detector for electret energy harvester [4].




**Key**

1 DUT: in-plane electrets energy harvester

2 $I_0$: internal induced current by the mechanical vibration of a part of DUT

3 $I_p$: current loss to the internal parasitic capacitance

4 $I(t)$: induced current by the mechanical vibration of a part of DUT

5 $C_p$: internal parasitic capacitance of DUT

6 $C_{pe}$: external parasitic capacitance of the A/D converter

7 $V(t)$: voltage difference between the counter electrode and the base electrode

8 output detector: read-out circuits for the DUT

9 R: external resistor of the voltage divider specified value for an example; 2.5 MΩ

10 r: resistor for voltage divider specified value for an example; 30 kΩ

11 $U(t)$: voltage difference across the resistor for voltage divider

12 Voltage follower: buffer amplifier with high input impedance

13 A/D converter: analog-to-digital converter for the voltage measurement

14 electret: dielectric film with trapped charges for electrostatic induction

15 base electrode: electrode attached to the bottom of the electret

16 counter electrode: electrode with narrow air gap from the electret

17 voltage divider: read out circuit parts to the voltage follower of the output detector

**Figure A.5 – Output detector for electret energy harvester**

## A.4 Experimental setup and procedure

An electromagnetic shaker is a device for applying sinusoidal vibration to the energy harvester. The energy harvester is fixed with metal screws onto the electromagnetic shaker. The external acceleration is measured with an accelerometer. The vibration test controller regulates frequency and acceleration to drive the electromagnetic shaker for different vibration frequencies. Figure A.5 shows the present output detector with a voltage divider and high-impedance voltage follower which typically consists of an operational amplifier with high input impedance. Output voltage across the 30 kΩ resistor is measured with a 16 bit A/D converter. Sampling frequency is 50 kHz. Optimum external load, which corresponds to the matched impedance, is about 2,5 MΩ, while the actual external load is 2,53 MΩ. Although the parasitic capacitance of the A/D converter including cables and its connection terminal is as large as 600 pF, its unwanted effect is almost negligible when the 66,7:1 voltage divider is used.

For the present test, the external load is kept constant, and the vibration frequency is changed while keeping the external acceleration constant. Based on the preliminary tests, low frequency sweeping rate of 0,5 octave/min (frequency is doubled in two minutes) is employed to minimize the unwanted transient effect during frequency sweeping.